Effects of Recovery Rate on Variable Speed Direct-Driven Tidal Energy Desalination

A. Jarquin-Laguna[1] and F. Greco[2]

1. Department of Maritime and Transport Technology, Faculty of Mechanical Engineering, Delft University of Technology, Delft, the Netherlands.
2. Department of Hydraulic Engineering, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, the Netherlands.

Keywords—**Renewable energy desalination, Seawater Reverse Osmosis, Tidal energy.**

I. Introduction

TIDAL energy has emerged as a promising source of renewable energy in recent years and its potential applications extend beyond electricity generation. Seawater desalination is a critical process in many water-scarce regions around the world, and renewable energies can be harnessed to power this process [1].

The combination of tidal energy and seawater desalination has several advantages, including a low carbon footprint, high reliability and stable energy output. The technical and economic challenges for such integration are not unique to tidal energy technologies, for example in the field of wind energy several advances have been made in the integration of desalination systems with horizontal axis turbines as has been presented in [2], [3]. One of the practical advantages of using hydrokinetic turbines, is the lower power ratings compared with wind turbines which allow to use off-the shelf hydraulic components. At the same time the high pressure pumps are already located under water so there is no need for priming the seawater flow. Tidal energy for seawater desalination is a promising area of research that could help meet the growing demand for clean drinking water in coastal regions and for off-grid applications.

This extended abstract presents part of the numerical results of an innovative direct-driven tidal desalination system with energy recovery device, where a single unit is evaluated for different recovery rates operating in the below rated variable speed region.

A. Direct-driven with energy recovery device

A proposed solution for direct-driven desalination, is to integrate the tidal turbine rotor with a fluid power transmission and a seawater reverse osmosis (SWRO) system, such that the desalination process occurs without intermediate electrical conversion. The proposed concept consists of a positive displacement high pressure-pump which converts the horizontal axis rotor's mechanical power into a hydraulic power in the form of a pressurised seawater flow. The seawater flow rate is directed into the reverse osmosis membranes where a permeate flow of fresh water is obtained from the pressure difference between the high-pressure feed and the membranes' osmotic pressure. The remaining brine is circulated through an energy recovery device (ERD) and pumped back to the membranes' feed flow. A schematic of the proposed configuration is show in Fig. 1.

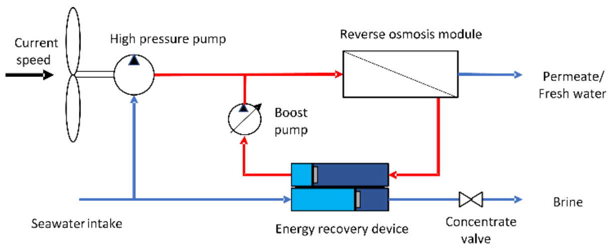

Fig. 1. Schematic of the proposed direct driven tidal stream SWRO system using an energy recovery device.

The ERD is used to recover the residual pressure in the discharged brine and transfer it to the feed flow, thereby enhancing the operating efficiency of the SWRO. An auxiliary boost pump is employed to control the concentrate flow and offset any pressure losses [4], [5].

B. Variable rotor speed control strategy

In order to achieve a variable speed operation of the rotor below rated current speed conditions, the pump's torque and therefore the rotor speed are controlled by adjusting the system pressure through the ERD's boost pump. The idea is to modify the effective concentration and consequently the osmotic pressure induced by the RO membranes by regulating the circulating flow towards them. The results from previous work [6] showed that this control strategy is in principle feasible, however a wide operating range of the ERD system is required, resulting in recovery rates up to 80% when operation is close to rated current speed conditions. In practice, the recovery rates of typical SWRO plants are closer to 50% [7], thus it is not known what is the effect of limiting the recovery rate on the proposed integrated system.

In this work three cases are analysed, where the recovery rate of the ERD device is capped to the maximum values of 50%, 60%, and 100%. The latter case corresponds to an ideal operation of the ERD where no constraints are imposed and the boost pump is able to deliver the required flow to achieve the desired recovery rate for ideal variable speed operation of the rotor.

II. METHODOLOGY

C. Numerical model

A numerical study of the tidal turbine integrated with the hydraulic transmission and the SWRO with ERD is implemented to assess the effect of the RR in the system behaviour. The set of algebraic and differential equations that describe the fully non-linear coupled model have been previously presented in [6]. In the following paragraphs only a brief description is made to highlight the coupling between the physical variables of the modules.

The horizontal axis rotor assumes a quasi-steady operation with the hydrodynamic behaviour characterised by the dimensionless coefficients of power, torque and thrust as function of the tip speed ratio [8]. A fixed pitch angle is considered so only the region below rated current speed is considered in this study. The hydroelastic and unsteady effects are not included. The positive displacement pump coupled to the rotor creates a flow rate as a function of the rotor speed while accounting for leakage losses as a function of the system pressure. Similarly, the torque transmitted depends on the pressure across the pump. The drivetrain is modelled through the conservation of momentum equation as a first order differential equation to solve for the rotor and pump speed according to the torques' balance.

For the reverse osmosis desalination process, the solution diffusion model is used to represent the transport mechanism of water across the membranes as well as the retention of salts and ions [9], [10]. The flow rate that passes across the RO membranes is characterised by the water permeability constant and the difference in pressure between the two sides of the membrane and the osmotic pressure difference. The model uses an effective concentration at the feed side of the membrane surface to obtain the average osmotic pressure difference, while the effective concentration also depends on the membrane characteristics and both the feed and the concentrate (or brine) flow rates [11]. Hence, there is coupling between the flow rates and solute concentrations with the osmotic pressure of the system. In addition mass balances over the RO membranes, and the ERD units are used to determine the overall mass flow rates of water and solute.

D. Case study on the SWRO recovery rate

For comparative purposes, the rotor and SWRO model parameters used in this study are identical to those described in [6]. Three cases are analysed, where the recovery rate of the ERD device is capped to the maximum values of 50%, 60%, and 100% respectively. The latter case corresponds to an ideal operation of the ERD where no constraints are imposed and the boost pump is able to deliver the required flow to achieve the desired recovery rate. The main characteristic of the tidal and SWRO system are shown in Table I.

TABLE I
MAIN PARAMETERS OF THE INTEGRATED TIDAL AND SWRO MODEL

Symbol	Quantity	Value
R	Rotor radius (m)	5
λ_{opt}	Optimal tip speed ratio[a] (-)	3.8
P_{rated}	Rated mech power (kW)	150
U_{rated}	Rated current speed (m/s)	2.0
V_p	Pump volumetric displacement (l/rev)	66.13
C_s	Pump leakage coefficient (m^3/sPa)	1.5e-10
p_{max}	Maximum membrane pressure (Pa)	6.9e6
K_w	RO Mass transfer coefficient (s/m)	6.4e-9
A_m	Total membrane area (m^2)	2.97e3
δ	Osmotic pressure coefficient (Pa/ppm/K)	0.2641
Cf_{in}	Intake feed concentration (ppm)	35500
M	ERD volumetric mixing (-)	0.06
V	System volume (m^3)	8
ρ_w	Seawater density (m^3/s)	1025
T	Water temperature (K)	295

[a]The optimal tip speed ratio $\lambda=\omega R/U$ is defined where a maximum power coefficient of the rotor is achieved at Cp=0.42

First, results are obtained for the operational window of the integrated system under steady-state conditions for a range of current speeds. The graphical results provide insight into the variable speed operation together with the system pressure and flow rates.

The second set of results allow to compare the dynamic response of the coupled integrated tidal stream SWRO system, through time-domain simulations under a given stochastic current speed.

III. RESULTS

E. Steady-state operating points

The operating range of the integrated turbine and SWRO system is given by the equilibrium points between the rotor torque-speed characteristics and the torque-speed load induced by the pump driving the SWRO unit. The resulting torque and power curves are shown for different rotor speeds and recovery rates in Figs. 2 and 3.

For the case when there is no constraint in the recovery rate of the ERD unit, the system pressure can be adjusted in such a way that the rotor is able to follow the ideal rotor speed-torque quadratic relation defined by the optimal tip speed ratio, i.e. where maximum power coefficient from the rotor takes place. A maximum rotor speed of 14 rpm is

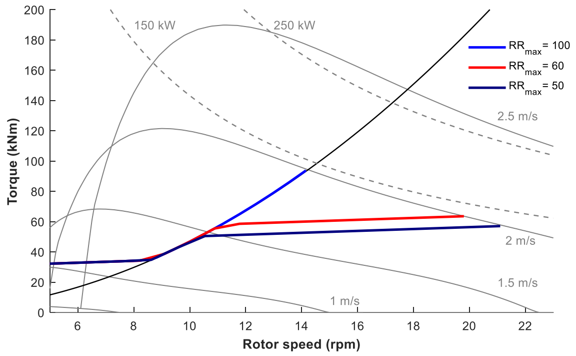

Fig. 2. Torque speed curves for different recovery rate values up to a rated current speed of 2 m/s.

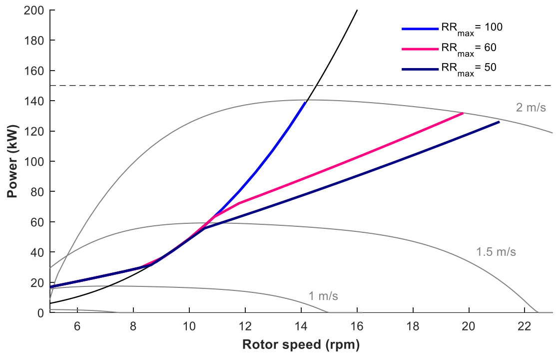

Fig. 3. Power speed curves for different recovery rate values up to a rated current speed of 2 m/s.

reached at a rated current speed of 2 m/s. On the other hand, when the recovery rate is limited to only 50 or 60%, lower concentrations are observed, resulting in lower osmotic pressures induced by the membranes. Without the capacity of adjusting the pressure above certain level, the ideal torque can only be achieved for a limited range of current speeds. Once the maximum recovery rate is reached, the rotor follows a linear relation with respect to the torque. The lower torques result in a higher range of operational rotor speeds, which can reach up to 20 rpm for the same rated speed of 2 m/s. For lower values of the recovery rate constraint, a lower torque and consequently a higher rotor speed excursion is obtained.

F. *Response to stochastic current velocity*

The time domain simulations were performed using an artificial time series for 800 s for an average current speed of 1.6 m/s and turbulence intensity of 14%. The non-linear algebraic and differential equations were implemented and solved numerically using the simulation environment Matlab-Simulink based on numerical integration scheme with variable time-step. The first 200 s of the simulations were accounted for transient effects. The results from the comparison between the time series of the rotor speed, the system pressure, the permeate flow rate and recovery are shown in separate graphs in Fig. 4.

It is observed that for lower recovery rates, the rotor speed experiences higher excursions with lower pressure fluctuations. Pressure differentials of up to 30 bars are observed between the unrestricted system and the one limited to a recovery rate of 50%. Higher fresh water production is achieved at lower recovery rates as the permeate flow rates exhibit a proportional relation to the rotor speed.

IV. Discussion & Preliminary conclusions

Despite operating at higher tips speed ratios, and therefore at suboptimal power capture performance from the rotor's point of view, a higher amount of permeate flow is achieved with lower recovery rates. From this perspective the maximum water production is not necessarily achieved at the optimal power capture of the rotor. In practice there is a limit on the maximum flow rate allowed in the membranes, while higher rotor speeds might lead to potential issues on cavitation, therefore further consideration should be taken to consider both limitations in the system design.

Further work will address the operation in above rated current speed condition and it will evaluate the option of extending from a single unit to a small array of turbines with centralized SWRO production.

References

[1] M.A. Abdelkareem, M. El Haj Assad, E.T. Sayed, B. Soudan, *"Recent progress in the use of renewable energy sources to power water desalination plants,"* Desalination, vol. 435, pp. 97-113, 2018.

[2] F. Greco, D. De Bruycker, A. Velez-Isaza, N. Diepeveen, and A. Jarquin-Laguna, *"Preliminary design of a hydraulic wind turbine drive train for integrated electricity production and seawater desalination,"* in Journal of Physics: Conference Series, vol. 1618, no. 3. IOP Publishing, 2020, p. 032015.

[3] F. Greco, S. Heijman and A. Jarquin-Laguna, *"Integration of wind energy and desalination systems: a review study,"* Processes, vol. 9, no. 12, p. 2181, 2021.

[4] R.L. Stover, *"Seawater reverse osmosis with isobaric energy recovery devices,"* Desalination, vol. 203, pp. 168-175, 2007.

[5] A. Jarquin-Laguna and F. Greco, *"Integration of hydraulic wind turbines for seawater reverse osmosis desalination,"* in Offshore Energy and Storage Summit, July 2019, pp. 1–9.

[6] A. Jarquin-Laguna and S. Ordonez-Sanchez, *"Utilising tidal stream energy to drive seawater reverse osmosis desalination processes,"* in Proceedings of the European Wave and Tidal Energy Conference, 2021, p. 2143.

[7] C. Fritzmann, J. Lowenberg, T. Wintgens and T Melin, *"State-of-the-art of reverse osmosis desalination,"* Desalination, vol 216, pp. 1-76, 2007.

[8] S. Ordonez-Sanchez, M. Allmark, K. Porter, R. Ellis, C. Lloyd, I. Santic, T. O'Doherty, and C. Johnstone, *"Analysis of a horizontal-axis tidal turbine performance in the presence of regular and irregular waves using two control strategies,"* Energies, vol. 12, p. 367, 2019.

[9] M. Qasim, M. Badrelzaman, N. N. Darwish, N. A. Darwish and N. Hilal, *"Reverse osmosis desalination: A state-of-the-art review,"* Desalination, vol. 459, pp. 59–104, 2019.

[10] J. G. Wijmans and R. W. Baker, *"The solution-diffusion model: a review,"* Journal of membrane science, vol. 107, no. 1-2, pp. 1–21, 1995.

[11] A. R. Bartman, P. D. Christofides, and Y. Cohen, *"Nonlinear model-based control of an experimental reverse-osmosis water desalination system,"* Industrial & Engineering Chemistry Research, vol. 48, no. 13, pp. 6126–6136, 2009.

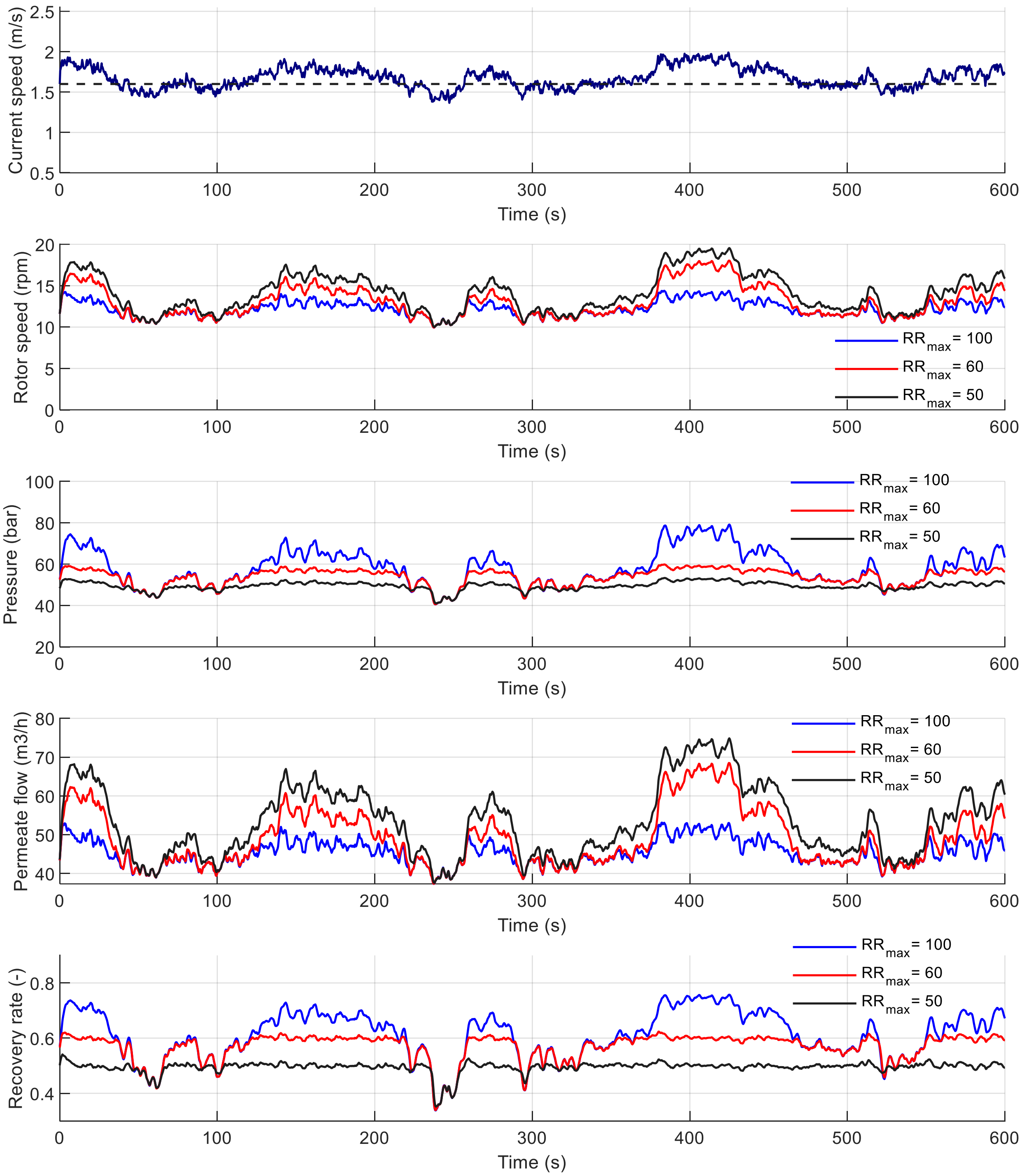

Fig. 4. Time-domain results of the comparison of the rotor and the SWRO system response for of three recovery rate limits. The current speed conditions correspond to 1.6 m/s with 14% turbulence intensity. The graphs show the current speed; the rotor speed ; the system's pressure; the permeate flow and the recovery rate.