Playing with Currents

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Abstract— **Due to the growing share of renewables, electricity companies are faced with growing needs for flexibility of their generating assets to follow the variations. Gas-fired power plants are the most favorable power plants to deliver this flexibility, because of the quick controlling behavior of the gas turbines. However, these plants are becoming less competitive on the current market due to high gas prices compared with a low price of coal and (subsidized) renewables.**

Another possibility to ensure the flexible behavior of energy production is the usage of a fast switching tidal or climate power plant. This fast switching usage is new and not yet applied on the market. Therefore the valve and turbines itself and the effect on the hydrodynamics need to be investigated.

This paper provides insight in the experimental setup of the fast switching tidal power plant with the Louvre valve to ensure the flexibility of the energy production, as well as the effect on the water velocity near the structure.

Keywords—fast switching, flexible energy, ***hydrodynamic*** *impact*

I. INTRODUCTION

THE Lake Grevelingen in the Dutch South-Western delta (surface area 14000 ha and water surface of 10800 ha (Deltares, 2017)) was a former sea arm, which is dammed since 1971 by the Brouwersdam and the Grevelingendam.

In 2017 a research project named Playing with Currents is started in The Netherlands to investigate if a tidal power plant in the Brouwersdam could be operated in a ultra-flexible way, to balance the portfolio of an electricity supplier and to prevent congestion in the electricity grid of the network operator at the same time. Therefore the turbines of the tidal power plant should be able to switch over between generating mode, holding mode and pumping mode in a very short time, preferably within 10 s, see Fig. 1.

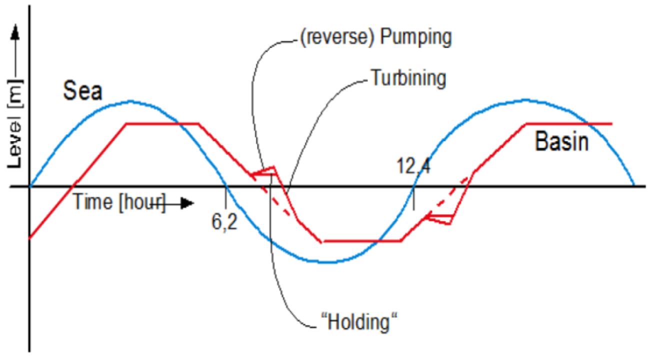

Fig. 1 Influence of switching between generating, holding and pumping mode.

On the one hand the question is whether a very fast (<10 s) switching of tidal power plants is technically feasible, on the other hand this will have an effect on the ecology and morphology of the tidal basin. Nowadays the lake Grevelingen has a lack of oxygen during dry summers, which can be partly prevented by opening the dam and allowing water exchange between the sea and the lake. The fast switching feature of the turbines could create a pulse increasing the water velocity and enhancing thus erosion.

In phase 1 of the project a laboratory model has been built to simulate these operation modes on lab scale, and to prove that this fast switching between the operation modes is feasible, using a Louvre valve.

In phase 2 of the project the environmental effects of this flexible tidal power plant on the water quality, coastal erosion, flora and fauna of the tidal basin have been investigated.

Results of laboratory experiments will be shown, as well as the results of the investigation of the hydrodynamic effects of the fast switching tidal power plant.

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II. CASE STUDY AREA

As previously mentioned the lake has a lack of circulation causing the water quality to deteriorate and creating anoxia in the deeper parts of the lake. Nowadays there is little circulation in the lake using small sluices on both sides of the lake (Brouwerssluis and Flakkeese spuisluis), with a discharge of respectively 125 m^3/s (constant) and 300 m^3/s (maximum). The discharge of the tidal power plant is expected to be up to 4000 m^3/s as maximum in case of 15 functional turbines [4].

The tide is reintroduced in this lake and varies nowadays between NAP -0.1 m and -0.3 m, during the breeding season the water level in the lake is reduced to an average of NAP -0.26 m. With the introduction of the fast switching tidal power plant, which creates an opening on the other side of the lake, the circulation within the lake increases and thus the water quality. The tidal difference in the lake in the future situation is 0.5 m and varies between NAP -0.45 m and +0.05 m., whilst the water level at the sea side varies between NAP -1.55 m and +2.70 m.

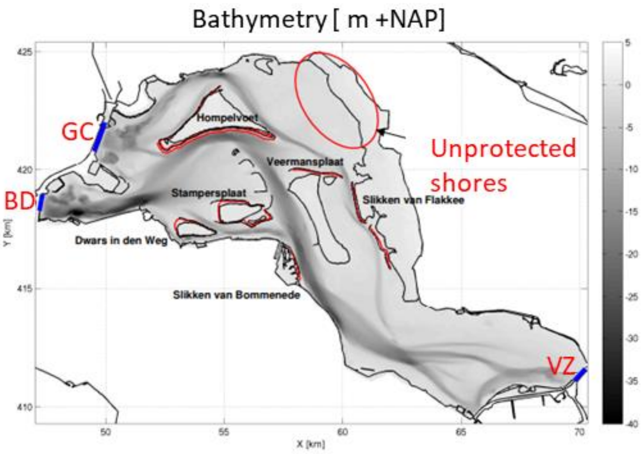

Fig. 2 Situation overview Lake Grevelingen, with indication of the Brouwerssluis (BD), the Flakkeese spuisluis (VZ) and the Tidal Power Plant (GC). Source: [4].

In Fig. 2 the overview of the situation is given. Most of the shores are protected with a hard revetment from the time that the lake was a sea arm. In the north there are some unprotected shores (encircled in red), which might face erosion due to the increase of the water level. However, these shores are very shallow and are sufficient for the safety of the water defenses behind. These shores need to be monitored intensively when the tidal difference is increased.

III. LAB MODEL OF FAST SWITCHING TIDAL POWER PLANT

After some initial studies in 2017 the HZ started with the construction of the laboratory model in 2018.
The design is made under supervision of the lector Jacob van Berkel and teacher-researcher Jan Maas. This design is realised with help of a construction firm. The pump, which can also operate as turbine, is delivered by Pentair, a pump manufacturer participating in the project, the frequency controller is provided by NIDEC.

The scale model is constructed in the big assembly hall of the HZ, the result is shown in Fig. 3.

Fig. 3 Scale model, with from left to right : water tank 1, diffusor with built-in Louvre valve, pump/turbine, diffusor, frequency controller and water tank 2.

The requirement of 10 s switching time of the large valve in the dam is translated to 1 s switching time for this small Louvre valve in the model. The company Hoogenboom, located in Kapelle, Zeeland, constructed the valve, as shown in Fig. 4.

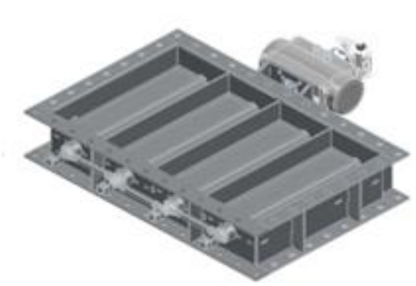

Fig. 4 Louvre valve 3D drawing.

In this setup the Louvre valve is an innovative solution for the fast switching feature, the incorporation in the model can be found in Fig. 5.

Fig. 5 Louvre valve.

The valve consists of four parallel blades and can switch much faster than a traditional butterfly valve.
After having pumped water from one tank to the other, the valve is closed and the operation mode is changed from pump to turbine after which the valve is opened to produce energy in generating mode.

With this set-up experiments can be executed to simulate the behaviour of a future tidal power plant, able to generate and pump and store energy in times the power prices are low.

Measuring the switching time of the Louvre valve, using the time tags on the command window and the open/close signal of the valve, it can be found that both opening and closing can be realized within 0.5 seconds.

In this scale model the gate opening at the end of the diffusor is 0.4 m², equal to the dimension of the valve.
In reality the gates in the Brouwersdam are 8 m high and 8 m wide, giving a cross sectional area of 64 m². The corresponding scaling factor is thus $\sqrt{64/0.4} = 12.65$. Assuming a similar valve is used in the dam the scaling factor is used in the different formulas to calculate the switching time in real life.

The used formulas are:

$$T = J * \alpha \tag{1}$$

$$J = (M_v + M_w)L^2 \tag{2}$$

$$\frac{1}{2}\alpha t^2 = 90° = \frac{\pi}{2}\ rad \tag{3}$$

where T is the driving torque of the valve in Nm, J is the inertia of the valve and the water columns around the blades in kgm², and α is the angular acceleration of the valve in rad/s². In (2) M_v is the mass of the valve and M_w is the mass of the water columns around the blades in kg, and L is the length of the blades in m. In (3) t is the time to close or open the valve by turning the blades over an angle of 90°.

When these formulas are used for the scale model, the result is a switching time of 0.25 s, not taking into account friction and losses in the driving technology.

Scaling up to the case study area with the factor 12,65 the masses M_v and M_w increase with a factor $(12.65)^3$ while L increases with a factor 12.65, so J increases with factor $(12.65)^5$. For the torque T the increase is a factor $(12.65)^3$ due to the bigger mass to move. Together this results in an angular acceleration α which is a factor $(12.65)^2$ lower and a switching time which is 12.65 times longer than in the scale model.

Assuming a close/open time in the model (including friction) of 0,5 s, the close/open time of a big size valve of 64 m² is expected to be around 6 s, well within the requirement of 10 s.

IV. FAST CHANGE OF WATER FLOW DUE TO VALVE

In order to give an impression on how fast the water starts to flow after opening the valve a measurement was done with the laboratory model to indicate the discharge through the valve. The result can be found in Fig. 6.

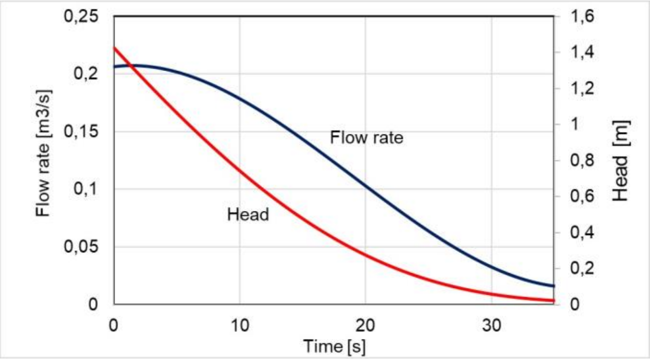

Fig. 6 Free flow after opening the valve while the machine is running no-load.

The water was pumped until a water head of around 1.4 m, after which the valve was closed and (when a stable situation was reached) opened again while the turbine was running in free flow without generating energy. The flow started with a discharge of 0.2 m³/s (3 m/s) and decreased due to the lower head difference until it reached a new equilibrium situation after 40 s. At this point the water level in both tanks is almost the same and thus the difference is zero. This dynamic behavior can also be expected in reality when the energy company is switching between operational modes when the power prices are fluctuating and this will possibly increase the effect on the morphological changes.

V. IMPACT ON ELECTRICITY TRADE AND NETWORK CONGESTION

By using this fast switching Louvre valve it is possible to switch very fast between the operation modes of a tidal power plant.

The three operation modes are (see also fig. 1):

- Generating mode
- Pumping mode
- Holding mode

Generating is the normal operation mode of the tidal power plant. But sometimes, when the prices on the electricity market are very low, it can be interesting to stop power production and hold the water level in the basin behind the dam on a certain level by closing the valve.
In such situations with low market prices the (cheap) electricity can be used to pump water from the sea to the basin and thus increase the water level in the basin.

Later, when electricity prices are higher again, the generating mode can be proceeded, while releasing the additional energy stored in the basin.

The fast switching feature (10 s in reality, 1 s for the model) is a requirement of an electricity company trading on the energy market. Fast fluctuations of wind and solar power cause fast fluctuations of the power prices as well. For an electricity company it is very advantageous to act as fast as possible on these fluctuations to maximize their profits.

Energy company PZEM, which is involved in the research program Playing with Currents, has made an analysis of the value on the APX and imbalance market of the electricity produced by the tidal power plant in the Brouwersdam, using the expected 25 MW. The smart usage of the gate operation (closing and opening of the valve on certain moments) can lead to 10% of additional revenues on the imbalance market. Also the effect of pumping is considered, but the added value appeared to be marginal.

An additional study with the network company Enduris has been performed to investigate if smart operation of the tidal power plant would lead to congestion relief of the network and/or defer or prevention of investments to strengthen the network. This work was done by a graduate student in 2018 [5].

Three connection points on the 50 kV grid in the north of the Province of Zeeland were considered to connect the 25 MW tidal power plant. Load flow simulations showed that two of them would not lead to overload or congestion situations. One of the three could lead to a possible overload of a transformer in certain situations. Reducing the power of the tidal power plant could solve the problem in this situation, but compensation should be paid then to the energy company for the missed profits of the power plant. It appeared that these compensation fees during 40 years were much higher than the investment costs in a new transformer with a higher capacity, so it was advised to invest in a new transformer if this connection point would be chosen. However, the other two connection points were preferred because there no congestion problems would occur.

VI. SIMULATION OF HYDRODYNAMIC EFFECTS

In another study an estimation has been made of the ecological and morphological effects near the turbines and the lake itself. First the hydrodynamic effect needed to be modelled. This is done using a 1D model to calculate the discharge and flow velocity through the turbine.

In the case of the tidal power plant in the Brouwersdam a diffusor type gate will be used. The discharge in case of an added turbine can be calculated using:

$$Q_s = A_s \sqrt{\frac{2g(|H_s| * (1-f)}{c}} \qquad (4)$$

In this equation Q_s is the discharge (m³/s), A_s is the cross sectional area of the culvert (m²), H_s is the prevailing pressure difference (m), f is the response rate of the turbine (-) and c is the loss coefficient (-) [3].

According to [2] the loss coefficient is 1.35 for diffusor types and the response rate due to the turbine is 0.67. The cross sectional area is 64 m², as already mentioned before, and the average system ratio is 1.64 m. In this case the discharge can be up to 180 m³/s per turbine, with a flow velocity of around 2.8 m/s.

The tidal turbines need to achieve a certain efficiency as well, therefore they are only turned on if there is a difference in water level between inside and outside the dam of 0.5 m and are turned off if the difference is less than 0.2 m. In Fig. 7 the daily situation is given, with in blue the water level on the sea side of the dam, in red the water level within the lake and in green the time frames for electricity generation. From this graph it can be observed that the majority of the day electricity (approximately 80% of the time) can be produced.

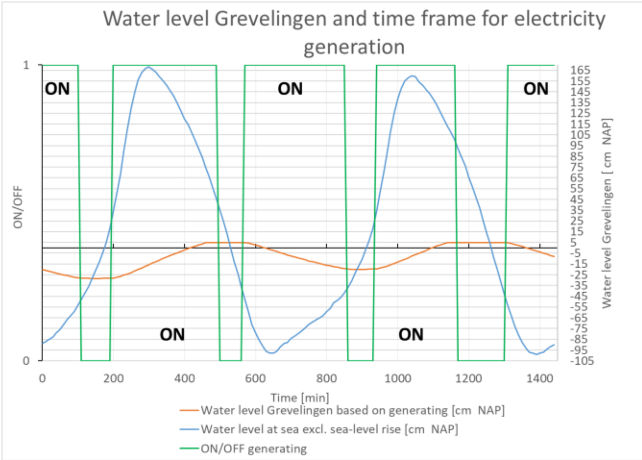

Fig. 7 Water level in Lake Grevelingen.

Taking the possible time frame into account the velocity during the generation can be estimated. This can be seen in Fig. 8, where the velocity development based on the difference in water levels using (4) is given. The velocity within the culverts is expected to be between 2.2 and 3.1 m/s, which also corresponds with the 2.8 m/s average velocity given before. In this case also the usage of the pumping function of the turbines is used to generate the maximum potential.

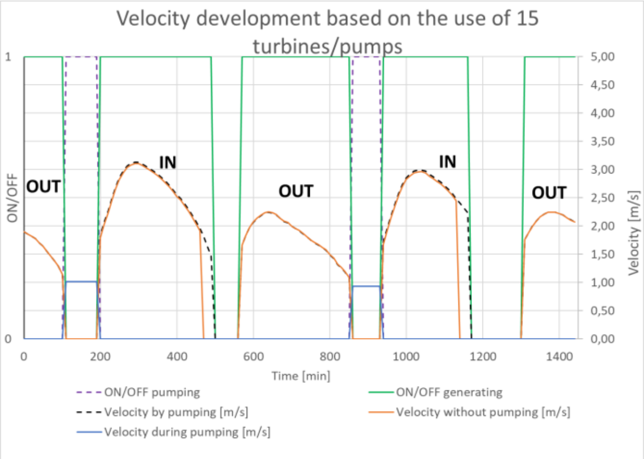

Fig. 8 Velocity development within the culvert.

With expected flow velocities well over 2.0 m/s there is need of bed protection. The water is spreading inside the lake, so the effect of the flow velocity is damping out very fast. The water pulse produced by the fast switching of the valves is not taken into account yet, but the expectation is that this will damp out fast. The most important effect on the water quality in the lake is the increase of circulation and thus less standing water in the lake, decreasing the anoxia during summers.

VII. CONCLUSIONS

This paper includes the possibilities of the usage of a fast switching tidal power plant in order to facilitate the flexibility in the demand on the energy market and its hydrodynamic effects. The following conclusions can be drawn:

1. More flexible operation of a tidal power plant can be a requirement of energy and network companies now and in the future.
2. This could imply that a tidal power plant should be able to switch between generating, holding and pumping mode within 10 s
3. A fast switching device built in the flow channel of the tidal power plant can play an important role for realizing this flexibility.
4. On laboratory scale a Louvre valve has been tested which can switch on and off within 0,5 s. Scaling up this value to a Louvre valve of 64 m^2 as would be applied in the future tidal power plant in the Brouwersdam results in a switching time of around 6 s, well within the requirement of 10 s.
5. Flexible gate operation with a tidal power plant by an energy company can lead to about 10% additional revenues on the imbalance market.
6. Flexible operation of a tidal power plant can also be useful for a network company to prevent overloads or defer investments in the network. But the costs of compensation should be less than the investment costs.
7. Taking a minimum head difference of 0.5 m the energy generation in the Brouwersdam would be possible for 80% of the time.
8. The flow velocities are approximately 2.8 m/s, resulting in a need of bed protection near the structure.
9. The circulation in the lake will be improved and so will be the effect on the water quality. This needs to be investigated further in the continuation of the Playing with Currents project.

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