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Description of the Power Take-off System on board the Wave Dragon Prototype

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ABSTRACT

The paper describes the power take-off system of the overtopping based wave energy converter Wave Dragon (WD). Focus is put on the hydro turbine arrangement used for the extraction of the potential energy in the water obtained by wave overtopping of the ramp into the reservoir.

INTRODUCTION

WD is an offshore wave energy converter of the overtopping type, invented in the late 1980's by M.Sc. Erik Friis-Madsen. Each unit will have a rated power of 4-10 MW depending on how energetic the wave climate is at the deployment site. As part of the development activities towards a full size production plant, a grid connected prototype of the WD is presently being tested in a Danish fjord (a scale 1:4.5 of a North Sea production plant).

WD consists of three main elements (see figure 1):

- Two patented wave reflectors focusing the waves towards the ramp, linked to the main structure. The wave reflectors have the verified effect of increasing the significant wave height substantially and thereby increasing energy capture by 70 % in typical wave conditions.
- The main structure consisting of a patented doubly curved ramp and a water storage reservoir.
- A set of low head propeller turbines for converting the hydraulic head in the reservoir into electricity.

When waves have been focused by the reflectors they overtop the ramp and fill the reservoir, which is situated at a higher level than the surrounding sea. This hydraulic head is utilized for power production through the hydro turbines.

WD uses the energy in the water directly via water turbines, i.e. a one-step conversion system, which yields a very simple construction and has only one kind of moving parts: the turbines. This is essential for any device operating offshore, where maintenance is difficult to perform and where the extreme forces, fouling etc. seriously affect any moving parts.

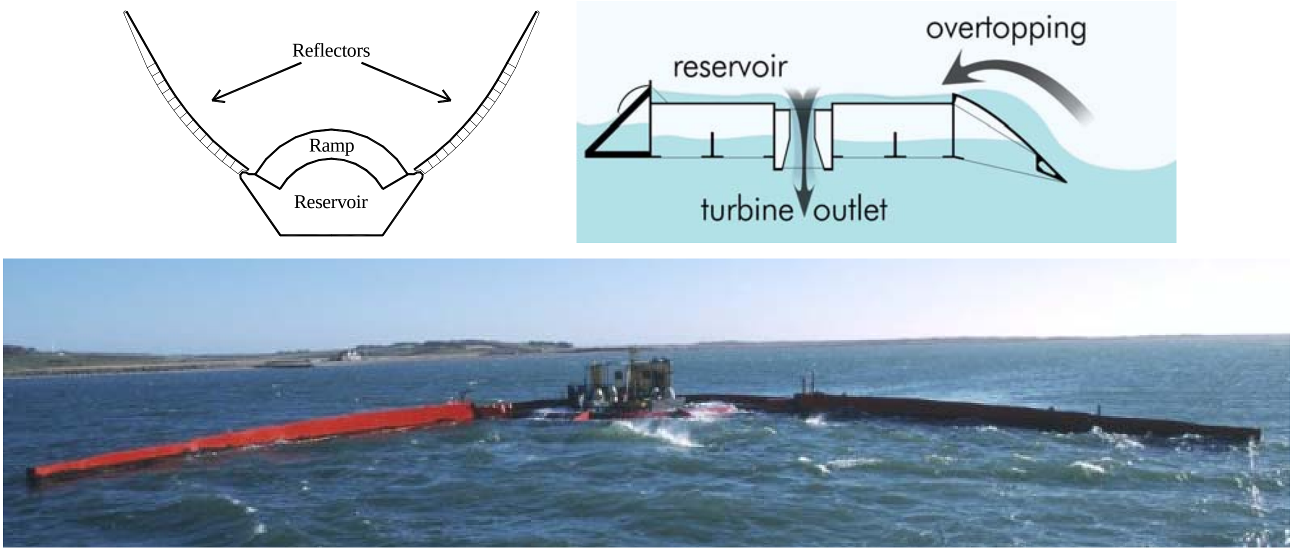

Figure 1. Top left: Main components of the WD. Top right: The basic principle of the WD,
1) waves overtopping a ramp, 2) water stored in a reservoir above sea level and 3) water discharged through hydro turbines. WD floats on open air-chambers used to adjust floating level.
Below: WD prototype at test site.

THE POWER TAKE-OFF SYSTEM

Once the overtopping water has overtopped the ramp on WD and reached the reservoir, the potential energy is harvested by the low-head turbines installed in the reservoir. The operating conditions of the turbines on the WD differ strongly from those in a normal river hydro power station:

- Firstly, the turbines have to operate at very low head values ranging from 0.4 m to 4.0 m (North Sea scale), which is not only on the lower limit of existing hydro power experience, but also an extremely wide variation.
- Secondly, due to the stochastic time distribution of the wave overtopping and the limited storage capacity in the reservoir, the turbines have to be regulated from zero to full load very frequently.
- Lastly, they have to operate in a very hostile salt water environment, with only a minimum of maintenance being possible on an unmanned offshore floating platform.

Early in the project it was concluded that the turbines had to be as simple and rugged as possible with an absolute minimum of moving parts. In order to be able to process the strongly varying discharge rates at a high efficiency, a relatively large number of small turbines is used rather than a few large turbines. Thus, the flow rate can be adapted by switching individual turbines on and off. By adapting the turbine speed to the pressure head, high conversion efficiency throughout the wide head range is obtained.

In order to keep the generator dimensions and cost low, the turbine design aimed a achieving a high specific speed; trying to attain a high unit discharge at the same time, which makes for a compact turbine.

The result has been a low head turbine specially developed by the WD team and tested at the Technical University of Munich, Knapp et al. (2000). A range of guide vane and runner blade settings has been investigated as well as both cylinder gate and siphon intake designs, see figure 2.

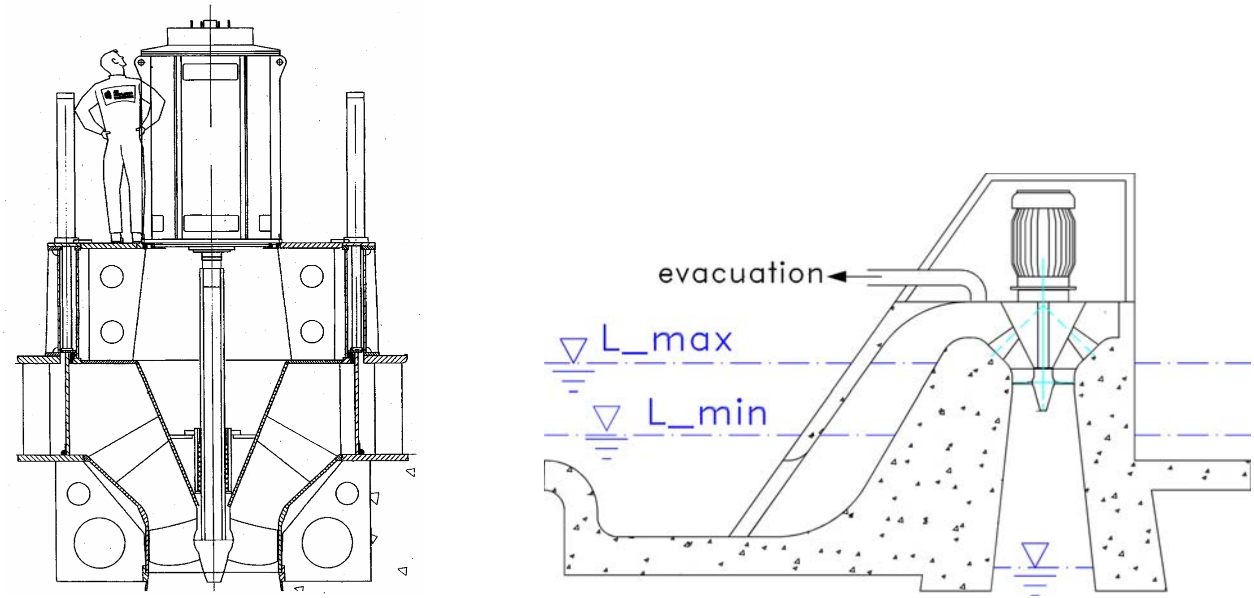

Figure 2. Sketches of cylinder gate on/off turbine (left) and siphon type on/off turbine (right).

The performed investigations resulted in the choice of a power take-off system consisting of 16 to 20 variable speed on/off low-head turbines of the Kaplan type with fixed runners and guide vanes. Each turbine is directly connected (no gear box) to a permanent magnet generator (PMG). Each PMG is connected to a frequency converter, which is used for control of the speed of the turbine and for supplying the power from each turbine onto a common DC rail. The power is then via another frequency converter put onto the grid with grid frequency and voltage.

A prototype of WD has been tested in real sea for almost two years in Nissum Bredning, Denmark. The prototype is a scale down (length scale 1:4.5) of a 4 MW North Sea production plant. Here, a total of 10 turbines have been tested:

- A Kaplan turbine with siphon inlet, see figure 4. The runner diameter of the siphon turbine is 0.34 meter, and the unit speed and discharge in the chosen operating point are $n^{1'} = 170$ min^{-1} and $Q^{1'} = 2.75$ m^3/s, resulting in a specific speed $n_q = 280$ min^{-1}. Rated flow is 0.22 m^3/s at 0.5 m head, and rated power is 2.6 kW (at 1 m head) corresponding to 500 kW in a full scale North Sea Wave Dragon.

- 6 Kaplan turbines with cylinder gates, see figure 3. These turbines have the same runner diameter and performance data as the siphon turbine. The turbines were fabricated in Austria by Kössler GmbH, and they were installed in September 2003. Installation of switchgear and generators was finished in February 2004.

- 3 dummy turbines, see figure 4. These turbines are not able to produce power; they are merely calibrated valves which let the overtopped water run back into the sea. The diameter of the valves is 0.43 meter, and discharge is about twice the one of the real turbines. The dummy turbines were introduced due to financial constraints in the project; they permit to simulate the discharge from further 6 real cylinder gate turbines at a fraction of their cost.

In order to avoid debris in the turbines the turbine area was enclosed by a trash rack. see figure 5.

Figure 3. Left: The six axial propeller turbines being assembled at Kössler GmbH. Right: Turbines on board of the prototype in Nissum Bredning.

Figure 4. Left: The siphon turbine on board the prototype in Nissum Bredning. Right: The dummy turbines on board of the prototype in Nissum Bredning.

Figure 5. Trash rack with 5 x 5 cm openings enclosing the turbine area.

Power simulation tools have been devised, enabling the overtopping of the individual waves and the operation of the turbines to be simulated. With the aid of the simulation software, optimum turbine operating strategies have been conceived, and the strategies are still being further refined and optimised. A paper Tedd et al. (2005) describing this work in more details is also presented at the workshop.

EXPERIENCES GAINED DURING THE PROTOTYPE TESTING

During the first years of real sea testing, the turbines have not been operated continuously. One of the reasons was a substantial delay in the delivery of the permanent magnet generators, the other one the difficulty of programming the frequency converters to suit the characteristics of the generators.

Experience has shown that the aggressiveness of the salt water environment had been underestimated. A design proven in many river hydro power turbines has been used for the main turbine bearing, but the bearings failed after a few months of operation due to problems with the shaft seals. The bearings of four out of the 7 turbines have been modified and rebuilt during the summer 2004, and the turbines have been operated without further problems from October to December 2004. The bearings of the remaining turbines have been modified and rebuilt during the summer 2005.

Dismantling the turbines during the above mentioned repairs has also shown that marine growth is a factor that may not been taken lightly. The draft tubes of the turbines had been made from different materials: uncoated stainless steel, black steel protected with conventional epoxy paint and black steel protected with a special silicone-based anti-fouling paint. The draft tubes painted with the conventional paint system were found heavily overgrown with a wide variety of flora and fauna, which was almost impossible to remove. The stainless steel tubes as well as the ones coated with the silicone paint had only a few mussels on them which could be swept off very easily.

The siphon turbine has been already been installed before the deployment of the prototype; the cylinder gate turbines have only been installed at sea in September 2003. During the first year of operation, the following problems became apparent:

- The generator of the siphon turbine became damp inside, despite being specified IP66.
- The seals of the turbine thrust bearings, which were a standard hydro turbine design, failed in the sea environment, with subsequent damage to the bearings.
- The supply pipes for the water lubricated radial bearings became blocked with marine growth.
- The draft tubes of one turbine group had been painted with a standard epoxy paint system. These developed extensive marine growth, reducing the turbine efficiency.

The following solutions were implemented to deal with the above problems:

- The generator was overhauled and fitted with a splash protection hood. It has worked without any further problems since.
- The seals and bearings have been completely re-designed.
- The water supply system has been modified in a way that avoids any piping.

- 4 out of the 7 turbines have been rebuilt including the above modifications during summer 2004. The turbines have been re-commissioned in September 2004 and have been in continuous operation from October to December 2004, without any further problems.
- The draft tubes of the other turbine group had been treated with a non-toxic silicone based antifouling paint and where still clean after being in the sea for one year. This coating and the above modifications were now applied to all turbines.

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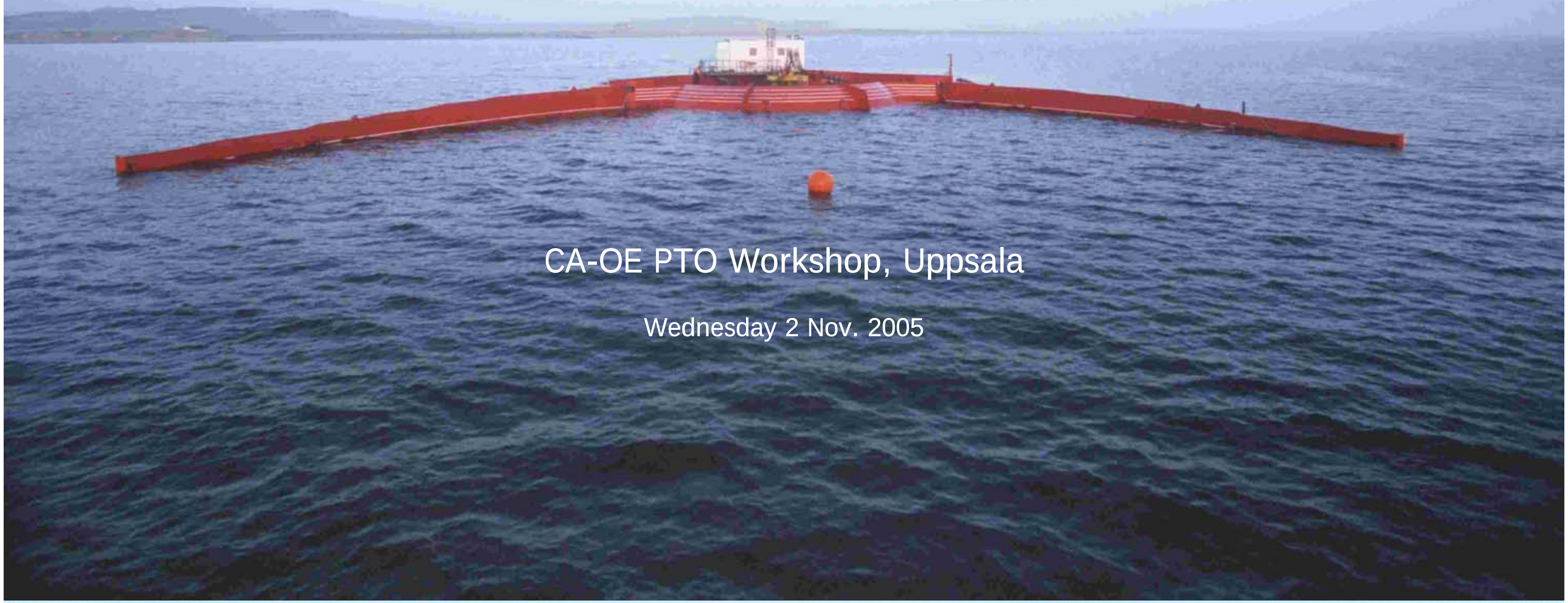

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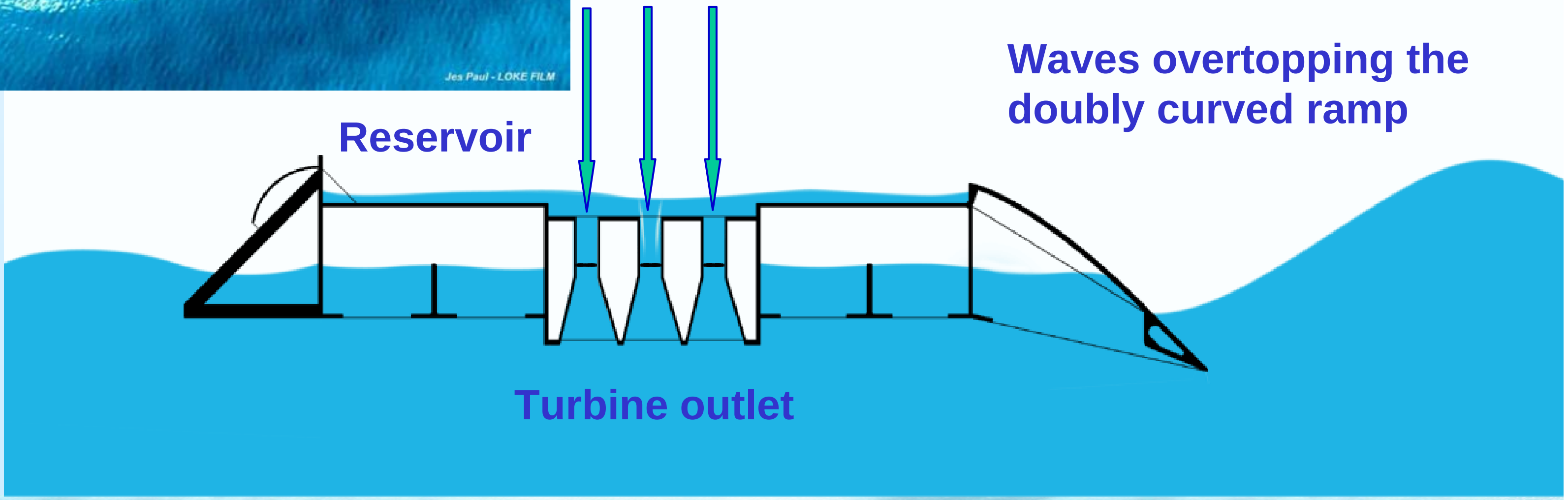
Wave Dragon principle

The *Wave Dragon* is a slack-moored wave energy converter that can be deployed alone or in parks wherever a sufficient wave climate and a water depth of more than 25 m is found.

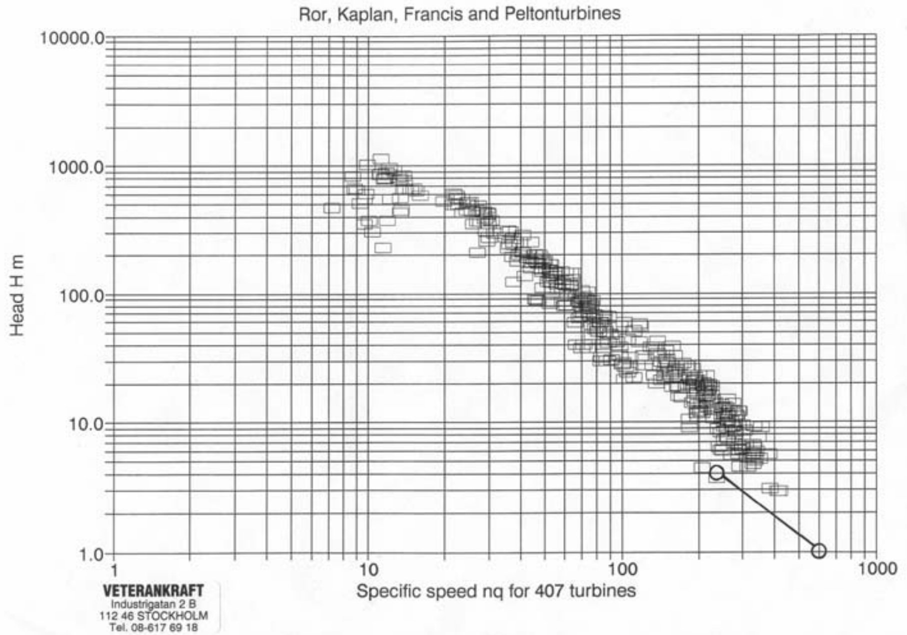
Climate	Power production
24 kW/m	12 GWh/y/unit
36 kW/m	20 GWh/y/unit
48 kW/m	35 GWh/y/unit

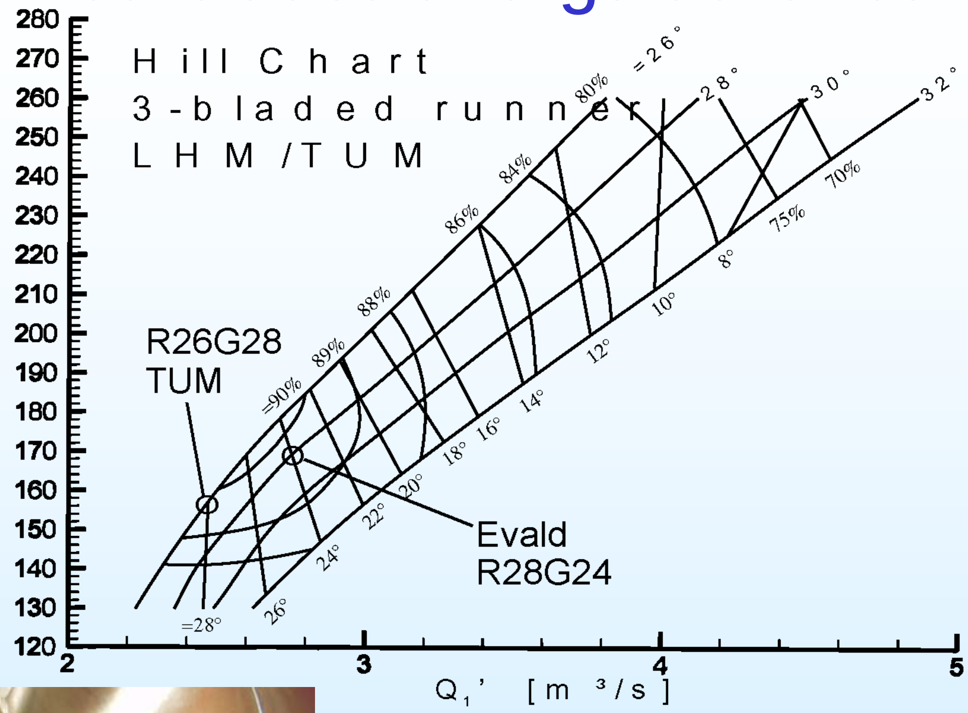


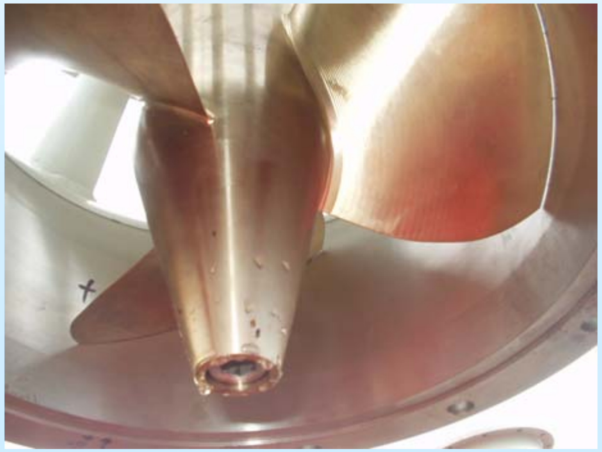
Wave Dragon basic data

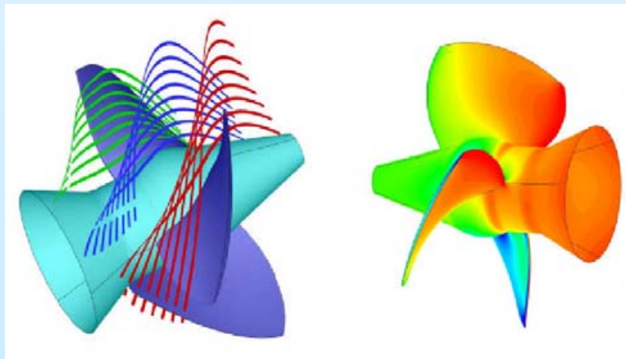
Key figures, units:	*0.4 kW/m*	*36 kW/m*
Weight, steel and concrete	*237 t*	*33,000 t*
Total width and length	*58x33 m*	*300x170 m*
Height	*3.6 m*	*19 m*
Height above sea level	*0.6-1.5 m*	*3 –7 m*
Reservoir	*55 m^3*	*8,000 m^3*
Number of turbines	*7 (+3)*	*16 – 20*
Generators	*PMG*	*PMG*
Rated power/unit	*20 kW*	*7 MW*
Annual power production/unit GWh/y	*0.04*	*20*
Water depth	*6 m*	*> 25 m*

Ø340 mm Kaplan turbine, fixed blades and guidevanes









Turbine arrangement

- 1 siphon turbine, rated flow 0.22 m3/s at 0.5 m head
- 6 cylinder gate turbines, as siphon turbine
- 3 dummy “turbines” (calibrated valves), double capacity

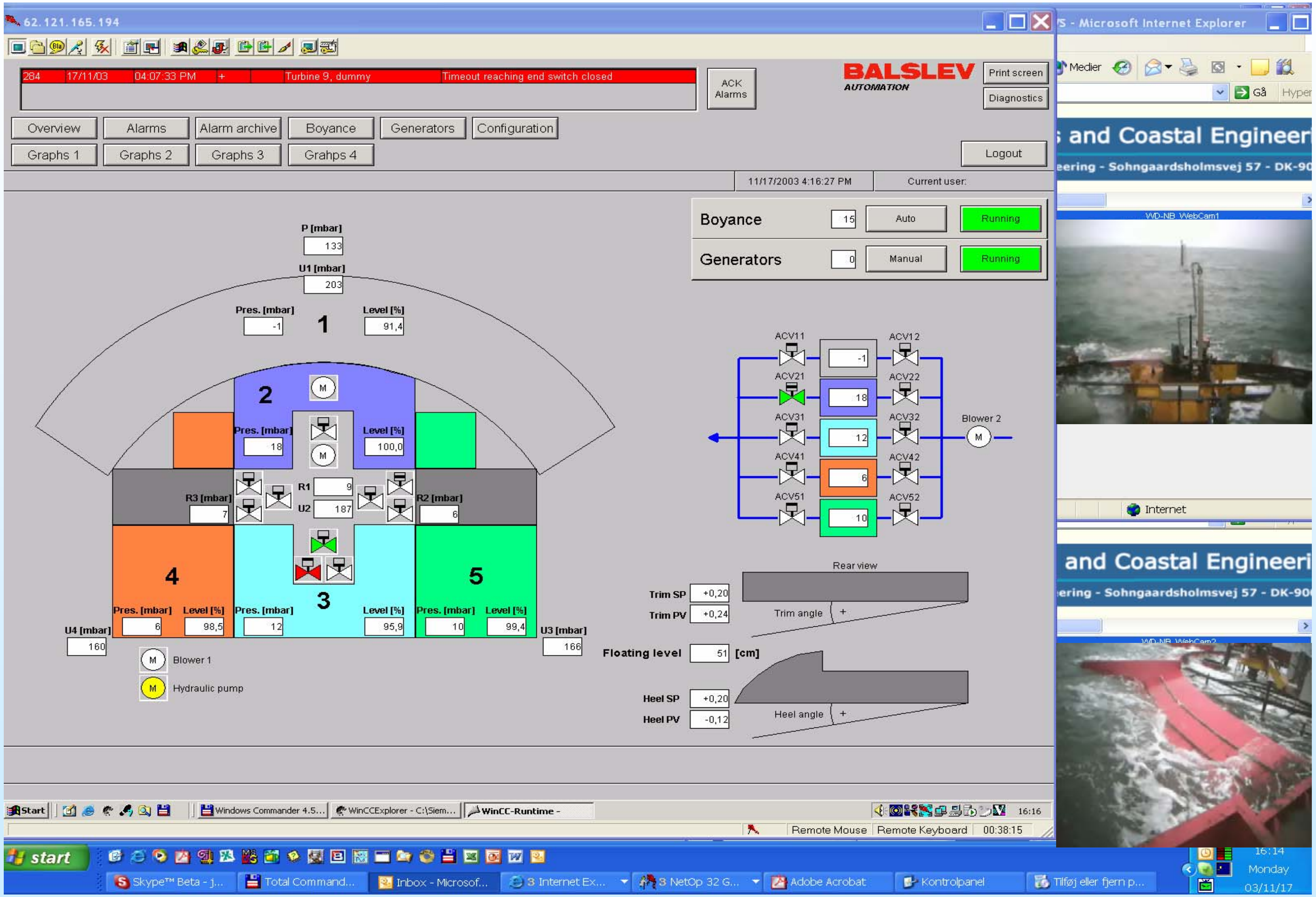
- 7 turbines equipped with 2.5 kW PMG’s
- Each PMG connected to a frequency converter controlling speed and supplying power on common DC rail
- DC rail connected to grid via frequency converter ensuring grid voltage and frequency

- Trash rack surrounding the turbine area

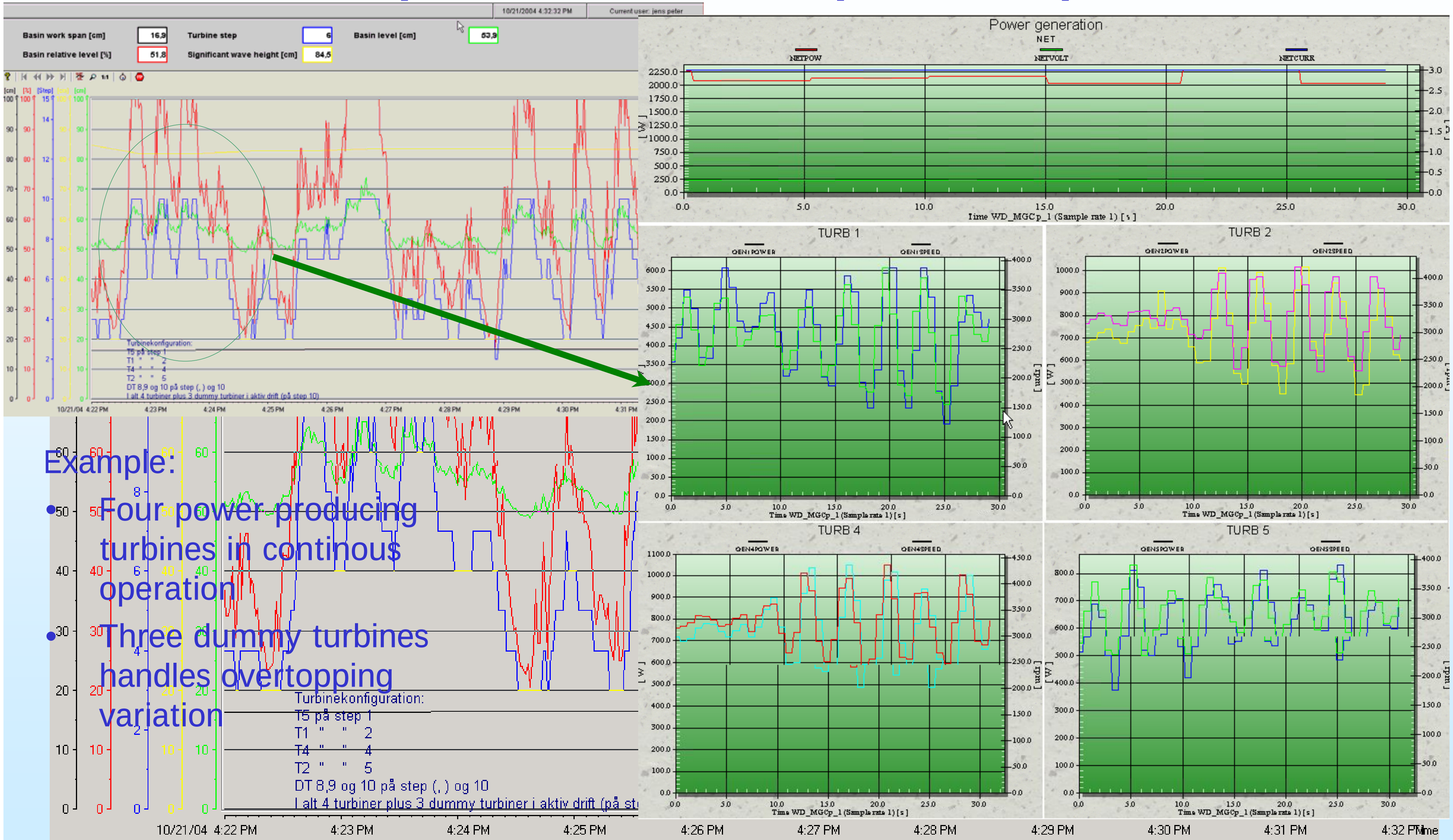
6 more turbines installed September 12

Cylinder gate turbines running

Remote control



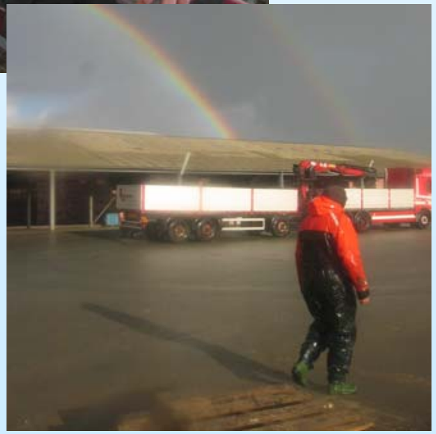
Turbine operation and power production



Example:

- Four power producing turbines in continous operation
- Three dummy turbines handles overtopping variation

Replacement of bearings at sea



Marine growth

Marine growth on structure and mooring lines below waterline: 5-10 cm




Marine growth in turbine draft tubes reduces PTO. Non-toxic antifouling tested.




Conclusions

- No PTO turnkey solution initially available for WD
- WD PTO designed and installed
- A working WD PTO is now a reality
- “Child deceases” pointed out – solvable, but requires engineering
- It is not trivial to take known and proven technology to a new environment
- Since it is unlikely that all problems have been seen yet, further testing at reduced scale and in real sea environments is needed
- Long term testing still required in order to provide reliable data for formulation of O&M procedures