All-Electric Wave Energy Power Take Off System with Improved Power Quality at the Grid Connection Point

Jonas Sjolte, Ida Bjerke, Aina Crozier, Gaute Tjensvoll, and Marta Molinas, *Member, IEEE*

***Abstract*—*Wave Energy Converters* (WEC) with all electric *Power Take Off* (PTO) systems have large fluctuations in output power, and have a peak to average power ratio way beyond most other energy producers. Special care must therefore be taken when designing such systems for power export to grid. This paper focuses on the electrical design of the PTO and how to optimize towards an optimum peak to average ratio for export. The optimization method is based on the possibility to design the electrical machine with a high ratio between nominal speed and maximum speed, termed the *overspeed ratio*. The design method is implemented into Fred Olsen's point absorber simulation model and run for various overspeed ratios. A full year of production based on a given scatter diagram is simulated and the resulting annual production and load hours is presented. The simulations show that a high overspeed ratio can be beneficial for most direct driven systems.**

***Index Terms*—Wave Energy, Power take off, Electrical, Generator, Overspeed, Load hours, Export**

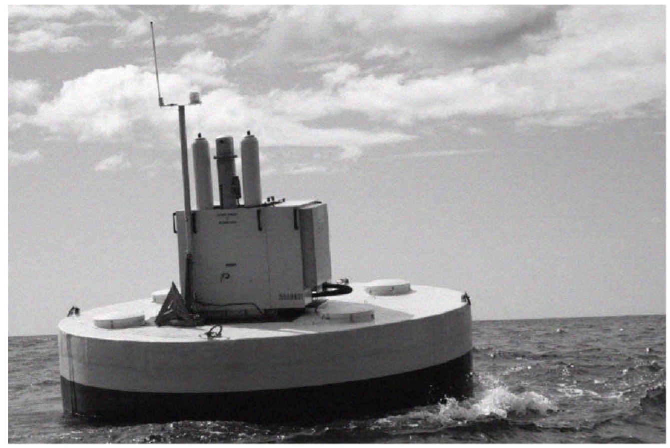

Fig. 1. Fred Olsens Wave Energy Converter *BOLT*® located outside Risør, Norway

I. Introduction

Wave energy producers are different from most other energy producers in that the prime mover operates with a sinusoidal velocity. When such a producer is directly connected to its generator, the generator also has to operate in a sinusoidal manner where the speed is continuously fluctuating from positive to negative. This leads to a continuously fluctuating power output that has to touch zero in every wave. This behavior can be seen in figure 2 which shows the power output from Fred Olsens *Wave Energy Converter* (WEC) *BOLT*® [1].

In addition to the power fluctuation in a single wave, the average power between consecutive wave groups is also fluctuating. This can also be seen in figure 2. These properties lead to a high peak power to average power ratio, often above 10 [2].

This paper focuses on how the peak to average ratio can be optimized in the *Power Take Off* (PTO) design in direct driven systems. The method pursued is based on designing the generator and converter system with a nominal speed that is less than the maximum speed. This is referred to as the *overspeed ratio* in the following. When the generator reaches its nominal speed, it enters a power saturation region that helps limit the peak to average power ratio.

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Manuscript received September 21, 2011; revised January 11, 2007.

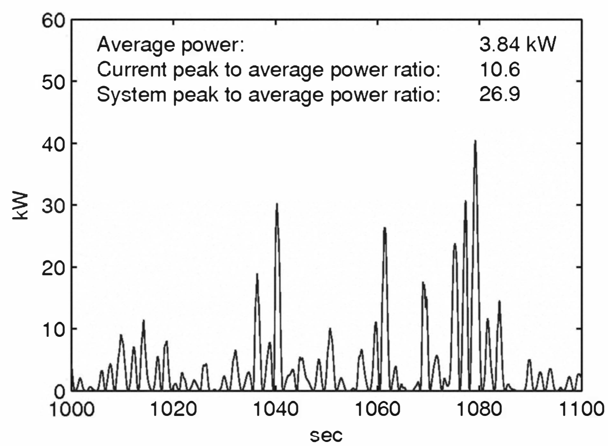

Fig. 2. Typical power output from BOLT in low waves

The peak to average ratio drives both the cost of the single PTO and the downstream power transmission system and grid connection. This is one of the greatest challenges when designing a grid connected WEC system. The method explored in this paper allows for some reduction in the cost driving elements and should always be included in the design process for direct driven generators.

There are two reasons why a high peak to average ratio is unfortunate. The first is that the peak power is driving costs while average power is driving income. The second is the power quality at the grid connection point.

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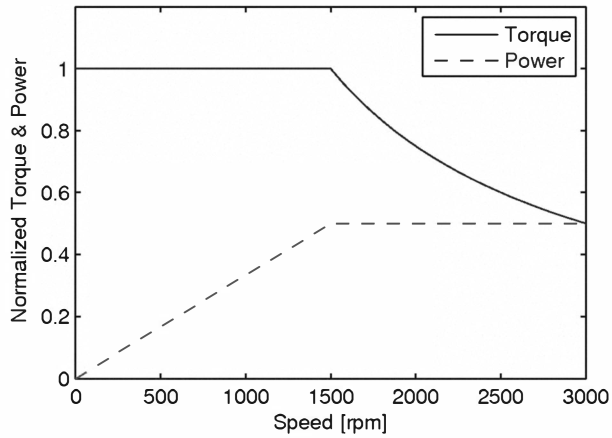


Fig. 3. Available torque from an electrical machine above and below nominal speed

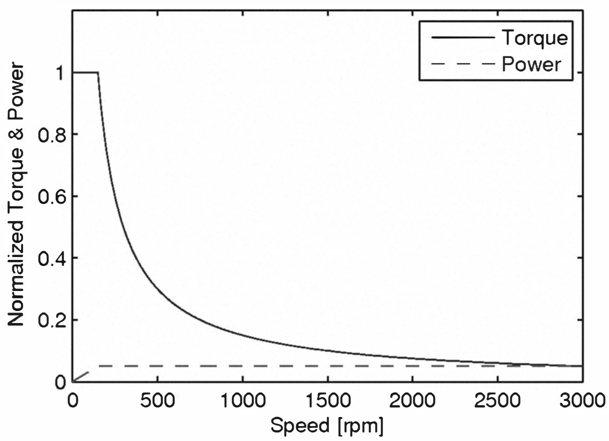


Fig. 4. Available torque from a PMSM machine with an overspeed ratio of 20

A. Fred Olsens Wave Energy Project

Fred Olsen, FO, started with Wave Energy in 2000. In 2004 FO built and launched *Buldra*®, the Wave Energy Converter based on the Aker H3 semi-submersible platform. Since then FO have tested out various concepts and built several different prototypes which have led to the the single body point absorber system *BOLT*®. This has not shown to be the most efficient wave energy absorber, but has shown to be most successful on total performance for cost of energy. *BOLT*® has been in operation outside Risør in Norway since June 2009 and is shown in figure 1. Currently FO is building the next generation of *BOLT*®, currently called *BOLT2*, through the *BOLT2Wavehub* project. This is a joint project between Fred Olsen and several UK companies funded by the UK *Techonology Strategy Board*, TSB. The goal of the project is to further develop BOLT into a commercial system that is ready for operation at the UK wave test facility *Wavehub* [3].

II. PTO DESIGN

Fred Olsen's WEC concept is based on a flat absorber with low mass that gives a high resonance frequency and thus a *Response amplitude operator*, RAO, [4] close to one for most of the relevant wave states. This gives a stiff system that is well suited for passive damping and less suitable for reactive control. The absorber is tightly moored to the sea floor by a winch. The winch connects to the generator through a gearbox. This is shown in figure 5 and is a well known conversion system that has been researched and tested by several parties [5]. Pre-tension in the mooring line is supplied either by a secondary spring equivalent system or by the main generator itself.

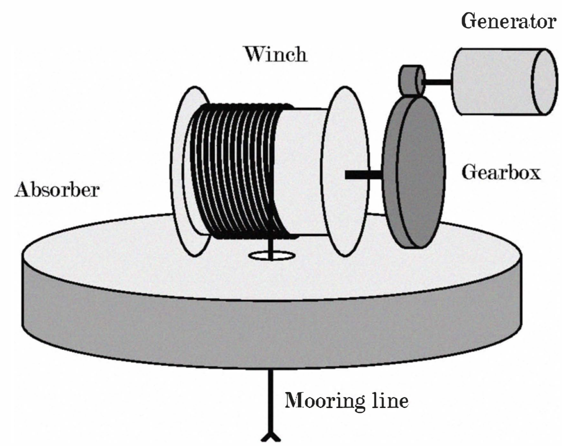


Fig. 5. Principal sketch of the WEC

The main design property for a PTO is the production force. This defines the mechanical structure and strength for most of the components. Since the WEC velocity is far below the critical speed for most of its components, speed and thus power has little impact. The PTO cost is therefore mostly force driven. This also applies to the generator where the size is determined by the required torque. It is not until one reaches the generator windings that the power domain is fully entered. From the generator output and all the way to the grid connection point, power is the main cost driving parameter.

A. Generator design

The generator has to be included in the mechanical PTO design and has to comply with the force and speed requirements of the system. These are the mechanical properties of the generator. The electrical properties of the generator is given by its pole count, rotor configuration and winding properties [6]. The electrical properties give the torque/current relation and the speed/voltage relation, which links the mechanical and electrical properties. In the following, the generator system is defined as a frequency converter controlled *Permanent Magnet Synchronous Machine* (PMSM) [7]. Figure 7 shows how the generator system is electrically integrated into the WEC system. As suggested by the figure several WECs can be connected together on the DC-Link for power smoothing before the power is transformed to AC.

Faradays' law of induction, as given in equation 1 defines the relationship between the induced voltage (ϵ), and rate of change in magnetic flux (ϕ) through a conductive loop.

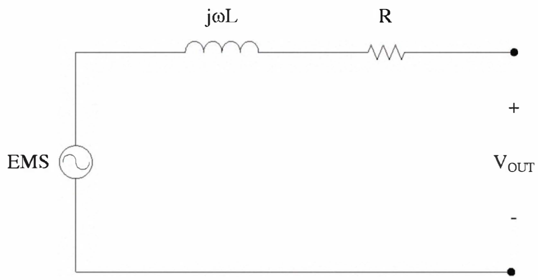


Fig. 6. Equivalent circuit for PM generator

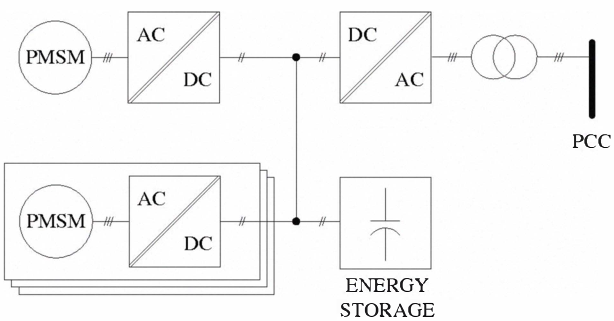


Fig. 7. Principal diagram for BOLT2

From this equation 2 can be derived which gives the induced voltage in n loops with area A that rotates with the speed ω in magnetic field with constant flux density B. This shows the relationship between open circuit voltage and speed of a PMSM. Since the magnetic flux generated by the permanent magnets and the geometrical properties are constant, equation 2 can be simplified into equation 3 where v_{out} is the open circuit voltage and k is a constant. The equivalent circuit of the generator is shown in figure 6.

From this, and by including the electrical impedance of the machine, the nominal conditions can be expressed as given by equation 4 where I_n is the nominal current and V_n is the nominal voltage. This shows that the number of pole windings works as a scaling factor between nominal current and voltage. The converter however, has a fixed nominal voltage and as shown by equation 5 where P_n is the nominal power, ω_n is the nominal speed and M_n is the nominal torque, the pole winding count defines the nominal power and the nominal speed of the machine. The nominal torque is assumed to be defined by the physical size and properties of the machine that was decided in an earlier stage of the design process.

$$\epsilon = -\frac{d\phi}{dt} \tag{1}$$

$$\epsilon\left(t\right) = n \cdot \omega \cdot B \cdot A \cdot \sin\left(\omega t\right) \tag{2}$$

$$v_{out}\left(t\right) = k \cdot n \cdot \sin\left(\omega t\right) \tag{3}$$

$$\frac{V_n}{I_n} = k \cdot n \tag{4}$$

$$P_n = V_n \cdot I_n = \omega_n \cdot M_n \tag{5}$$

Above nominal speed, the output voltage must be kept within limits by field weakening. For PMSMs, this leads to a reduction in available torque that is inversely proportional to the speed. Figure 3 shows the speed torque curve for a common PMSM.

In context of the rather extreme peak to average speed ratio it would be interesting to explore an extreme overspeed ratio of the generator. *BOLT*® for instance is operating with an average speed of 0.3 m/s in the most common wave state, but has to handle above 5 m/s in the most extreme wave state. The overspeed ratio is inversely proportional to installed power and an increased overspeed ratio will therefore reduce the cost through the power chain and improve the capacity factor. In the following systems with very high maximum to nominal speed ratio are investigated.

B. Control strategy

The absorbed power form a point absorber is greatly influenced by the control strategy applied by the PTO. In general the optimal energy extraction is achieved when the point absorber is moving with a 90° phase shift to the waves. Several methods of approaching this production mode are described, the best known being *reactive control* [8], [9] and *latching control* [10]. Figure 8 shows an electrical equivalent circuit for the WEC. The dynamic behaviour of the WEC is modeled as an RLC circuit and the PTO is modelled by a power extracting element (resitance) and a reactive element (impedance). The goal of reactive control is to tune the reactive element of the PTO so that it compensates for the reactive elements of the WEC as a whole and thus maximizes power extraction.

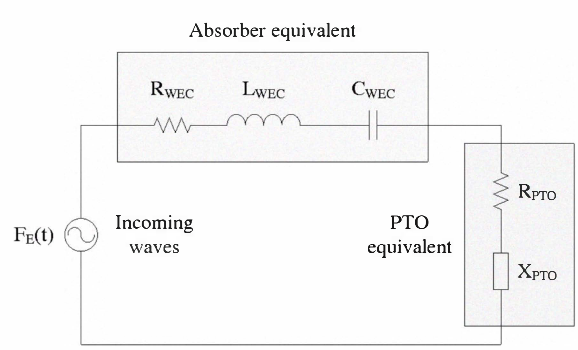


Fig. 8. Equivalent circuit for Wave Energy Converter and Power Take Off

However, with the current design of the BOLT concept the PTO is too small to have significant impact by advanced control. Passive damping therefore serves as the primary production model. In the lowest sea states however, advanced control algorithms can improve output [2], but is not currently performed. The reason for the small PTO is the result of economical optimization and Fred Olsen acquired viewpoint that direct driven electrical PTOs should be designed so that they are saturated on force and power already in low sea states.

Passive damping is defined by equation 6 where the damping coefficient B is optimized towards the highest efficiency region of the machine to produce the highest possible net power output. M and ω is torque and speed on the generator. Figure 9 shows the torque and speed characteristics for the generator used on BOLT2 [11]. The thick line shows the optimal torque that result in maximum net power from the generator. The first saturation mechanism is the mechanical force limit of the gearbox and is reached already at 0.27 m/s. The second is the power limit of the generator, which is reached at 1.55 m/s. The linear region from 0 - 0.27 m/s corresponds to a damping coefficient of ca 350 kNs/m which is the chosen value for B on BOLT2.

$$M = -B \cdot \omega \tag{6}$$

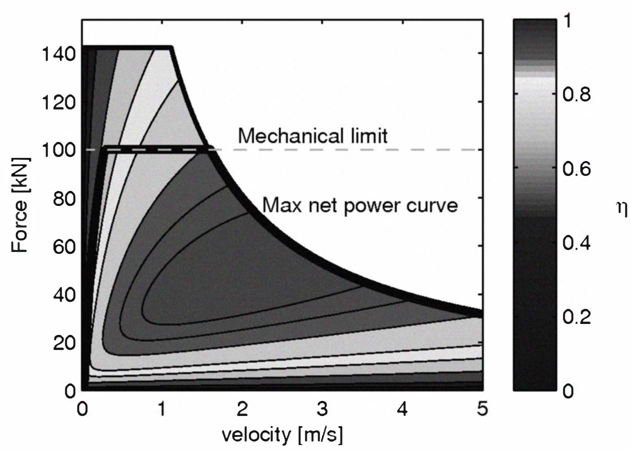


Fig. 9. Efficiency plot for the generator used at Bolt2Wavehub. The thick line shows the torque that result in maximum exported power from the generator. The thin line shows maximum available torque from the genearator. The dashed line shows the mechanical limit for the gearbox.

III. Simulation model

The simulation model used [12], [13] simulates BOLT2 (ref section I-A) for operation at Wavehub.

$$F_{e,i}(t) - F_{D,i}(t) = M\frac{d^2\zeta(t)}{dt^2} \tag{7}$$

$$F_{D,i}(t) = F_{r,i}(t) + F_{d,i}(t) + C_i \cdot \zeta_i(t) + F_{PTO}(t) \tag{8}$$

The simulation model solves the differential equation 7 for $\zeta(t)$ in the time domain. The index denotes the mode of motion, given by the 6 degrees of freedom of motion for the floater. The excitation force matrix $F_{e,i}$ is the time dependent force due to incident waves and M denotes the mass of the system. $F_{D,i}$ accounts for the sum of all the damping forces given in equation 8. Here $F_{r,i}$ 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 like 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.

The simulation is based on a detailed 6DOF model for BOLT2 and Fred Olsen therefore keeps the simulation model confidential. However, the high level of complexity is not required for this study and a simplified 1DOF model would produce much the same result. It is therefore possible for a third party to verify the results published here without detailed knowledge about the simulation model used.

For each wave state a 20 minutes time series of irregular waves are generated based on the Wavehub spectrum. The subsequent excitation forces are then calculated and the simulation is run 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 minutes time series of exported electrical power from the WEC. The average of this time series is then presented as produced power for that wave state as shown in figure 10(b).

The simulation model is developed through many years of development and testing and is verified against real production data from several prototypes, including BOLT.

A. Scatter diagram

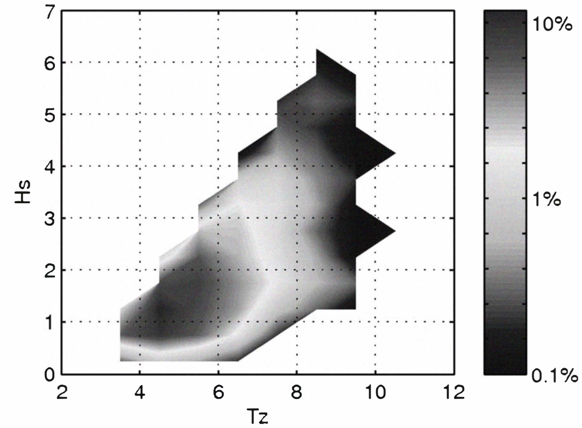
All simulations are based on the Wavehub scatter diagram [3] shown in table I. A probability representation for the scatter is shown in figure 10(a). By simulating the power production for Bolt2Wavehub for all occurrences in the scatter, an overall performance plot can be made. Figure 10(b) shows the simulated operation of BOLT2 in various sea states. The output power is normalized to the defined nominal output of BOLT2 as specified later in this section. The WEC power scatter can now be multiplied with the probability scatter to calculate annual energy production. This is shown in figure 10(c). The plot shows the amount of the annual energy production that occurs in the various sea states.

These three diagrams are an important tool for further WEC optimization. For instance it can be calculated that the most frequent wave height is hs=1.25m and occurs 25% of the time. However, less than 10% of the annual energy is produced on this wave height. The most producing wave state is hs=2.25 and tz=5.5sec and contributes to 9% of the annual energy.

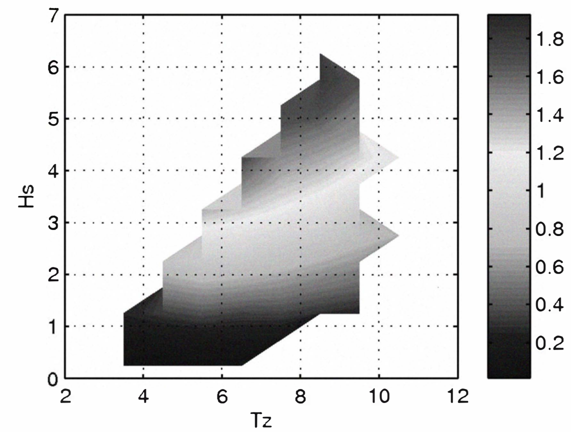
It can be seen from figure 10(b) that the average power from BOLT2 increases with wave height. The theoretical maximum power produced from the PTO, which would occur at constant optimum speed, is even higher. This is typical for most WECs and complicates the definition of rated PTO power. Fred Olsen has decided that the average power in the wave state that produces most annual energy shall be defined as the nameplate power rating. Hence, the most producing wave state hs=2.25 and Tz=5.5sec defines unity in figure 10(b).

Significant wave height hs [m]	Wave period Tz [sec] 3,5	4,5	5,5	6,5	7,5	8,5	9,5	10,5	11,5
0,25	26	79	44	18	0	0	0	0	0
0,75	499	832	491	140	18	0	0	0	0
1,25	184	1051	604	307	70	26	9	0	0
1,75	0	587	701	333	149	53	26	0	9
2,25	0	96	534	254	123	44	9	0	0
2,75	0	0	237	228	105	26	9	9	0
3,25	0	0	26	175	123	44	9	0	0
3,75	0	0	0	79	96	35	18	0	0
4,25	0	0	0	9	44	26	9	9	0
4,75	0	0	0	0	26	18	9	0	0
5,25	0	0	0	0	18	26	18	0	0
5,75	0	0	0	0	0	18	9	0	0
6,25	0	0	0	0	0	9	0	0	0

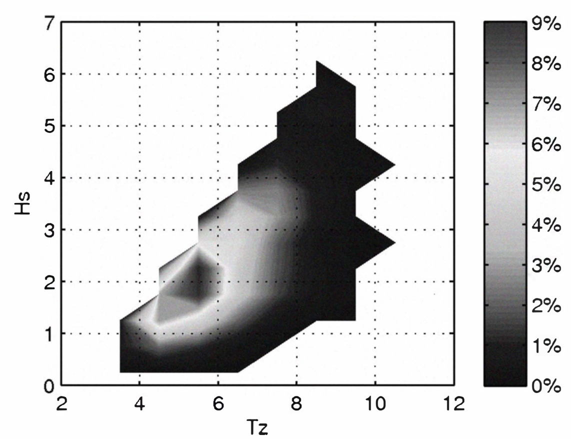
TABLE I
SCATTER DIAGRAM AT WAVEHUB, HOURS PER WAVE STATE



(a) Wave state scatter diagram Wavehub



(b) Normalized exported power from BOLT2



(c) Annual energy production scatter

Fig. 10. Simulated performance of BOLT2 at Wavehub

IV. OVERSPEED OPTIMIZATION

The overspeed optimization is performed by creating generator models for a list of different overspeed ratios. These models are then implemented into the simulation model and a full simulation for all the wave states in the scatter is run for each of the generator models. The resulting annual energy production for the different overspeed ratios is shown in table II. Annual energy and load hours are shown in figures 13 and 12 respectively. The basis for the power normalization is the defined rated power for BOLT2 as described in section III-A. The normalized annual energy is normalized power multiplied with hours.

A first important observation is that the overspeed ratio can be raised to 5 without significant loss of annual production. This corresponds to a 5 times reduction in installed power. Further increase must be done as part of an economical optimization.

A. *Capacity factor optimization*

For power export, the capacity factor is of great importance. The capacity factor is defined as the annual exported energy divided by installed power and shows how well the electrical export capacity is utilized. Capacity factor is usually expressed as the corresponding number of hours per year that the installed power is fully utilized, termed *load hours*. Figure 11 shows the average power production for every hour through a year sorted in descending order. Each line represents a generator configuration with a given overspeed ratio. The figure is a good tool for sizing of the export system and clearly shows the effect of the overspeed ratio. A higher overspeed ratio results in a lower peak power rating, less fluctuation in power production and more load hours. This is mostly achieved by reducing production from the high sea states, but some energy is also lost in the low sea states due to the high irregularities always present.

It can be seen from figure 11 that the overspeed ratio does not appear as a constant power limit, but instead leads to a continuous reduction. This is because the overspeed ratio defines the peak instantaneous power while the exported energy is given by the average power over 20 minutes. The goal is maximum utilization of the export capacity, and it is likely that other measures such as energy storage and averaging between groups of WECs also will be used. Another option for improvement of power quality is therefore to implement a saturation mechanism in the controller that regulates against a total defined maximum average power. This can further be improved to aim for a total export capacity from an array of

Overspeed ratio	Installed power [pu]	Annual energy [pu · hours]	Load hours [hours]	Max avg power [pu]
1	33.3	5093	1840	2.77
3	11.1	5081	1928	2.64
5	6.67	5017	2180	2.3
7	4.76	4878	2511	1.94
10	3.33	4593	3026	1.52
15	2.22	4070	3690	1.1
20	1.67	3547	4128	0.859
30	1.11	2832	4773	0.593
40	0.833	2368	5244	0.452
50	0.667	2041	5611	0.364

TABLE II
WEC PERFORMANCE WITH DIFFERENT OVERSPEED RATIOS

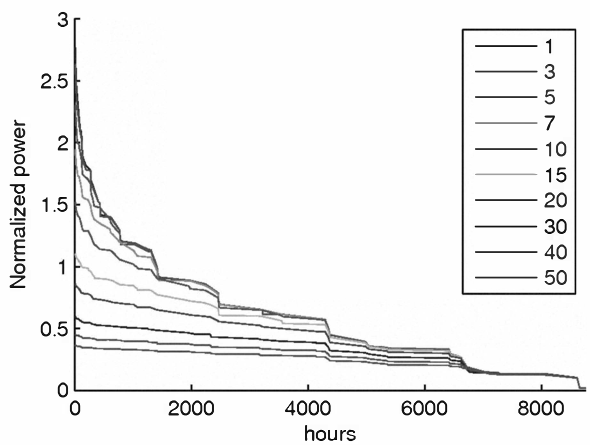


Fig. 11. Annual power distribution per hour

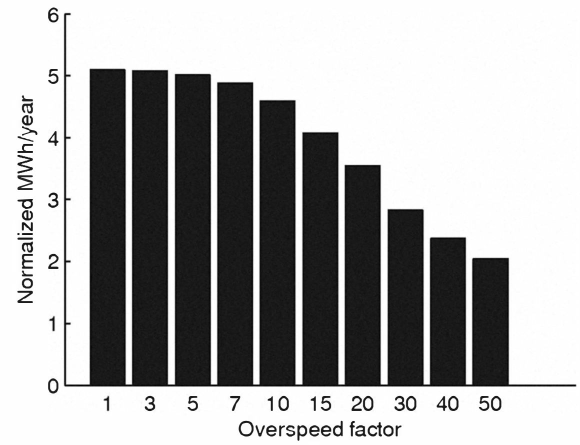


Fig. 12. Annual energy production with different overspeed ratios

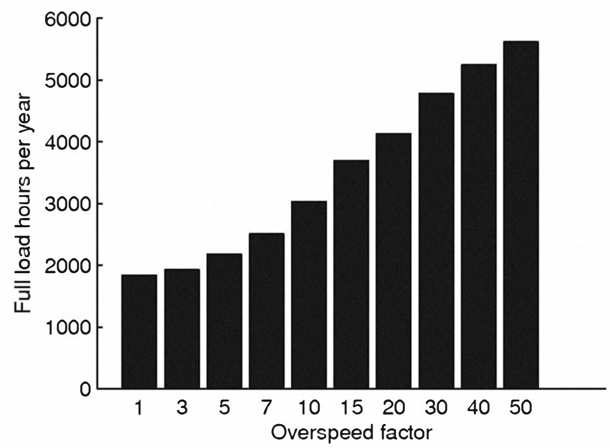


Fig. 13. Annual load hours with different overspeed ratios

WECs. This, however, is not within the scope of this paper and should be subject for further research.

V. CONCLUSION

The study shows that the overspeed factor can be increased to a factor of five without significant loss in annual energy production. Thus, the peak power rating of the converter and the power export system can be reduced to one fifth without trading away produced power. Hence, overspeed optimization should be a part of every design study that involves all-electric PTOs. Further increase in overspeed factor can be done as a part of economical analysis. This study indicates an annual loss of energy production of 10% at an overspeed factor of 10. This is probably around where the lost energy production goes beyond the cost reduction of the power system. Overspeed ratios significantly higher than 10 therefore seem less likely.

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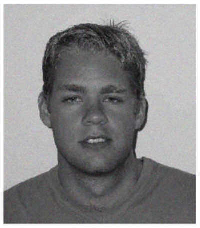

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Aina Crozier has a Master of Science in Energy and Environmental Engineering from the Norwegian University of Science and Technology (NTNU) in Trondheim, Norway. She graduated in the spring of 2011 after spending 5 years at NTNU, including a one-year exchange to the University of British Columbia (UBC) in Vancouver, Canada. Her academic background touches on a variety of engineering fields; from Power Electronics and Control Systems to Heat and Energy Processes, Fluid Mechanics and Hydrodynamics. Her Master's thesis consisted of the design and fully-coupled simulation of a floating offshore wind turbine. Her interest lies in the renewable ocean energy industry and she is currently employed as a Project Engineer at Fred.Olsen, where she is working on developing wave power technologies.

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Gaute Tjensvoll is the development manager of the Fred Olsen Wave Energy project, Bolt. He got his masters degree in product development from NTNU (Norwegian University of Technology and Science) and DTU (Denmark Technical University) in 1997. He also has a master's degree in Technology Management from NTNU and MIT (Massachusetts Institute of Technology) from 2002. His professional career started in an entrepreneurial company called Think, developing an electric vehicle. His product development experience was further broadened through managerial positions in a product development consultancy called Kitron Development. For the last five years he has been dedicated to realizing wave energy concepts in Fred Olsen.