Considerations for Water Turbines to be used in Wave Energy Converters

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ABSTRACT

In wave energy converters (WECs) of the run-up type, the kinetic energy of the sea waves is used to store seawater in a reservoir above the mean sea level. The potential energy of the water in the reservoir can be exploited in a most effective way using low head water turbines. These turbines have been developed to a very high level of efficiency and reliability for use in run-of-the-river hydro power plants. If they are used in a WEC however, a radically different mode of operation is required due to the stochastic time distribution of the energy input. Thus, special criteria for the choice and construction of water turbines for WECs have to be chosen.

This paper gives a detailed insight into the operating conditions to be expected, and compares the suitability of different types of low head turbines for use in WECs. Double, single and unregulated Kaplan turbines are covered as well as fixed and variable speed drive. It is shown that a bigger number of simple fixed blade turbines in conjunction with variable speed drive and a simple and reliable means of switching individual turbines on and off provide a promising solution to the problem.

NOTATION

D [m]	turbine runner dia.
H [m]	turbine head
H_s [m]	significant wave height
R_c [m]	crest freeboard height
l [m]	basin level, measured from crest
n [min^{-1}], ω [rad/s]	rotational speed
$n_q = n \frac{\sqrt{Q}}{H^{3/4}}$	specific speed
$\text{Re}_D = \frac{\omega \cdot D^2}{2 \cdot \nu}$	turbine Reynolds number
Q [m^3/s]	flow rate
η_{Tu} [-]	turbine efficiency
η_{WD} [-]	overall eff. of WEC
ν [m^2/s]	kinematic viscosity of water ($\nu = 1.3 * 10^{-6}$ m^2/s at 10° C)

1. INTRODUCTION

In Wave Energy Converters (WECs), the use of water turbines is primarily interesting in devices of the run-up type. These converters consist basically of a ramp which is directed against the oncoming waves and a storage basin. When the waves hit the slope of the ramp, the kinetic energy contained in them is converted into potential energy, i.e. the water runs up the ramp and fills a reservoir which is situated above the mean sea level. The potential energy of the water in the reservoir is then exploited by releasing it back into the sea through water turbines. Low head water turbines which are suitable for this purpose have been used in run-of-the-river water power plants for many decades and have been developed to a high level of efficiency and reliability. Thus, in contrast to most of the other WEC principles, a proven and mature technology can be used for the production of electrical energy.

However, the turbine operating conditions in a WEC are quite different from the ones in a water power plant. In WECs, the turbine head range is between 1 and 5m, which is on the lower bounds of existing water turbine experience. While there are only slow and relatively small variations of flow and head in a run-of-the-river water power plant, the strong stochastic variations of the wave overtopping call for a radically different mode of operation in a WEC. The head, being a function of the significant wave height, is varying in a range as large as 1:3, and it will be shown that the flow has to be regulated from 0% to 100% within time intervals as short as 10 seconds in order to achieve an optimum efficiency of the energy exploitation. From a river hydro power installation which is properly maintained, a service life of 40 - 50 years can be expected. On an unmanned offshore device, the environmental conditions are much rougher and routine maintenance work is much more difficult to perform. Thus, special criteria for the choice and construction of water turbines for WECs have to be chosen, and it seems advisable to aim for constructional simplicity rather than maximum peak efficiency. In the following paragraphs the operating conditions to be expected will be shown in detail and the suitability of different available turbine types will be discussed.

2. SHORE-BOUND AND FLOATING WEC'S

Basically, a WEC of the run-up type can either be conceived as a shore-bound installation or as a floating offshore device. The floating variant has the following advantages and drawbacks compared to the shore-bound variant:

+ operation independent of the tidal level
+ self-aligning to wind direction if suitably moored
+ crest height adaptable to different sea states
+ operation also in off-shore wind direction if placed in sufficient distance from the shore
+ big farms can be realised in the open sea
- limited storage basin capacity
- immersion of the device due to filling of the reservoir
- costly power transmission to the shore
- difficulty of maintenance

As far as the turbine operating conditions are concerned, the main difference between both variants is due to the limited storage capacity of the floating type. It has been found that the volume of the basin will be in the same order of magnitude as the overtopping resulting from a single big wave. This means that the turbine control will have to react onto single wave events or at least onto the arrival of individual wave groups, thus calling for frequent and rapid changes of the flow rate.

3. OPERATING CONDITIONS

The present study originates from experience gained during the development of the Wave Dragon, see (1), (2), which is a device of the floating type; thus all considerations are mainly done from this point of view. A number of them, however, do also apply for shore-bound WEC's of the run-up type.

Maximising the overall efficiency or the annual energy output of a WEC is a very complex task, as a great number of parameters need to be optimised and the effect of any parameter change has to be studied for a number of different sea states.

Fig. 3.1. is giving a schematic view of the whole device. Starting from a chosen value for the initial crest height Rc_0, the turbine characteristics Q(H) and $\eta(H,Q)$, a given regulating strategy and a certain wave height H_s, the following instantaneous quantities need to be determined:

- crest height $R_c = f(R_{c0}, \text{Immersion})$
- Overtopping flow rate $Q_{ov} = f(H_s, R_c)$
- Basin level $l = f(Q_{ov}, Q_{Tu}, Q_{Spil})$
- Immersion = f (l)
- Spillage flow $Q_{Spil} = f(Q_{ov}, Q_{Tu}, l)$
- Turbine head $H_{Tu} = f(R_c, l)$
- Turbine flow rate $Q_{Tu} = f(H_{Tu}, n_{Tu},$ regulating strategy)
- Turbine efficiency $\eta_{Tu} = f(H_{Tu}, Q_{Tu})$
- Power Output $P_{el} = f(H_{Tu}, Q_{Tu}, \eta_{Tu}, \eta_{Gen})$

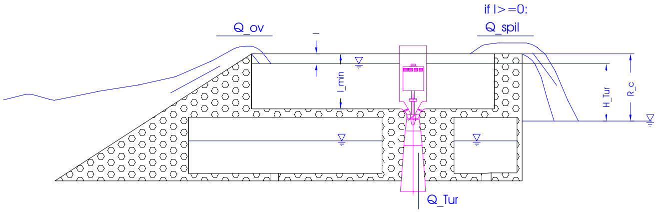

Fig. 3.1.: Schematic view of the Wave Dragon

By integrating the output P_{el} over a suitable period of time and comparing it to the incoming wave power, the overall efficiency of the WEC can be evaluated. This procedure has to be repeated for different sea states in order to predict the annual output or the average overall efficiency.

Considering the complexity of this optimisation task and the multiple interdependencies between the parameters involved, the only practical approach seemed to be a software simulation of the system behaviour combined with a systematic parameter variation. An empirical function that had been determined in wave tank tests (3) has been used to calculate the wave overtopping probability of synthetically generated wave sets, taking into account the wave characteristics and the slope geometry as well as the variation of the crest height due to the immersion. Based on this equation, the whole operating process was simulated in small time steps (4),(5), calculating the time-dependent behaviour of all the quantities mentioned above and integrating the power output. By selective variation of the adjustable parameters, an optimum configuration could be determined for different sea states and different basic layouts of the turbine set.

In the following, a few general considerations which are important for the choice of the turbine type are explained.

3.1. Turbine head range

Tab. 3.1. gives a typical North Sea wave distribution; the waves that contribute significantly to the total energy are ranging from 1 to 5 m significant height. At wave heights above 5m the operation of the WEC is suspended for safety reasons.

Efficient operation at different sea states requires suitable adjustment of the inlet slopes crest height. During the parameter study, the optimum crest height has been found to be closely associated with the significant wave height, while the corresponding turbine head is slightly lower due to the immersion caused by the weight of the water in the basin, see last column in Tab. 3.1. It can be seen that the turbine has to cope with head values ranging from 1.4 to 3.0 m.

Tab. 3.1.: Turbine head in different sea states

H_s [m]	Probability [% time]	% of total Energy	initial crest height Rc_0 [m]	max. turbine head [m]	min. turbine head [m]
0	11				
1	38	6.3	1.50	1.45	1.40
2	27	22.9	1.75	1.70	1.65
3	14	30.5	2.25	2.15	2.05
4	6	25.8	2.75	2.60	2.45
5	2	14.6	3.25	3.00	2.75
>5	2				

3.2. Turbine flow range

If the turbines are only stopped when the reservoir is completely empty, some of the water volume is used at an unnecessarily low head, thus wasting a part of the potential energy. Ideally, the turbines should be stopped as soon as the basin is just empty enough to receive the water volume that the next wave is going to bring without any spilling. Unfortunately, neither the arrival time nor the overtopping volume of the next wave can be accurately predicted.

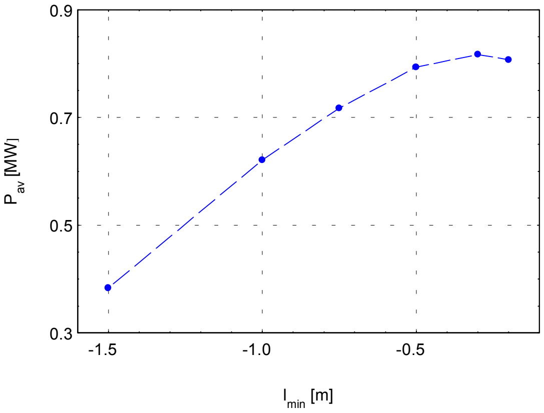

Fig. 3.2.: Average Output Power vs. minimum basin level l_{min} at h_s=4m

However, it has been found that it is a

reasonable strategy to operate the turbines at maximum flow rate when the basin is full, and decrease the flow as the basin empties until all turbines are stopped at a certain minimum basin level l_{min}. Different regulation strategies have been evaluated and the highest energy production has been obtained when the basin was emptied only very little, see fig. 3.2.

In low sea states, the optimum values for the minimum level were found to be -0.05 ... -0.10m, with values up to -0.5m at high seas.

In order to keep the basin level within this small range, the turbine flow has to be changed very frequently and rapidly, with relatively frequent periods of complete shutdown. Fig 3.3. shows a time history of the operation at a significant wave height h_s=3m.

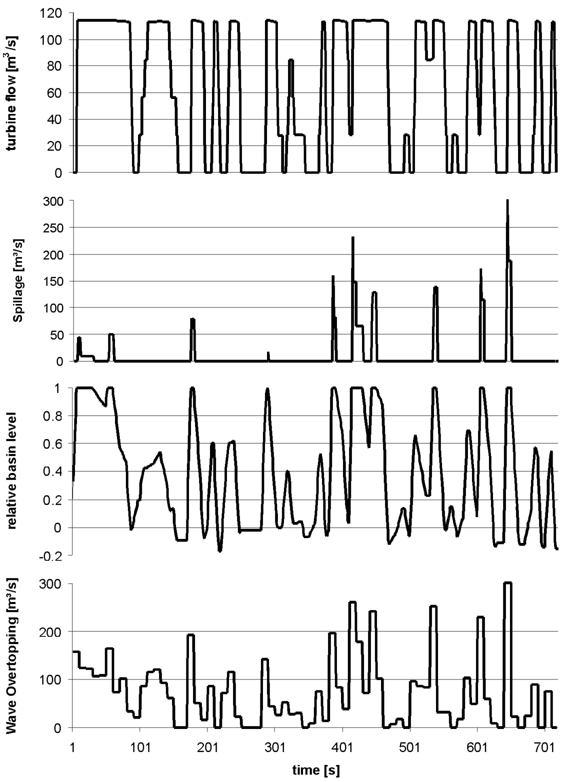

Fig 3.3.: Time history of overtopping, basin level, spillage and turbine flow rate

4. AVAILABLE TURBINE TYPES

Fig. 4.1. shows the application ranges of the known turbine types in a graph H vs. n_q. The specific speed n_q is a turbine parameter characterising the relative speed of a turbine, thus giving a measure of the turbines power density. Evidently, all turbine types except the Pelton and the cross flow type are to be found in a relatively narrow band running diagonally across the graph. Experience has shown that an optimum turbine layout is always situated within this band. Transgressing the left or lower border means that the turbine will run too slowly, thus being unnecessarily large and expensive. The right or upper border is defined by technological limits, namely material strength and the danger of cavitation erosion. However, the Pelton and the cross-flow turbine do not follow these rules, as they have a runner which is running in air and is only partially loaded with a free jet of water. Thus, they have a much lower specific speed and lower power density. The cross flow turbine is not very suitable for wave power applications, as it is very difficult to ensure that its runner does not touch the tailwater surface when there are wave-induced pressure fluctuations. For this reason, this type of turbine has not been further evaluated.

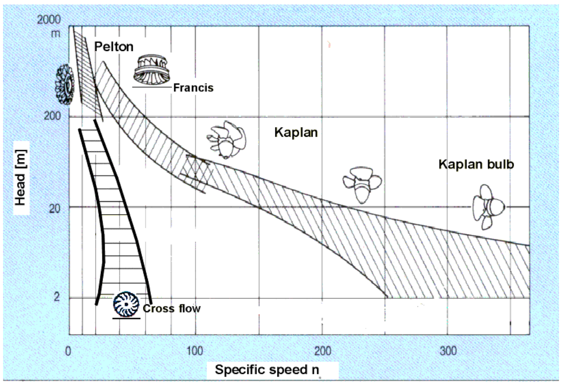

Fig 4.1.: Head range of the common turbine types, after Voith and Ossberger

Thus the Kaplan bulb type is the only turbine suitable for the head range in question. Its general construction is shown in fig. 4.2.

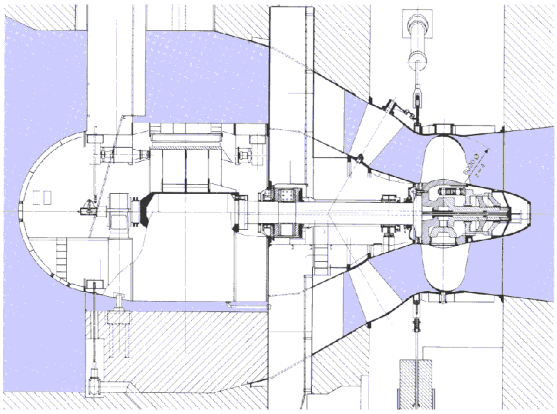

Fig 4.2.: Double regulated Kaplan bulb turbine (Voith Hydro)

The shape of a turbines guide vanes and runner blades is designed to give an optimal energy conversion in its design point, which is defined by optimum values of head and flow (H_{opt} and Q_{opt}) at a given speed. For every other operating point, there will be a discrepancy between the flow angles and the blade angles, decreasing the efficiency of the turbine. Whenever a turbine is required to operate in a relatively wide head and flow range it is important that the efficiency curve is flat and widely spread. This criterion is best fulfilled by the double regulated Kaplan type, see figs. 4.3 and 4.4.

In this type of turbine, both the guide vanes and the runner blades are adjustable, thus making the turbine very adaptable to varying operating conditions. This is only achieved by a relatively complicated construction which implies an oil-filled runner hub with a number of critical bearings and oil seals and a great number of joints and bearings in the guide vane operating mechanism. This is not only reflected in higher manufacturing costs, but also in a higher demand for maintenance, especially when the turbine is operated in an aggressive environment i.e. saltwater with possible silt contents. For these reasons single regulated variants of the Kaplan turbine have been constructed, namely the Propeller type with fixed runner blades, the Semi-Kaplan type with fixed guide vanes and the unregulated on/off turbine with fixed runner blades and fixed guide vanes. These turbines are simpler in construction, but they have a much narrower efficiency curve, see figs. 4.3. and 4.4.

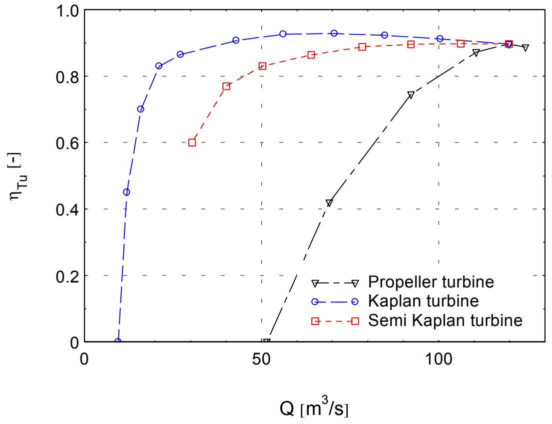

Fig 4.3.: Efficiency vs. flow at design head

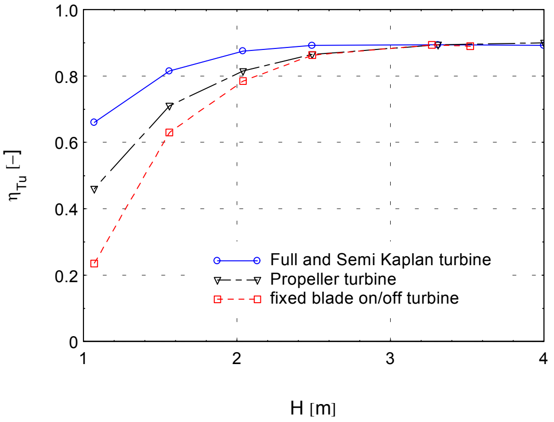

Fig 4.4.: Efficiency vs. head at optimum flow rate

Tab 4.1.: Comparison between double, single and unregulated turbines

	Double regulated Kaplan	Semi-Kaplan turbine	Propeller turbine	16 fixed speed on/off turbines	16 variable speed on/off turbines
η_{opt}	.93	.90	.90	.91	.91
$\bar{\eta}(H=H_{opt})$	.85	.68	.39	(.90)	(.90)
$\bar{\eta}(Q=Q_{opt})$	.87	.87	.81	.66	.90
D [m]	5.4	5.4	5.4	1.2	1.2
n [min^{-1}]	50	50	50	250	100-250
robustness	-	o	+	+++	+++
turbine price	1.4	1.2	1	.9	.9
price of generator	1.0	1.0	1.0	0.9	1.2
price of turbine + generator	2.4	2.2	2.0	1.8	2.1
overall rating	++	++	+	+++	++++

Table 4.1. is giving a comparison of the turbine types discussed so far. The example is based on a layout point of H=3m and Q=125 m³/s. The second row is giving the average efficiency for the flow range from 10% to 100% while the average efficiency for the head range from 1.4m to 4m is shown in the third row. Rows 6 and 7 give a rough ranking of the robustness and the manufacturing price.

From this comparison it is obvious that the double regulated Kaplan turbine is the technically most efficient solution, but at the expense of being costly to manufacture and difficult to maintain. The two single regulated types are distinctly lower in average efficiency, but have advantages due to their simplicity. However, this comparison is only valid for a single turbine running at constant speed. The last columns are giving the corresponding values for a set of 16 very simple fixed blade turbines running at fixed and variable speed, see paragraphs 5 to 7. The ranking given in the last row is taking into account the data given above as well as the considerations made in paragraphs 5 to 8.

5. MULTIPLE TURBINES

If the projected plant is of a certain size, it should be considered to use a number of smaller turbines instead of a single big turbine.

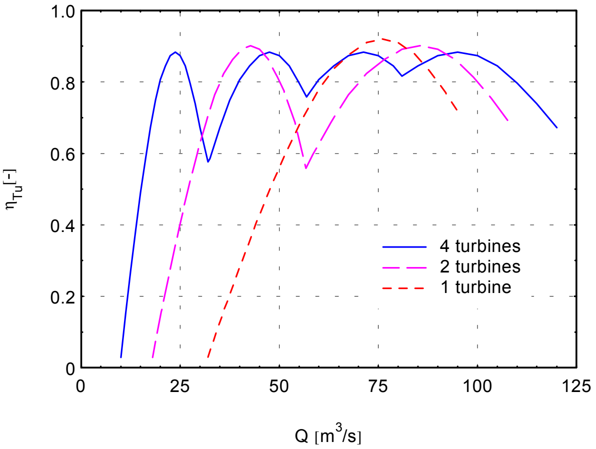

Fig. 5.1.: Turbine efficiency vs. flow rate for a single and a multiple turbine configuration.

This has the following advantages:

- By stopping a number of turbines at lower flow rates, the flow rate can be regulated over a wider range without sacrificing efficiency, see fig. 5.1.
- Single units can be taken out of service for maintenance without stopping production.
- The smaller turbines have shorter draft tubes, which is advantageous for the layout of the whole device, see fig. 5.2.
- The smaller turbines have a higher speed (see fig. 5.3.), which makes the generator cheaper.

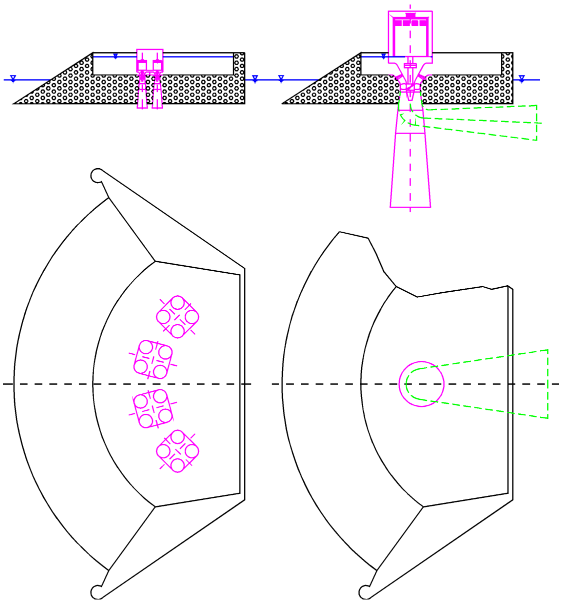

Fig. 5.2.: Installation of 16 small turbines vs. a large single turbine

Fig. 5.3. depicts the results of a parameter study in which the turbine number i_t has been varied in a wide range while adjusting the size of the turbines in a way that the total discharge was kept constant. From the similarity laws and cost statistics, the following proportions can be derived:

runner diameter $D \sim i_t^{-0.5}$
speed $n \sim i_t^{0.5}$
cost of all turbines $C_t \sim i_t^{0.1}$
cost of generators $C_g \sim i_t^{-0.05}$

The increase in the production cost of the smaller turbines is partly compensated by the fact that the generators become cheaper at higher speeds.

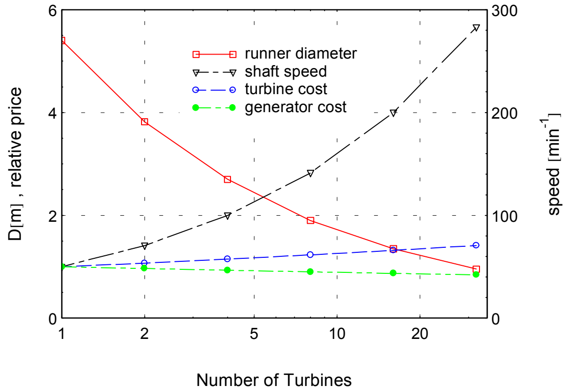

Fig. 5.3.: Runner diameter, speed and relative production cost vs. turbine size

Apart from the slightly increasing production cost there is one more reason for not using too

many small turbines: the turbines peak efficiency decreases along with Reynolds number Re_D in a smaller turbine, see fig. 5.4.
It can be seen that the Reynolds effect is not too pronounced as long as the turbine is not too small. As a general rule, Re_D should not be smaller than $1.5*10^7$.

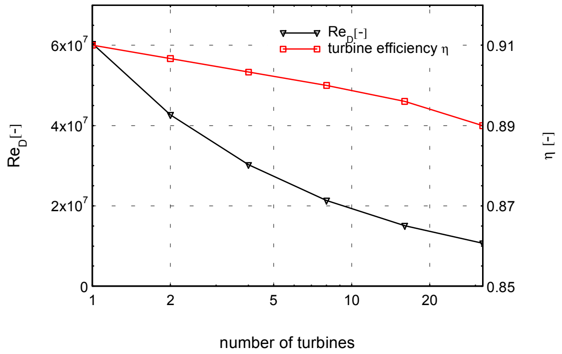

Fig. 5.4.: Reynolds number and turbine efficiency vs. turbine number

6. VARIABLE SPEED DRIVE

In normal hydro power stations, the turbines are operated at constant speed, as they are coupled directly to the synchronous generators feeding into a fixed frequency grid. However, if the generator is connected to a frequency converter, the turbine can be operated in a relatively wide speed range. This is very advantageous in situations where a large variation in turbine head occurs. By adapting the speed to the actual turbine head, the efficiency of the turbine can be kept almost constant, see fig. 6.1.

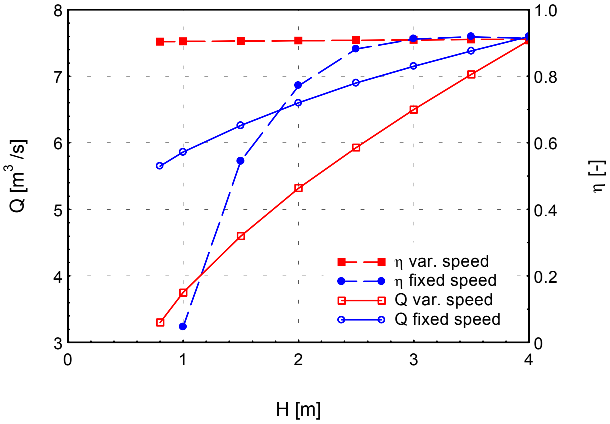

Fig. 6.1.: Turbine efficiency and flow rate vs. head for fixed and variable speed drive

In this case, the flow rate drops strongly along with the head, which has proved to be advantageous as well. In the development of the Wave Dragon, different turbine regulation strategies have been evaluated by means of a simulation software. Maximum overall plant efficiency was obtained when the turbine flow was reduced along with the emptying of the reservoir. Fig 6.2. shows an optimum flow control function Q_{Tu} vs. basin level l :

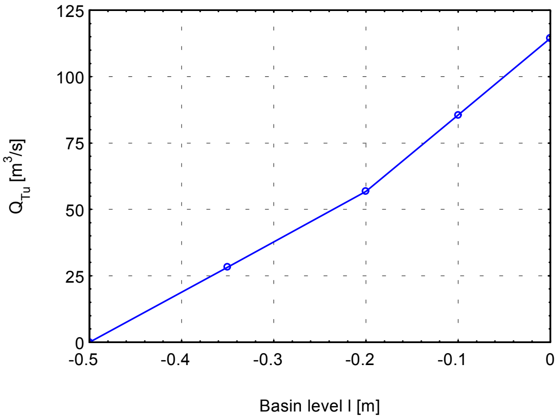

Fig. 6.2.: Control function $Q_{Tu}(l)$

In order to regulate the flow over such a wide range without getting too low turbine efficiencies, a number of turbines has to be stopped at lower basin levels, which is resulting in very frequent turbine start/stop cycles. Variable speed turbines have a distinctive advantage in this respect, as their steeply drooping head vs. flow characteristic (see fig. 6.1) provides a very advantageous self regulating effect. This does not only lead to an increase in yearly energy production, but also to a much smoother power delivery, see fig. 6.3. Both of the graphs are based on a system of 4 unregulated on/off turbines.

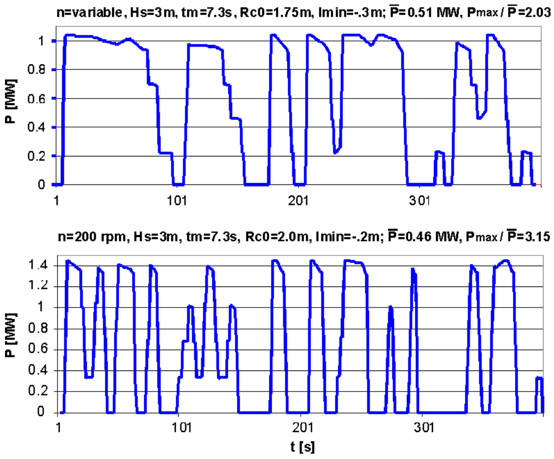

Fig. 6.3.: Power delivery vs. time with variable speed and fixed speed turbines

7. UNREGULATED (ON/OFF) TURBINES

It has been shown that variable speed drive turbines can be operated in a wide head range and have a flow vs. head characteristic which does by itself fulfil a part of the regulation strategy. If the projected plant is big enough to justify the use of a relatively big number of turbines it is possible use very simple and rugged on/off turbines in conjunction with any means of interrupting the flow to switch the turbine on and off. In the case of the Wave Dragon, it has been shown that 4 on/off turbines are already sufficient to regulate the flow as needed. Two alternative methods for interrupting the flow have been analysed, the first one using a big hydraulically operated cylinder gate, the second one using a siphon principle, see fig. 7.1. and 7.2. The operation of the gate is obvious from fig. 7.1. The siphon type is stopped by simply admitting air into the top of the inlet duct; the turbine is started again by partly evacuating the air until the flow starts again and takes the rest of the air along with it.

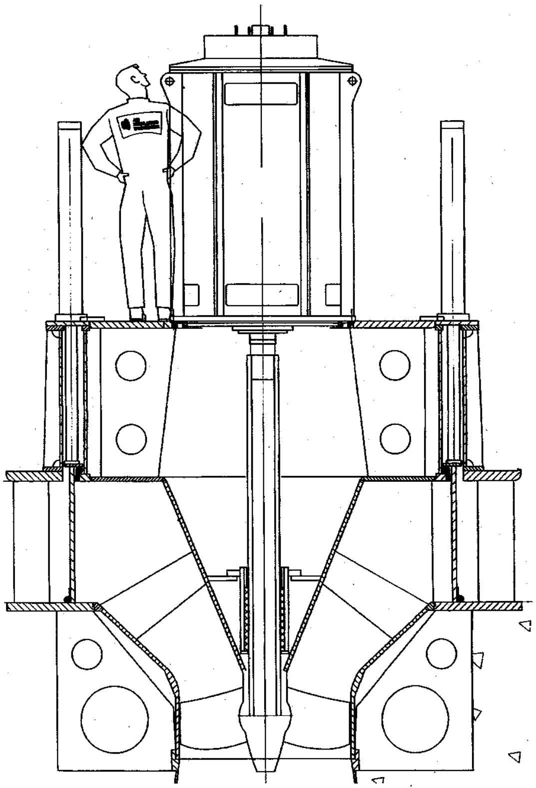

Fig. 7.1. Cylinder gate on/off turbine

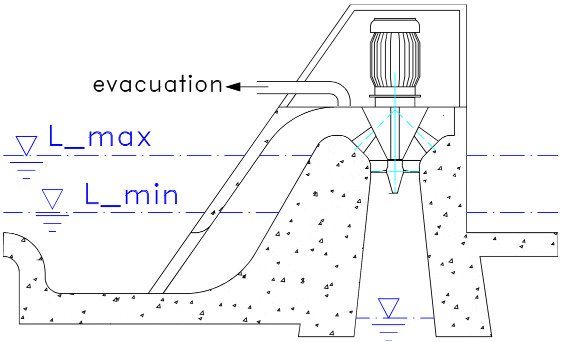

Fig. 7.2. Siphon type on/off turbine

It has been found that the cylinder gate type has the advantage of shorter start-up time and slightly better efficiency, while the siphon type has less moving parts and would thus appear to require less maintenance. It is planned to evaluate both types in model and prototype tests.

8. COMPARISON OF DIFFERENT TURBINE CONFIGURATIONS

For a given layout of the Wave Dragon WEC, the following turbine configurations have been compared:

- 2 double regulated Kaplan turbines
- 2 Propeller turbines
- 2 Semi Kaplan turbines
- 16 fixed speed on/off turbines
- 16 variable speed on/off turbines

For each of these layouts, an optimum operating strategy and optimum values of crest height and minimum basin level for each of the sea states given in tab. 3.1 have been determined in order to calculate the annual energy production $E_{tot, yr}$.

As the propeller turbine has a very narrow range of high efficiency, see fig. 4.3, this turbine was operated in on/off mode, using its guide vanes only for optimum adaption to the current head value.

The first row in table 8.1. shows the yearly production that can be expected from each of the configurations.

In the second row, a comparison of the maximum output at the highest sea state and the yearly averaged output is given. As the maximum output determines the dimensioning of the generators and power transmission train, this ratio is has a great influence onto the

specific production cost EUR/KWh. Variable speed is an advantage in this respect as well.
Finally, the standard deviation of the electrical power averaged over all sea states is given in the last row as a measure of judging the uniformity of the power production. The small values found for the regulated turbines indicate a relatively uniform power delivery, whereas the turbines operated in on/off mode show much bigger standard deviations. However, this disadvantage is largely reduced by using variable speed drive.

Tab 8.1.: Comparison between the different turbine configurations

	2 Double regulated Kaplan turbines	2 Semi-Kaplan turbines	2 Propeller turbines	16 fixed speed on/off turbines	16 variable speed on/off turbines
$E_{tot,\ yr}$ [GWh]	1.79	1.69	1.49	1.69	2.04
P_{max}/P_{av} [-]	12.4	13.0	13.8	12.7	10.1
$Sdev_{P,av}$ [-]	0.66	0.57	1.61	1.33	0.85

9. CONCLUSION

Taking into account the demand for a turbine concept with minimum maintenance requirements, high efficiency, low specific installation costs and a relatively uniform power delivery, the layout with 16 variable speed on/off turbines was considered the optimum solution. Further cost benefits which can be expected from serial production of a big number of small turbines and from further development of the frequency converter technology make this concept even more attractive.

10. ACKNOWLEDGEMENTS

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