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Contributions for Carbon-Neutrality in the Water Sector: From Theory to Practice †

Helena M. Ramos * and Dídia Covas

CERIS, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais 1, 1049-001 Lisboa, Portugal; didia.covas@tecnico.ulisboa.pt

* Correspondence: hramos.ist@gmail.com or helena.ramos@tecnico.ulisboa.pt

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Abstract: This research aims to present relevant developments carried out in the domains of energy recovery and the associated digital technology in the water sector. These include the implementation of digital twins of a PRV and energy converters. Several performance tests have been carried out in pumps operating as turbines (PATs) when replacing pressure-reducing valves (PRVs) or coupled to them. Based on virtual prototype of turbines, the numerical modelling of a PRV and tested PATs, with radial and axial impellers, have been developed. On the other hand, Digital Twins (DTs) provide useful data collection/analysis tools for reproducing disruption scenarios for resilience assessment purposes and analyzing asset prognosis and the system efficiency to determine proactive management models.

Keywords: smart water grid (SWG); energy recovery; digital twin

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1. Introduction

Smart water grids (SWGs) represent a critical advancement in water management, particularly in the context of smart cities. These networks use state-of-the-art information and communications technologies (ICTs) to improve the efficiency, reliability, and sustainability of water distribution networks. Key features of SWGs include the integration of ICT: for example, SWGs seamlessly integrate sensors, meters, digital controls, and analytical tools [1]. These components work together to automate monitoring and control processes within water networks. Real-time monitoring enables live monitoring of all system components. This dynamic monitoring ensures rapid responses to any anomalies or problems. By integrating ICT, SWGs will be able to facilitate resource quality control measures. The distribution and operations of SWGs can be optimized by dynamically adjusting flow rates, pressure levels, and valve settings. This fine-tuning improves overall system efficiency. Deploying an SWG requires a more complex implementation process compared to traditional networks. However, the benefits are significant as they reduce water–energy losses and improve the entire system's efficiency.

One critical factor contributing to water scarcity is the loss of water within water distribution systems [2]. These losses primarily result from inadequate knowledge during the design process, suboptimal water availability optimization, excess of pressure, and insufficient system maintenance and management. To address these challenges and achieve sustainable and integrated water resource management using SDGs, enhancing system efficiency becomes a paramount issue. In this context, the concept of a smart water grid (SWG), which leverages a Digital Twin (DT) to enhance monitoring, management, and overall system effectiveness is crucial [1–4].

The SWG framework is built upon two main platforms: the water grid platform and information and communication technology (ICT). The fundamental premise of smart water

management systems lies in achieving a global balance by comparing water demand with available water resources. Water systems must be viewed as cyber–physical entities, comprising interconnected sensors, processors, and actuators. These components continuously communicate and report relevant information within a control management system.

2. Materials and Methods

2.1. Digital Twin

The transition to carbon-neutrality in the water sector is a multifaceted challenge that encompasses a range of innovations and sustainable practices. The adoption of advanced technologies, such as renewable energy systems for water and wastewater treatment, can significantly reduce the carbon footprint of water operations. The integration of renewables are cases of how the sector can move towards energy self-sufficiency and emission reduction. Optimizing water treatment and distribution processes is vital. This includes modernizing infrastructure, minimizing leaks, and implementing intelligent management systems that monitor and control water and energy use in real time. This can be achieved through the enactment of laws and incentives that encourage sustainable practices and investment in clean technologies.

In summary, the shift towards carbon-neutrality in the water sector requires a collective commitment to adopt sustainable practices, invest in technology and innovation, and foster a culture of conservation. Through concrete actions and collaboration, it is possible to turn theory into practice and ensure a more sustainable future for all. On the other hand, the integration of SWGs and DTs (Figure 1) holds immense promise for enhancing water system efficiency, ensuring sustainable resource management, and addressing the challenges posed by water scarcity.



Figure 1. DT technology.

2.2. Energy Recovery

There are several different energy recovery configurations which can be applied to generate power, namely hydraulic regulation (HR), electric regulation (ER), hydraulic and electric regulation (HER), and no regulation (NR). All these configurations can provide interesting energetic results depending on the water distribution network conditions, presenting great economic benefits for water utilities if implemented correctly. While the NR mode operates with the nominal rotational speed of the PAT, the ER mode enables the selection of the rotational speed, which maximizes energy production, with the aid of a variable speed drive (VSD) which controls the frequency and voltage of the motor connected to the PAT. Although no valves are installed to optimize a PAT's operating conditions (as in the HR and HER modes), some measures ensure these energy production methods do not interfere with the network's stipulated pressure levels. Firstly, a flow control valve (FCV) can be placed in parallel with the PAT in the HR and ER. Secondly, also unlike the standard modes, the existing PRV can be kept to ensure pressure levels do not exceed the stipulated limit in case the flow rates become too low to induce a higher head drop in the PAT. Additionally, the PRV is a critical element in cases where the PAT does not operate correctly. The HR and ER configurations are displayed in Figure 2.

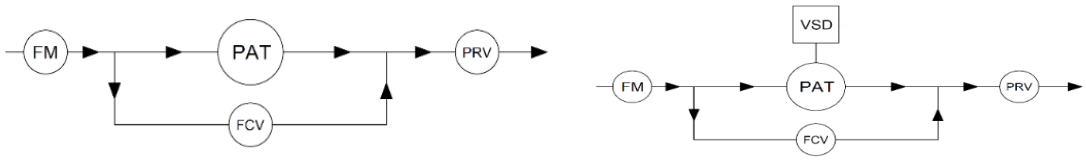
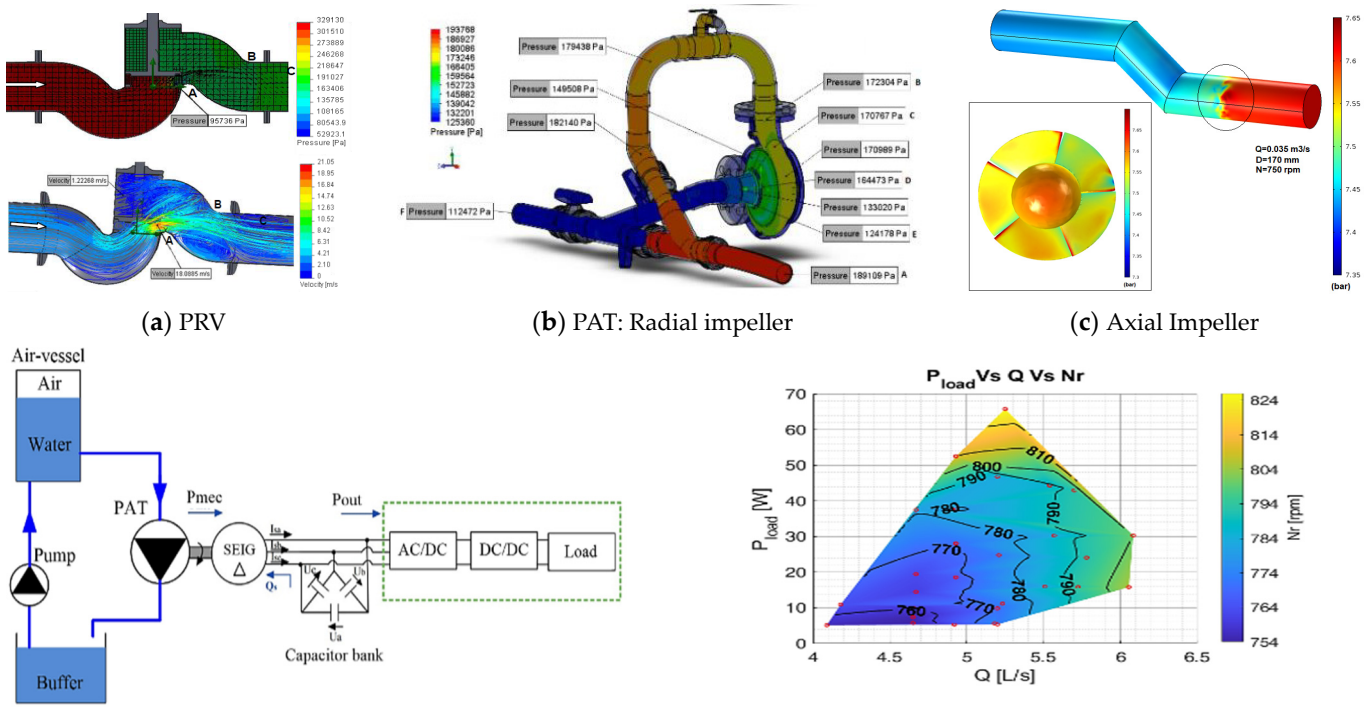


Figure 2. HR (**left**) and ER (**right**) configuration schemes. FM, flow meter; PRV, pressure-reducing valve; PAT, pump-as-turbine; FCV, flow control valve; VSD, variable speed drive.

In order to calculate the alternative rotational speed characteristic and efficiency curves for each PAT for both HR and ER modes, the affinity law of turbomachines can be applied to the respective nominal rotational speed curve.

2.3. CFD Analyses and Lad Set-Up

In WDN management, pressure-reducing valves (PRV) are frequently used to regulate excessive pressure and to minimize water–energy losses. Pressure contour plots are used to show the flow characteristics of the PAT. A cross-section plane of the impeller and along the device for a specific flow is shown in Figure 3a–c. As the fluid moves within the domains and along the impeller, from the inner to the outer region, the pressure decreases.



(**a**) PRV (**b**) PAT: Radial impeller (**c**) Axial Impeller

(**d**) Hydraulic–Electric system (**e**) Contours of the system behavior

Figure 3. PRV versus PAT (**top**); Energy recovery system (**bottom**): (**a**) PRV; (**b**) radial PAT; (**c**) axial PAT; (**d**) hydraulic–electric energy recovery system; (**e**) power vs. Q vs. Nr system behavior.

The energy converter is analyzed for a hydraulic–electric coupled system for different values of flow (Q) and rotational speed (Nr) (Figure 3d,e).

3. Conclusions

Replicating disruption scenarios for resilience assessment purposes and analyzing asset prognosis and system efficiency are some of the useful data provided by Digital Twins and SWGs. The used DT model requires continuous adjustments and learning process techniques based on AI, supported by a large amount of field data stored on big data platforms in order to offer an effective solution regarding water–energy losses. CFD

models are used to predict the performance of PRVs for pressure control and of different impellers in PATs more suitable to the field conditions in terms of available head and flow, for a large range of operating conditions. After being calibrated and verified, CFD models can be used in the same conditions as the experimental ones, allowing improvements to the system's operation and efficiency. Numerical models and experimental tests help to better understand the system's behavior to achieve the best performance within the water–energy nexus.

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