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REVIEW

The contribution of low-head pumped hydro storage to grid stability in future power systems

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Abstract

The pan-European power grid is experiencing an increasing penetration of Variable Renewable Energy (VRE). The fluctuating and non-dispatchable nature of VRE hinders them in providing the Ancillary Service (AS) needed for the reliability and stability of the grid. Therefore, Energy Storage Systems (ESS) are needed along the VRE. Among the different ESS, a particularly viable and reliable option is Pumped Hydro Storage (PHS), given its cost-effective implementation and considerable lifespan, in comparison to other technologies. Traditional PHS plants with Francis turbines operate at a high head difference. However, not all regions have the necessary topology to make these plants cost-effective and efficient. Therefore, the ALPHEUS project will introduce low-head PHS for regions with a relatively flat topography. In this paper, a grid-forming controlled converter coupled with low-head PHS that can contribute to the grid stability is introduced, emphasising its ability to provide different AS, especially frequency control, through the provision of fast Frequency Containment Reserve (fFCR) as well as synthetic system inertia. This paper is an extended version of the paper "The Contribution of Low-head Pumped Hydro Storage to a successful Energy Transition", which was presented at the 19th Wind Integration Workshop 2020.

1 | INTRODUCTION

In accordance with the regulations of the European Network of Transmission System Operators (ENTSO-E), 3000 MW of primary reserves have to be provided for the continental European synchronous network at all times [1]. Therefore, energy storage is essential for providing the balancing reserves and other ancillary services which are needed for grid stability and security of supply. Pumped Hydro Storage (PHS) is currently the most mature and cost-effective way of storing energy. However, countries such as the Netherlands and Belgium do not have the natural topography required for PHS with large gradients in altitude in their landscape. Therefore, the energy reserves in these countries consist almost exclusively of fossil fuels and thermal power plants [2]. As part of the ALPHEUS project (Augmenting grid stability through Low-head Pumped Hydro Energy Utilisation and Storage), Reversible Pump-Turbine (RPT) technology will be improved and conceptual designs for new and retrofitted low-head PHS basins will be developed, along with the adjusted civil structures needed to make PHS economically viable in shallow seas and coastal environments with flat topography [3]. A literature review [4] identified the main failure mechanisms of a low-head PHS station to be piping, dam micro-stability and bursting of the clay layer. These are well-known phenomena that can be tackled with the current hydraulic structures knowledge. Besides, other important factors for implementation will be costs and regulatory hurdles, which are currently being investigated. For high-flow low-head PHS applications, it has been proposed that axial-flow pump-turbines with variable speed drives are a promising solution. For such a scenario with high torques and low speeds, axial-flux motor-generators are well suited offering high efficiencies and power density [5]. The objectives of this paper are to show the concept and rationale of the ALPHEUS project and explain how it will contribute to grid stability and flexibility through low-head pumped hydro energy storage.

This paper is an extended version of the paper "The Contribution of Low-head Pumped Hydro Storage to a Successful Energy Transition", which was presented at the 19th Wind Integration Workshop 2020. In Section 2, the turbine design and civil structure are discussed. Compared to the initial conference paper, new civil engineering findings and turbine design results are included. The research that ALPHEUS will carry out with respect to pump-turbine technology and the test rig for data acquisition on the operation of the pump-turbine are described. Next, Section 3 describes how the pump-turbine is integrated in the energy storage system. This section has undergone a major revision in regard to the original paper. Additional content has been added discussing the need to provide large-scale energy storage to the grid, and the increasing demand for energy storage within our electricity grids, before diving into the approach and potential of ALPHEUS to provide grid-scale storage and ancillary services. Additionally, the methodology of integrating and validating the turbine and power-take off is introduced. In Section 4, the proposed power take-off systems are further elucidated. Furthermore, the viability of the control architectures is discussed, with additional citations of relevant papers compared to the original conference paper. Finally, in Section 5, the grid integration is described. Block diagrams and equations to calculate frequency control reserves are included. Moreover, the system separation in the Continental Europe Synchronous Area (CESA) on 8 January 2021 has been simulated and results are introduced which shows that a low-head PHS connected to the grid via grid-forming converter enables it to provide frequency control reserves that could be provided to the CESA during the system separation.

2 | TURBINE DESIGN AND CIVIL STRUCTURE

Hydroelectricity generation is a mature technology where the potential and/or kinetic energy of the water is converted into electricity when flowing thought a turbine. In Pumped Hydro Storage (PHS), the turbine also acts as a pump. In pump mode, electricity is consumed, and water is pumped from a lower to an upper basin, increasing the potential gravitational energy of the water. This storage happens during off-peak time and is later used to balance the variable loads from other power generation sources such as solar or wind [6]. Such bi-directional machines are called Reversible Pump-Turbines (RPTs). Impulse turbines are more efficient for high head low flow situations whereas reaction turbines such as Francis turbines and axial flow propeller turbines have a better performance at low head and high flow sites [11]. Francis and propeller type turbines with fixed pitch runners experience a sudden drop in efficiency at off-design operation due to a flow mismatch between swirl generated by the wicket gates and the runner. Severe unsteady pressure fluctuations happen at off-design conditions due to Rotor-Stator Interaction (RSI) and they are significant for pump- turbines [12]. This makes it challenging to design an RPT which is highly efficient in both pump and turbine mode of operation. RSI can cause fatigue cracks in the runner, thereby affecting the turbine lifetime and reliable operation [12]. Variable speed RPTs can improve the performance of RPTs and change mode of operation in a shorter time. In turbine mode, it improves the efficiency and enlarges the operating range for a given head. Additional flexibility of operating at fixed speed for different heads is also possible. In pump mode variable speed extends the operating range and helps with start-up [12]. Pumps acting in reverse direction as turbines, known as PAT (Pump As Turbines), are a cheap RPT design. However, they generally offer lower efficiency, and the technology needs to be further developed to generate wider acceptance [12]. Compared to centrifugal pump- turbines, axial type pump-turbines offer better efficiency at high flow rate and low head conditions. Furthermore, the Contra-Rotating (CR) type design can make it more compact for the same power rating [15]. Kim et al. use a Design of Experiments (DoE) method, combining with Computational Fluid Dynamics (CFD), to improve the efficiency of a CR RPT. They found that a trade-off relation exists between pump and turbine mode performances [15]. Kinemoto et al. propose a pump system with a smart control CR mechanism, which can improve the unstable performance region and cavitation performance compared to a conventional single-stage impeller pump [14]. Next to the discussed shaft-driven concepts, rim-driven concepts can be an interesting opportunity because of their compactness and flexibility for installation [16]. They are commonly seen in marine propulsion systems. Here, the blades are driven from the blade tip by an electric machine, designed along the outer periphery. One important difference is the blade loading. Since tip vortices are absent, there is the opportunity to increase the load at the outer part of the blade. However, root vortices can be introduced, which can affect performance significantly [16].

CFD has led to significant improvements in turbine performance [13]. Powerful post-processing capabilities help designers to understand the flow physics better. 3D inverse design method provides designers a way to compute the blade geometry by using hydrodynamic parameters such as blade loading. The ability to use flow physics parameters in 3D inverse design removes empiricism associated with geometry parameterisation method of conventional or direct design method. This has helped designers to achieve good performance improvements in different kinds of turbomachines including pumps and turbines [13]. The ALPHEUS project is developing low to ultra-low head (1–20 m) RPTs with a round trip efficiency of 70–80% and a faster mode switching between pump and turbine modes of operation (90–120 s) [3]. In addition, the solution has to be fish friendly, seawater tolerant, cost effective and scalable for a range of power outputs. Based on the wide and complex requirements, the following three promising RPT technologies are studied in ALPHEUS:

1. Shaft-driven variable-speed contra-rotating propeller
2. Rim-driven variable-speed contra-rotating propeller
3. Positive displacement

This section outlines the initial design optimisation of the Shaft-Driven (SD) and Rim-Driven (RD) CR propeller RPT. Advance Design Technology's (ADT) turbomachinery design software TURBOdesign Suite is used for the design. A mean-line design of an SDCR pump is created using TURBOdesign Pre based on a head of 9 m at BEP; the machine is sized for a power output of 10 MW when run in turbine mode. At design conditions, the two rotors operate at different speeds with a speed ratio of 0.9. The resulting design has a shroud diameter of more than 6 m. The meridional geometry generated by TURBOdesign Pre was then used to generate 3D geometry of both rotors using TURBOdesign1. This software uses the 3D inverse design approach which generates a blade design satisfying the user specified blade loading (pressure distribution over the blades) [7–9]. This initial design is shown in Figure 1; it is analysed in pump mode and turbine mode in CFD. A simple domain consisting of rotor blades, inlet and outlet is used for simulation in ANSYS CFX. A very high efficiency of more than 90% is obtained in both modes across a range of flow rates. Figure 2 shows the efficiency and power obtained in turbine mode of operation for different head of the SD CR RPT design. RD CR RPT is designed following the same methodology and design conditions as above. A hollow centre of the RD

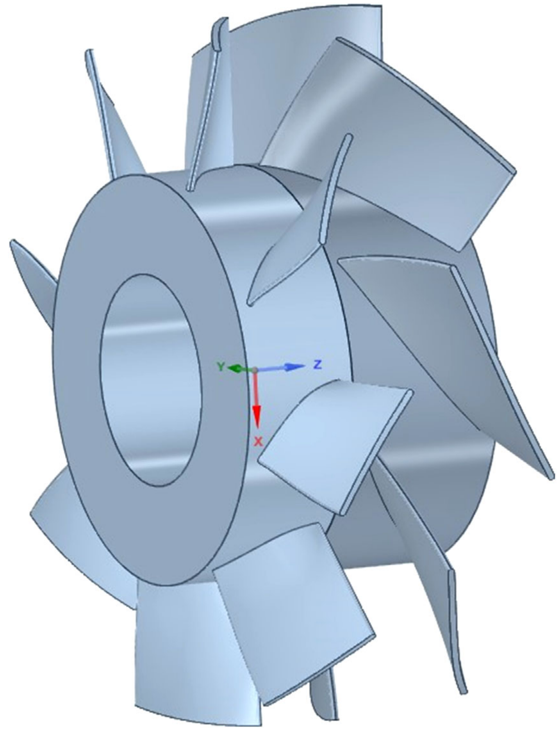

FIGURE 1 Initial Shaft-Driven Contra-rotating Reversible Pump Turbine (SD- CRRPT) design

concept resulted in secondary flows and related losses; hence design iterations with adjusting the work distribution and blade loading is performed in TURBOdesign1 to finally arrive at a design that could meet the power objective in turbine mode. This design is less efficient in pump mode with 8% points lower peak efficiency than the SD counterpart, but it has much flatter characteristics with a smaller efficiency drop from the Best Efficiency Point (BEP) for a wide range of flow rates.

Unsteady CFD simulations are made with the open source CFD software OpenFOAM, ESI version on a complete domain containing two full rotating rotors, hub, support struts and contraction/expansion parts before and after the runners. A comparison of performances between the simplified sector model and the full unsteady simulations reveals that the simplified model is in good agreement with the more complex simulations. An FEA evaluation of both SD and RD CR RPT using ANSYS Workbench with Stainless Steel (SS 17-4 H1075) as material show that the stresses are well within the material limits. Initial optimisation is aimed exclusively at maximising the hydraulic performance. The optimisation process involves a sensitivity study to identify important parameters. Then, a design matrix is generated using DoE method. For each design in the design matrix, CFD simulations are performed at multiple operating points in both modes and performance data is obtained. This is used for a surrogate model-based approximation of the generated data and optimisation using Multi-objective Genetic Algorithm [10]. For the RD RPT, a design improvement is made based on several manual design iterations. For both SD and RD configurations, the optimisations produced better designs.

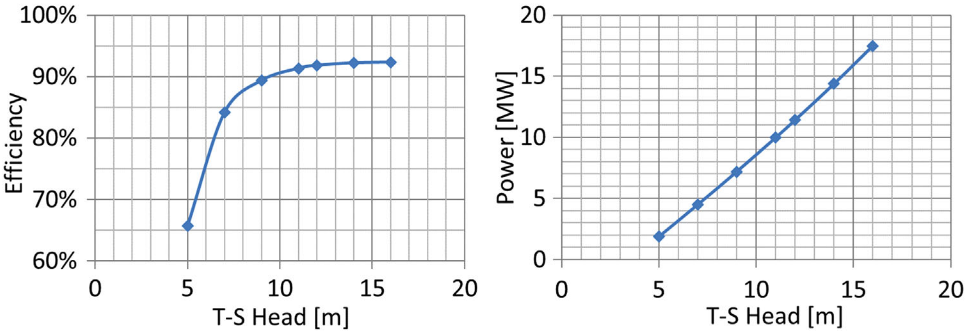

FIGURE 2 Efficiency and power versus total to static head in turbine mode for initial SD-CRRPT design

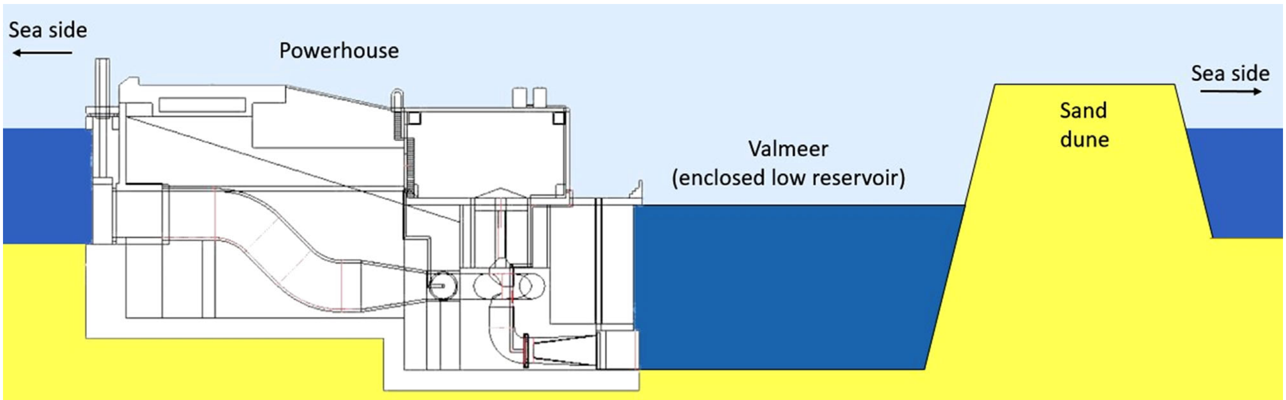

FIGURE 3 Powerhouse design from Ansorena 2020 [24]. Notice that the depicted powerhouse considers a Francis' turbine unit.

Laboratory testing of a model scale SD CR RPT is to be performed at TU Braunschweig. Velocity and pressure data will be collected in front and between the runners in both pump and turbine mode to validate the CFD model. To meet the discharge and head capacities of the test site, the machine has to be scaled down by a factor of approximately 22. Standard scaling laws are used to scale down to model scale. An optimisation of the initial design is performed at the model scale for both SD and RD CR RPT. The optimised SD design will be developed and tested in the facility. The scaled runner will be tested for head differences ranging between 7.15 and 8.45 m and discharges up to 500 l/s in turbine mode and up to 330 l/s in pump mode. Working both in turbine and pump mode, data about velocities and pressures before, after and between the runners will be collected to validate the CFD model. Conventional test rigs for pump- turbine units include the use of pumps to provide pressurised water to the pump-turbine [26]. Others such as [27, 28, 25] make use of pumps and pressurised water tanks that provide head. To simulate the real conditions of a low-head PHS station as shown in Figure 3, the LWI laboratory uses an elevated tank (see Figure 4) and a lower tank with a free water surface. This allows the researchers to analyse the inflow and outflow conditions, which is an attractive feature of this tests setup compared with the previously cited test rigs.

The water is initially stored in an underground sump from which it is pumped to the elevated tank. After the water has been used in a test, it flows through an existing drainage system to the underground water sump. In Figure 4, the proposed test rig for experimental validation of the SD CR RPT is visualised. A detail of pipe 1 containing the SD CR RPT is shown in Figure 5.

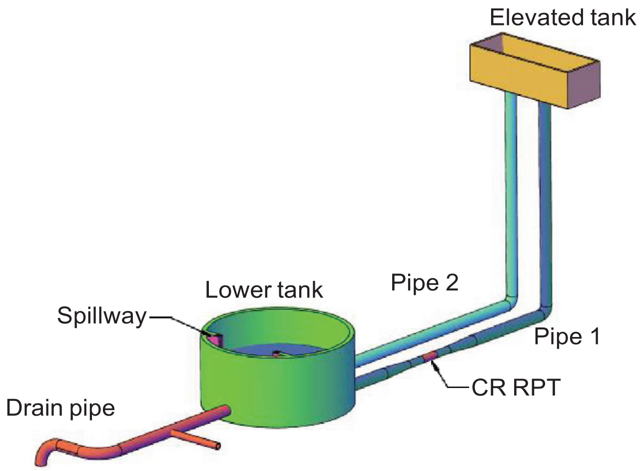

FIGURE 4 3D representation of the laboratory setup for the CFD validation tests

The elements depicted in Figure 4 represent the elements in the real system (Figure 3). The seaside will be represented by the elevated tank, the powerhouse by the CR RPT and the Valmeer by the lower tank.

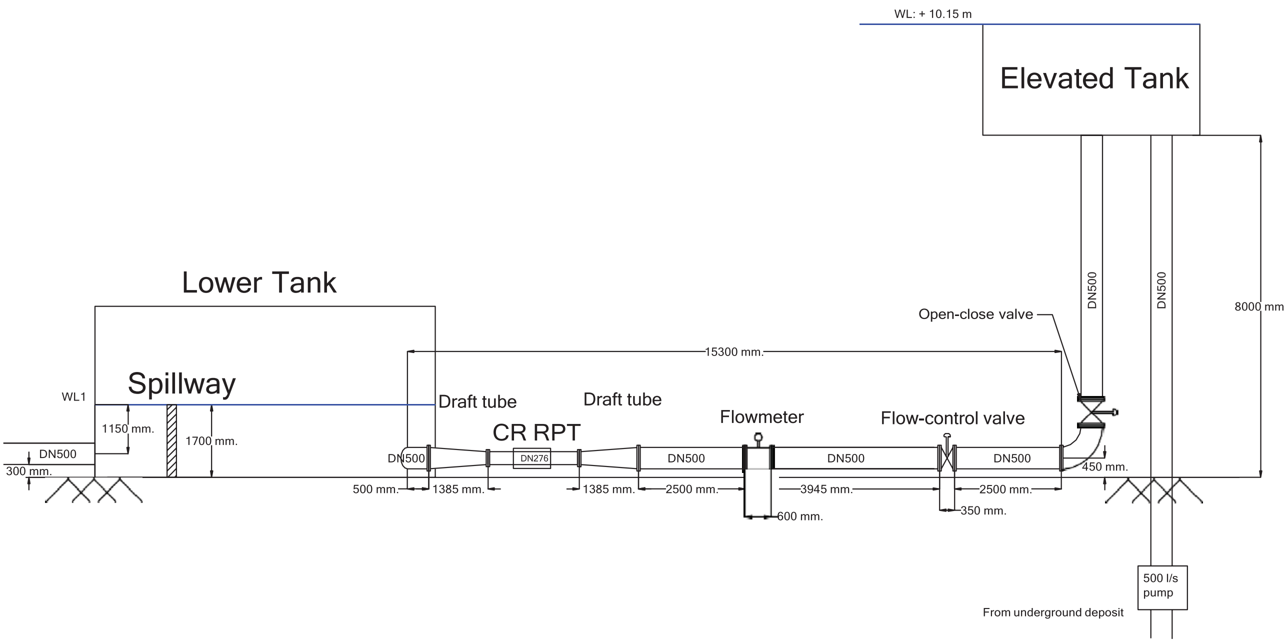

FIGURE 5 Pipe 1 design

All the elements shown in Figure 4 allow for the functioning of the test in both pump and turbine mode:

1. Turbine mode: Water flows from the elevated tank into the Lower tank via the pipe 1, making the CR RPT operate in turbine mode. Within the lower tank, the turbined water overflows a spillway and leaves via the drainpipe towards the underground water sump. The spillway in the lower tank is used to keep a constant water level within it.
2. Pump mode: Water goes into the lower tank via pipe 2. Then, it is taken through the pipe 1, by the action of the CR RPT working in pump mode, back into the elevated tank. The water flow in pipe 2 must be larger than the one in pipe 1 to ensure a constant water level within the lower tank.

A scaled-up version of the optimised design will be used for further studies regarding other aspects including operation (range with speed and speed ratio variation, mode switching, fish friendliness etc.), mechanical integrity, costs etc. Based on these studies, the final design optimisation will include other critical design parameters. As mentioned above, beyond technical and economic goals, attention is also paid to environmental aspects such as the fish friendly design of the CR RPT unit. Mean mortality rates heavily depend on turbine type and fish species. For Francis turbines, rates above 20% or even 30% are reported while the mean mortality of Kaplan Turbines lays between 5% and 14% [31]. For contra-rotating designs this will be achieved through fish screens in adequate distance to the runners minimising both hydraulic losses and stress on fish.

Furthermore, the ALPHEUS project will investigate several aspects related to the low-head PHS construction. Civil structures for low-head pumped hydro technology in seawater have not been built anywhere in the world. They are a very innovative concept, just a few studies have been performed [4]. To illustrate the reader, two significant low- head PHS plans are the Lievense Plan [17] and the Energy Island [18], both considering a circular-like dike ring in the sea. The original Lievense plan consisted of a 100 km dike ring with its crest at +73.8 m height, covering an area of 12 km^2. The water level inside the island ranges between +70 and +56 m, giving an output power of 2000 MW. The height of the water inside the island is a great safety threat in case of dike breaching. Besides, very large dike structures would be needed to elevate the water level well above sea level, which makes it uneconomical when compared with the construction of lower dikes together with excavation of the interior reservoir [4], such as the Energy Island later considered. The Energy Island is composed of a smaller dike ring since the water level within the island is below sea level (−40 to −32 m), which is achieved by dredging within the ring dike. Considering 40 km^2 of storage area, the expected power output was 1500 MW. On the other hand, the DELTA21 plan [19] comprises both an energy storage facility and a storm surge barrier. This is one of its biggest advantages since the construction costs of the project are not only allocated to energy generation but also to water safety. This plan is currently being developed in the Netherlands with a storage area between 15–20 km^2. The design energy output is 1800 MW. The literature review of [4] found that the most critical aspects for implementation of low-head PHS are costs and regulatory issues. Initial investment costs are high due to the scale of the dike and powerhouse structure. Additionally, building in a marine environment enhances the need for maintenance and thus its costs. However, examples such as the La Rance tidal power station, show that operation and maintenance of power structures is feasible in seawater [20]. Bureaucratic processes are not well-defined for structures like low-head PHS in seawater because these plants are a novelty. As an example, the project iLand has faced delays because its implementation faces bureaucracy and negotiations with four different European jurisdictions [21]. Another issue could be social acceptance of the project, already discussed in other mega-projects [22] and renewable energy projects such as inland wind power [23]. Public opposition may stop development of a renewable energy plan. To avoid this, ALPHEUS will inform stakeholders about its development and findings respecting low-head PHS and it will work closely with stakeholders to consider their feedback in the design of low-head PHS. This will be carried out by sending stakeholder surveys and by the organization of two stakeholder meetings.

Regarding the civil structure a caisson dam type is considered. Where for onshore or sheltered locations a dune type could be used for a more natural integration into the surroundings, exposed offshore locations demand a more robust solution. Considering a building process of several years, a caisson dam is much less vulnerable to storms during construction than a rubble mound or dune type dam. For construction the gantry slipform method is best applicable for the large number of caissons. It still needs to be evaluated whether they can best be built on land using existing port infrastructure, on land at the project site with a temporary working island or by using a floating dock at the project site. Similarly, the best way of transporting the caissons and the overall construction planning needs to be elaborated to support the costs assessment of the dam structure.

3 | ENERGY STORAGE AND TURBINE INTEGRATION

Besides the provision of ancillary services (AS), balancing the mismatch between the energy supply of Variable Renewable Energy (VRE) and a fluctuating demand is the core purpose of the proposed solution. At current renewable penetration levels, alternative approaches such as demand management, grid expansion or improved generation forecasting are still capable to compensate for intermittent generation and a reduction in spinning reserves. However, based on Germany as an example, it is estimated that when the share of renewables reaches between 40% and 60% additional short-term storage will become necessary. Furthermore, between 60% and 80% additional long-term storage will be required [29]. With ambitious targets being set across the world to reduce emissions and ultimately become carbon neutral by 2050, the imminent need to develop and implement large-scale energy storage becomes clear.

The system proposed by ALPHEUS project is aimed at being a stand-alone energy storage system without the need of integration into a hybrid solution with other storage technologies. The goal is to provide sufficient power balance within the timescale of minutes to days. Major parameters to evaluate this capability are the total storage capacity and a smart operation control synchronously adapting to the offshore conditions of the Greater North Sea area. However, with increasing land use as a significant disadvantage of many renewable technologies, energy density is an important factor to take into account [30]. In the case of low-head PHS, instead of gravimetric or volumetric energy density it is rather relevant to look into storage capacity per unit area. Using existing estimates of round-trip efficiencies and considering a minimum operational head of 2 m, storage capacities of 21.5, 98.1 and 404.7 MWh/km^2 could potentially be achieved for maximum gross heads of 5, 10, and 20 m, respectively.

The development of the overall system is conducted in a highly modular approach. This enables vast scalability in terms of power rating for each turbine in the range of 300 kW to 10 MW, while allowing the adaptation of the technology to a variety of topographic conditions as well as local demand and supply characteristics. Integrating the individual components while utilising synergies between technological advancements such as the novel contra-rotating pump-turbine runners, newly developed Power Take-Off system (PTO) as well as grid and machine side control, imposes at the same time challenges and potential for optimisation. The main aims include the achievement of high efficiencies in both turbine and pump mode ensuring economic viability, the reduction of the time required to switch between operational modes and high-power ramp rates. To ensure optimised balancing of VRE it is of great advantage to switch fast enough between the power supply and demand. Francis RPT machines can take between five and ten minutes to switch modes with reduced efficiencies in low-head operation. The ambition of the proposed solution is to reach mode switching times of less than a minute. This in combination with a high round-trip operation in low and ultra-low heads will effectively increase the regulation capabilities of the system. Increasing power ramp rates will allow for enhanced capability to provide AS. Pushing for technological advancements in the fields of turbine design and integration, power take-off and control as well as grid integration with the aim to fulfil these goals, will for once improve the potential contribution to grid stability. However, with an increasing demand for balancing and AS such progress will also help making it a cost-effective solution.

Realising these goals is a crucial part of the system integration. In a first step, a comprehensive numerical model of the system will be developed, evaluating performance in steady state, but also investigating transients and potential unstable behaviour of the system when performing mode switching or during the provision of synthetic inertia. Additionally, an experimental model-scale machine set will be developed as described in the previous section. Using this 1:20 scale model, initial experiments will validate the performance of both runners in turbine and pump mode. In a second series of experiments a newly developed PTO will be integrated analysing the overall performance as well as transient behaviour.

4 | POWER TAKE-OFF SYSTEM AND CONTROL

To allow the proposed variable-speed Reversible Pump-Turbine (RPTs) to support and stabilise the grid efficiently, great attention goes out to the design of the Power Take-Off system (PTO) and its control. To allow for an adjustable speed ratio between

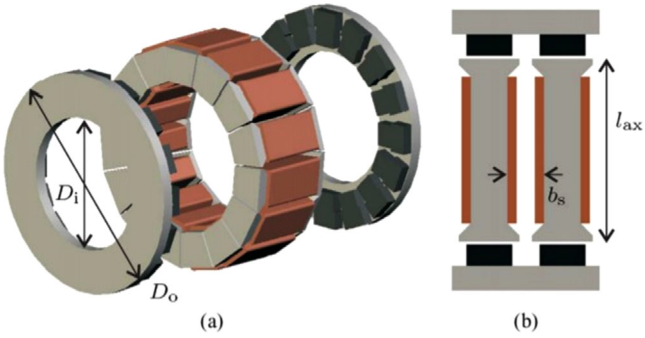

FIGURE 6 YASA topology AF-PMSM. a) Overview b) Detailed view of tooth pitch [36]

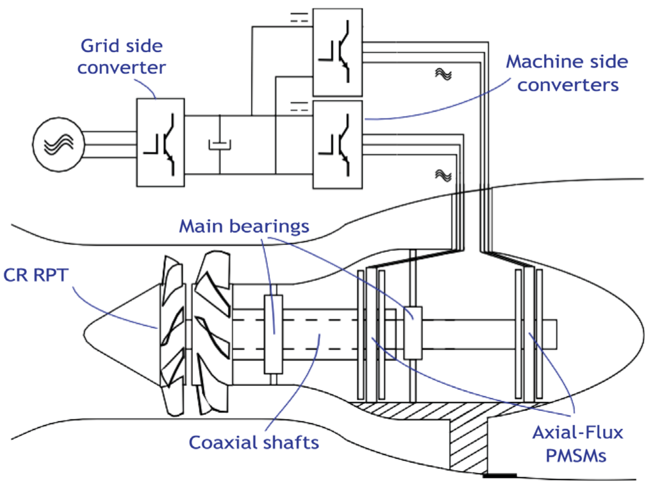

FIGURE 7 Schematic of the PTO configuration with coaxial shafts and bulb

the runners in the Contra-Rotating (CR) RPT concepts, they are independently driven by two separate electric machines. This allows to maintain the optimal efficiency at different reservoir heads and power set-points. Due to the low-speed nature of hydro-turbines, a synchronous machine with a high pole pair number is used. This averts the use of a gearbox, which accounts for significant energy losses and reduced reliability in traditional slow turning systems [32, 33]. In the ALPHEUS project, an Axial-Flux Permanent Magnet Synchronous Machine (AF-PMSM) is used due to its high-power density, high efficiency and suitability for low-speed-high-torque applications [34, 35]. An AF-PMSM with a double rotor design alleviates undesired axial forces and has an efficient flux path as a classical stator yoke is absent. Therefore, the Yokeless and Segmented Armature (YASA) topology AF-PMSM offers less iron losses and low weight [36–38]. Further efficiency improvements can be achieved by using segmented rotor magnets, concentrated pole windings and thin laminated grain-oriented material for the stator teeth [36]. The machine will be designed to have an efficiency above 90% in the operating range where torque and speed are between 20% and 100% of their respective nominal values. Figure 6 shows the proposed machine topology with important design parameters indicated. Using electric machines in a grid supporting hydropower system induces thermal cycling in its stator windings. References [39, 40] show that this increases thermomechanical stress and aging of the winding insulation, which reduces the lifetime of the machine. There fore, it is critical that direct coil cooling is applied instead of (or in addition to) water jacket cooling) [41]. For AF- PMSMs, possible direct coil cooling architectures are out- lined in reference [42]. In existing hydropower installations, the system water is used to cool the machines [43, 44]. Although this method is straightforward, using system water in direct coil cooling structures would require excessive filtering. Therefore, the system water is used as a secondary cooling circuit, which collects heat from a primary glycol-water cooling circuit.

For the drivetrain architecture of the shaft-driven CR RPT with AF-PMSMs, a bulb concept with coaxial shafts has minimal flow impact and reasonable bearing loads [45]. Figure 7 represents this PTO architecture concept. Here, two coaxial shafts with opposite rotational motion provide the mechanical energy transmission. This structure allows the PTO to be on one side of the runners and hence, not disturb the flow on the pump inlet side, which is the most critical for RPT efficiency [45]. In this mechanical structure, the electric machine is placed inside a bulb, which is located inside the water tube. This bulb can be accessed for maintenance through the struts, which secure the bulb [45]. A PTO with separate non-concentric shafts is also feasible but has the disadvantage of increased flow disturbance in the water tube or increased frictional losses in the bevel gears [45].

For a coaxial shaft, the arrangement of bearings needs to be carefully considered. Since the RPT is reversible, so are the axial forces exerted on the shafts. A combination of a locating double tapered bearing and a non-locating radial bearing is suitable on account of its axial load ability and tolerance for shaft expansion. The radial bearings (one for each drivetrain) will be integrated in the electric machines. Figure 7 shows the location of the double tapered (main) bearings of the shafts. Here, both main bearings are placed inside the bulb, which limits flow impact. However, the main bearing of the first runner (left runner in Figure 7) has a significant high lever to the runner and thus a high radial load. Another option is to place this bearing in the water tube, directly next to the runner. This significantly reduces the bearing load at the cost of flow impact and access for maintenance. Also, a considered alternative is to place this bearing in between the two coaxial shafts, reducing this bearings lever and load, but approximately doubling the radial load of the main bearing of the second runner.

The rim-driven CR RPT allows for a PTO design with no impact on the water flow, maximising the RPT efficiency.

Here, the permanent magnets are secured on the outside of the runners. Therefore, the runners act like a rotor in a PMSM. The PMSM stator is then placed around the tube and runner. A large diameter locating bearing secures the runner's axial and radial position. In hydropower applications, this design has been used with radial-flux PMSMs [47–49]. However, AF-PMSMs could be more suited for this purpose, since they typically have a high diameter-to-length ratio along with the improvements in power density and efficiency. Recently, rim-driven propellers with integrated AF-PMSMs are proposed and designed [50, 51].

As shown in Figure 7, both AF-PMSMs are connected to a full-power active converter to allow for variable speed operation, which is vital for grid supporting services. These two converters are coupled to a common DC-link, where also the grid-side converter is connected. The machine- side converters are controlled by the machine-side control, consisting of a low-level and high-level control layer. The control strategy of the grid-side converter is explained in Section 5. The machine-side control will be optimised to ensure optimal operation in terms of flexibility and efficiency. It needs to be able to satisfy grid needs with minimal time delay within boundaries set by wear and fatigue loads, while maintaining optimal efficiency. For the low-level machine-side control, Field Oriented Control (FOC) is used. In FOC, the current vector is regulated in the rotating reference frame to be aligned with the quadrature axis, that is, the *d*-axis current is regulated at zero. Then, the torque is directly proportional to the *q*-axis current which allows efficient torque control.

The torque set-points for the low-level control of the two contra-rotating runners are given by the high-level control, which controls the power of the machines. Furthermore, the high-level control can adjust the inlet valve angle and thus control water flow. Conventionally, Maximum Power Point Tracking (MPPT) systems are used, which are derived from wind turbine technology [52, 53]. For a given water flow rate, the power versus speed curve of the turbine has a single maximum. So, whenever the head height and/or flow rate changes, the torque set-point changes until the optimal rotational speed is achieved. Direct MPPT methods reach the power set-point using an iterative seeking control, that is, perturbing the rotational speed and analysing the power output [54–56]. Indirect MPPT utilises power curves [57–59] or lookup tables [60, 61], obtained analytically or by experimental data. Here, the generator and converter should be considered. Their losses depend on the rotational speed, so that the overall maximum power point can differ from the RPT maximum power point [62, 63]. In ALPHEUS, the RPT consists of two contra-rotating runners. Each control action of one runner influences the other, complicating the effective use of MPPT. Furthermore, MPPT does not consider the hydrodynamic transient effects. While MPPT can still be practised with a set speed ratio between the runners, a more advanced control system is worthwhile investigating.

One possible advanced control system is Model Predictive Control (MPC), which is already applied in a few hydropower systems [64–66]. MPC makes use of a detailed model of the full system, modelling the water flow, inlet valve, runners and all internal influences. During operation, the MPC simulates how the power would change, given changes in control parameters in the next few machine cycles. Therefore, it is excellent for reacting to power set- points from the grid, since it already knows what sequence of control parameter adjustments would give that certain power output as fast and efficient as possible through an internal optimisation algorithm.

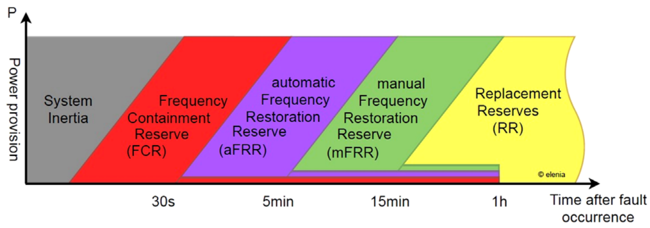

FIGURE 8 Frequency control measures in ENTSO-E area [69]

While adjusting power flow, MPC makes the parameter changes within set boundary constraints, which account for the systems hydraulic, mechanical, and electrical limitations, preventing wear and fatigue loads.

Instead of limiting the runners speed to a set speed ratio, the two runners can be operated independently, to increase reaction speed to grid needs and preserve the optimal efficiency in the sub-nominal operating range. The challenge here is to accurately model the flow influence between the two runners. More advanced techniques such as machine learning and AI can be explored to enhance the control system.

5 | GRID INTEGRATION

For the low-head Pumped Hydro Storage (PHS) system developed in ALPHEUS project, an appropriate control method for the grid-side converter is studied. Next to the vital ancillary services, especially frequency control is investigated. The ability to provide frequency control comprises the capability of a power-generating module or High-Voltage Direct Current (HVDC) system to adjust its active power out- put in response to a measured deviation of system frequency from a nominal value, that is, 50 Hz in the European Network of Transmission System Operators for Electricity (ENTSO-E) area. To maintain stable system frequency, the frequency control consists of consecutive balancing services within a specific time frame, the typical frequency control measures nowadays in the ENTSO-E area are as shown in Figure 8. The frequency control starts with the system inertia which is inherent behaviour of the synchronous machines that instantaneously supports the grid frequency in case of all frequency deviations [67, 68]. The next measure in frequency control in case of system imbalance is the Frequency Containment Reserve (FCR), which acts in few seconds after the system inertia if the deviation from the nominal frequency oversteps ±10 mHz (above 50.01 Hz or under 49.99 Hz) and it will be fully activated at ±200 mHz (50.2 Hz and 49.8 Hz) within 30 s. The Deadband of ±10 mHz is provided to prevent the activation of FCR with a false sign in case of measurement error. The automatic and manual Frequency Restoration Reserve (FRR) will be activated after FCR and will be fully activated in 5 min to recover the frequency back to its nominal value following any disturbance. The Replacement Reserve (RR) will be activated within 15 min to restore FRR for further system imbalances [68, 70].

The main source of system inertia in today's grid are the directly-coupled synchronous generators. In case of any

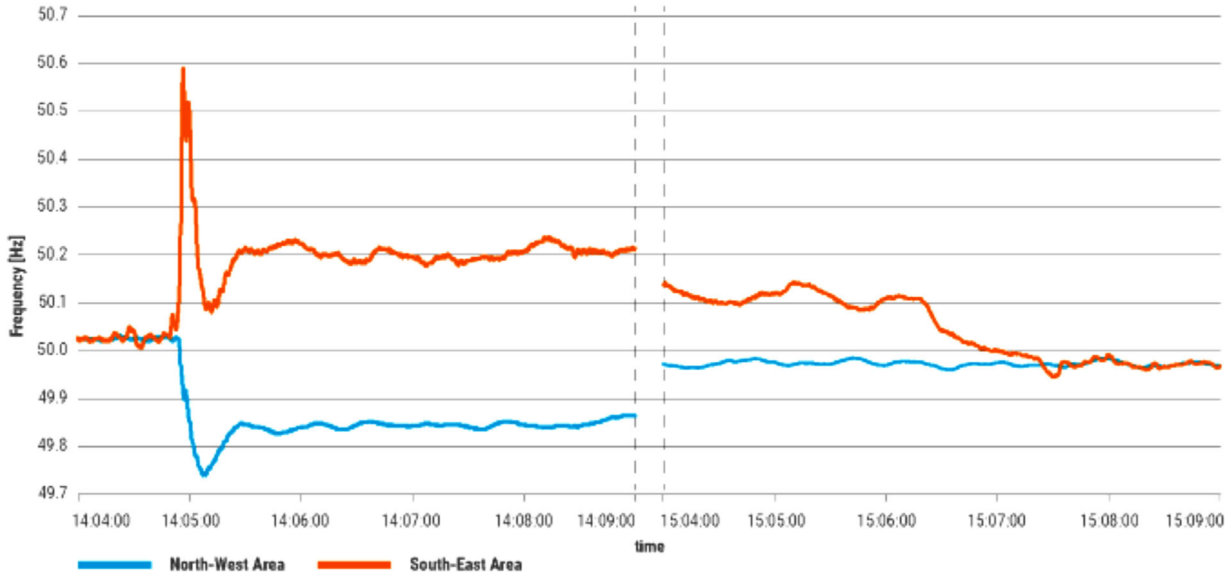

FIGURE 9 Frequency in continental Europe during the system split on 08 January 2021—on the right side, after the disturbance and during re-synchronization [73]

sudden imbalances or frequency deviations, the inertia of their rotating masses contributes significantly to the stabilisation of the system. However, as the modern power grid is gravitating towards a converter-dominated system, these must also be able to replicate this characteristic. The low-head PHS system of ALPHEUS is connected to the grid via back-to-back fully rated converters. Therefore, it is important to study the possibilities of frequency control, mainly, the provision synthetic inertia along the fast Frequency Containment Reserves (fFCR), which is a relatively new control reserve located in the time frame between FCR and inertia. Synthetic inertia from converter and storage together with fFCR will be able to play the role of the today's system inertia in frequency control [70]. For this matter, a grid-forming control mode is currently being discussed. Here, the controlled converter acts as an AC voltage source with stated voltage, phase, and frequency. By controlling the voltage magnitude and frequency, the behaviour of the converter becomes very similar to that of a synchronous generator. The fundamental difference between grid-following and grid-forming is the synchronisation method. Applying the swing equation, grid forming tracks and calculates voltage angle and amplitude deviation using current power transfer and is thus self-synchronising [71, 72].

An important recent event that shows the importance of studying frequency control in the future power systems, is the system split occurred in the continental Europe synchronous area on 8 January 2021, at 14:05 CET. The European synchronous area was split into two areas due to the tripping of a 400 kV busbar coupler in the substation Ernestinovo in Croatia at 14:04:25.9, which served as the initial event which led to outages of several transmission network elements in a very short time. At the beginning of the event, the frequency in the North-West Area dropped to 49.74 Hz for approximately 15 s before it raised back to a steady state value around 49.84 Hz. Simultaneously, the frequency in the South-East Area raised to 50.6 Hz before settling at a steady state frequency between 50.2 Hz and 50.3 Hz [73] as shown in Figure 9.

Due to the under frequency in the North-West area, around 1.7 GW of contracted interruptible services in France and Italy were disconnected for the purpose of reducing the frequency deviation. On the other hand, 420 MW from the Nordic Synchronous areas and 60 MW of power reserves in Great Britain were automatically activated and due to the large over frequency in the South-East area, automatic and manual countermeasures were activated (i.e. reduction of the feed-in of generation units) in order to stabilise the frequency [73].

The net electricity generation in Germany on 08 January 2021, at 14:00 CET was 65.98 GW including 1.71 GW from solar and 4.19 GW from wind, so the energy mix was almost 8.9% from wind and solar energy [74]. This means, enough feed-in power from traditional power plants had supported the system with the necessary inertia to support the frequency at time of the system split, but what would have been the scenario if the energy mix at that time had a very high share of Variable Renewable Energy (VRE) feed-in? This event is an eye-opener to the necessity of providing synthetic inertia and fFCR from VRE.

This important issue is currently being examined to investigate the contribution of low-head PHS to grid stability. In a first step, the frequency measurements of 08 January 2021 are collected, imported, and evaluated in MATLAB to examine how much synthetic inertia, fFCR and FCR could be provided with a 10 MW ALPHEUS power plant. The Block diagram in Figure 10 is used for calculations of FCR.

For calculating FCR, initially, the deviation between the measured frequency and the nominal frequency is determined as $\Delta f = f 50$ Hz, where f is the measured frequency in Hz. If this deviation is within the ±10 mHz of the dead band, no measures will be activated, otherwise FCR will be activated after 3–5 seconds time delay and will be fully activated in 30 s [70]. In the

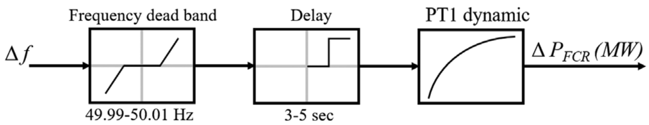

FIGURE 10 Block diagram of calculating FCR, based on block diagram from [70]

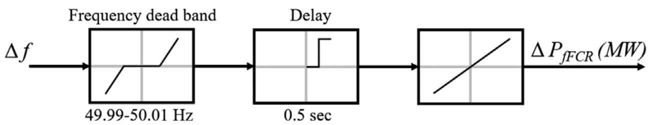

FIGURE 11 Block diagram for calculating fFCR

same way is the fFCR calculated, but it will be activated within 0.5 s after a frequency deviation and will be fully activated within 1 s. The block diagram in Figure 11 is used for calculation of fFCR. Both FCR and fFCR power are limited at a maximum power of ±10 MW.

To validate the Simulink simulation model for calculating fFCR and FCR, a simulation test using a frequency down-ramp from 50 Hz at $t = 1$ second to 49.8 Hz at $t = 2$ s, comprising a frequency drop of 200 mHz. As shown in Figure 12, because of this frequency deviation, the fFCR of 10 MW was fully activated within 1 s, and FCR also fully activated in 30 s.

Figure 13 shows the frequency measurements of 1 s resolution on 08 January 2021 at time of the system split. This measurement is from the German Transmission System Operators (TSO) TransnetBW. As Germany is in the North-West area, a frequency drop of 49.75 Hz is measured at the beginning of the event. As the frequency deviation exceeds 10 mHz, the simulation with Simulink shows that fFCR was fully activated within 1 s to provide a maximum power of 10 MW, the FCR is activated after a few seconds to be fully activated after 30 s with 8.42 MW.

To calculate the inertia, opposed to fFCR and FCR, no time delay is used in this case, as the inertia must be activated instantly after any frequency deviation. First, the Rate of Change of Frequency (RoCoF), which is the time derivative of the frequency df/dt must be calculated. RoCoF is a significant parameter that describes the power grid robustness [75], and can be calculated using the following equation:

$$RoCoF = \frac{\Delta P_{im}}{P_L} \cdot \frac{f_o}{T_A} \tag{1}$$

where

ΔP_{im} is the system inertia in MW,
P_L is the nominal power in MW,
f_0 is the mains frequency in Hz,
T_A is the starting time constant in s.

For simplicity, H as inertia time constant is used to represent the total inertia of the electrical grid, where

$$T_A = 2 \cdot H \tag{2}$$

By substituting Equation (2) into Equation (1), we can obtain ΔP_{im} as:

$$\Delta P_{im} = \frac{P_L \cdot RoCoF \cdot 2 \cdot H}{f_0} \tag{3}$$

By using Equation (3) the inertia of the system can be calculated.

To validate the Simulink simulation model for calculating inertia, a simulation test using a frequency down-ramp from 50 Hz at $t = 1$ s to 49.8 Hz at $t = 2$ s is carried out, this a frequency drop of 200 mHz in 1 s. As shown in Figure 14, because of this frequency deviation, the inertia is activated instantly at $t = 1$ s and provides a maximum power of 1 MW and then no provision for the rest of the simulation takes place, the reason for this is RoCoF = 0 after that. As the inertia is proportional with the inertia time constant (H). The latter H is a key parameter to take into consideration while setting up parameters in the "future" grid-forming controlled converters.

Figure 15 shows the frequency measurement of 1 s resolution on 08 January 2021 at time of the system split. As the frequency started to drop, the simulation with Simulink shows that inertia was instantly activated to provide a power of 0.265 MW.

These simulation results give initial indication on the contribution of low-head PHS to the frequency stability and thus to grid stability in future power systems. In the next step of the project, this simulation will be conducted with taking into consideration the time constants of ALPHEUS low-head PHS such as, the time constant that describes the time needed to open the valves and to build pressure inside the reservoir, the time constant that describes the time needed for the water flow from the higher basin to the lower one, the RPT take-off time constant, the machine side converter time constant, and the grid-side converter time constant will give a better initial indication on the reaction speed of the plant and whether it is able to provide the required synthetic inertia and fFCR.

This ability to provide synthetic inertia together with fFCR, will augment the grid stability. By providing these vital ancillary services, the grid-forming controlled converters would enable the grid towards an energy supply largely based on renewable energy sources unlike the toady's grid-following controlled converters [67, 71].

In addition, the control system has to be designed and studied for the grid-side converter taking into consideration all the unique characteristics of the new low-head PHS of ALPHEUS under the consideration of the EU directives and regulations such as commission regulation (EU) on requirements for grid connection of generators [67] and the directive (EU) 2019/944 on common rules for the internal market for electricity [76].

These requirements especially encompass the relevant network codes set by the ENTSO-E as well as national grid codes and ensure the compatibility as well as a grid-stabilising behaviour of all devices operating in the transmission network. The second design aspect will focus on creating a converter that is compliant with the turbine characteristics in all operation scenarios considered in the ALPHEUS project. The resulting grid-side control will be implemented in a simulation model

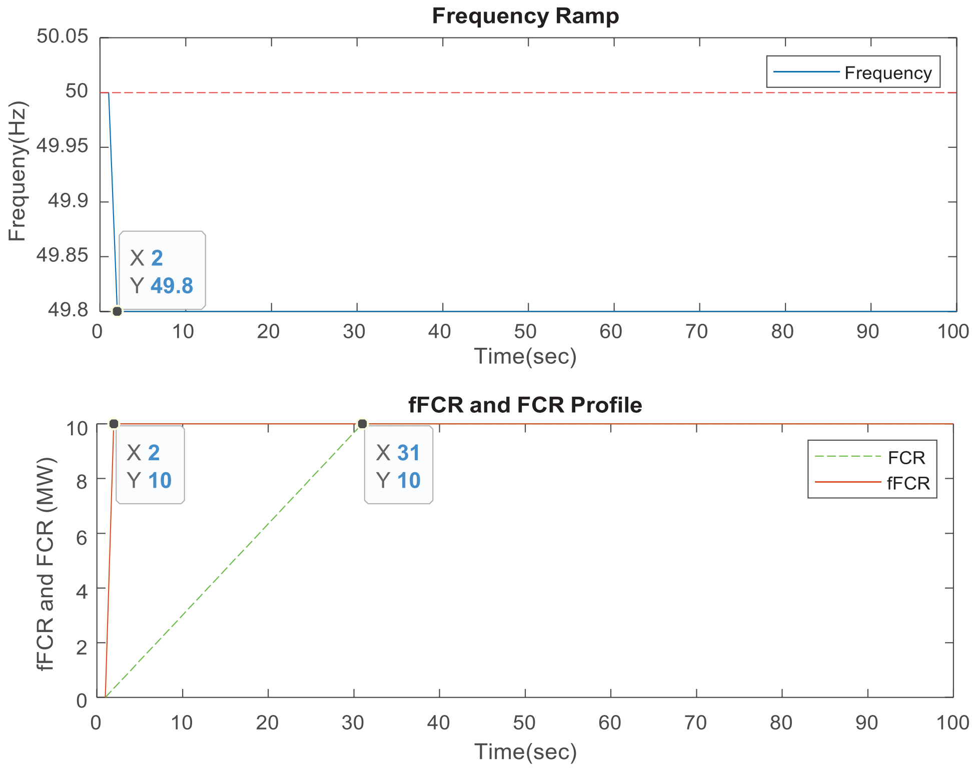

FIGURE 12 Validation of simulation model for calculating fFCR and FCR

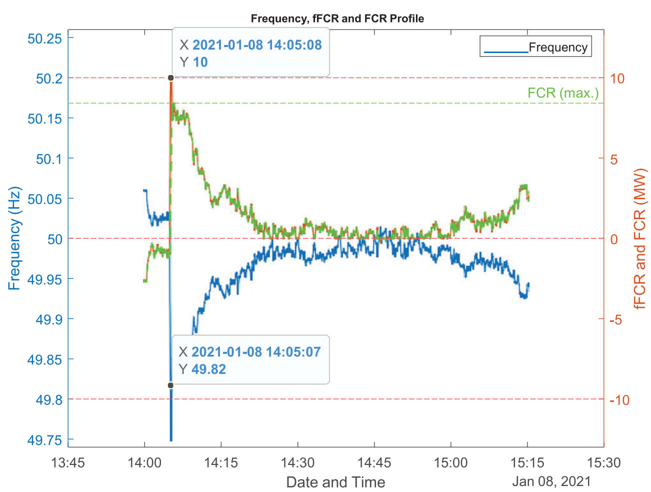

FIGURE 13 Frequency on 08 January 2021, and fFCR and FCR could be provided from ALPHEUS 10 MW power plant

to be used for further grid integration studies. This new control design coupled with the new low-head PHS of ALPHEUS will be tested in Hardware-In-the-Loop (HIL) simulation at the elenia energy laboratory at TU Braunschweig.

In addition, an economic evaluation of flexibility will be performed. As the project ALPHEUS is concerned with enabling the power plant to provide required and optional operational services to the grid; many of these services are tendered on market-based platforms to ensure provision of the most cost-effective bidder. The potential revenue that can be achieved using a storage power plant therefore varies based on the individual market conditions. Against this background, within the project, an economic evaluation based on the calculation of the levelized cost of storage and energy storage on investment of the proposed concept will be performed. Based on these, this work seeks to propose a strategy to maximise financial revenue by comparing individual gains for each service and to estimate the cost-effectiveness of revenues achieved with providing services on markets that are best suited to the technical and economic abilities and constraints of the proposed storage plant concept. Additionally different regulatory constraints in the EU countries will be considered during the project, for example, according to the directive (EU) 2019/944 on common rules for the internal market for electricity, article 31, tasks of distribution system operators, and article 40, tasks of transmission system operators, which basically demands market-based provision of non-frequency ancillary service, which are:

1. Steady state voltage control (reactive power)
2. Black start capability
3. Inertia for local grid stability
4. Short-circuit current
5. Fast reactive current injections
6. Island operation capability

This will be implemented in Germany, according to the German energy act (EnWG §12), from 2021, initially, for reactive power and black start capability, in the midterm, the provision

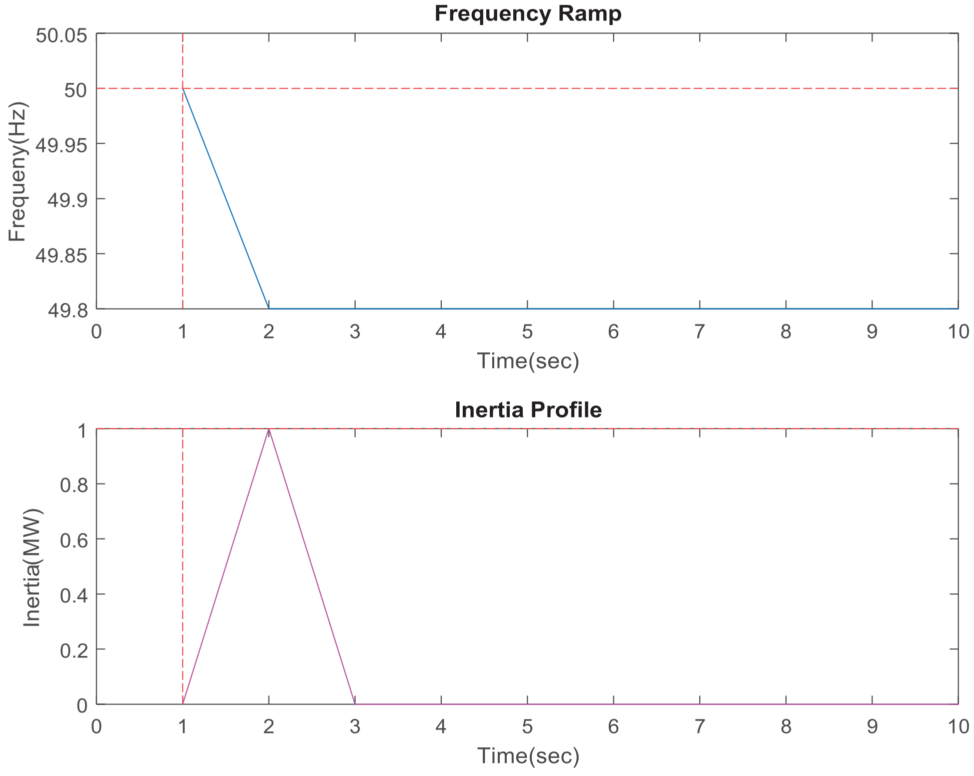

FIGURE 14 Validation of simulation model for calculating inertia

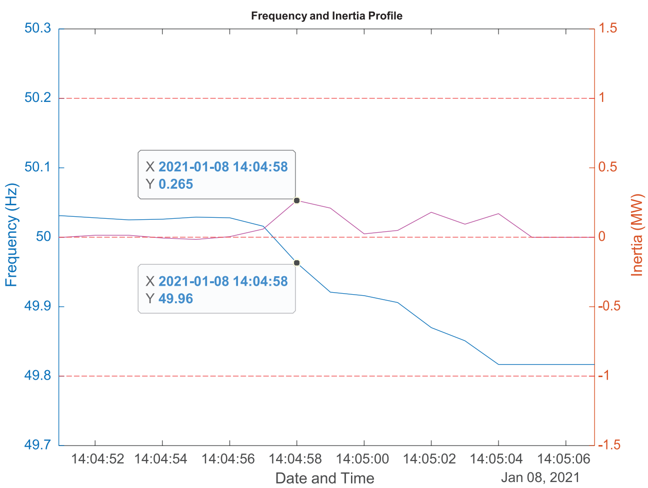

FIGURE 15 Frequency on 08 January 2021, and potentially provided inertia from ALPHEUS 10 MW power plant

of market-based-inertia is required [76, 77]. Such important regulatory constraints are to be followed up in ALPHEUS.

6 | CONCLUSION

With the new concept of low-head PHS, including the integrated and highly efficient reversible pump-turbine, power take-off system, DC-link and power electronics, along with grid-side converter control equipped with functions for European Union standard compliant operation, the ALPHEUS project will introduce a new storage system. This system will serve as new flexibility option contributing to the security of supply and grid stability with the advantage to provide vital ancillary services, especially frequency control, and thus, promoting the energy transition in the EU.

The uniqueness of the ALPHEUS project lies in the multi-faceted innovations that must be achieved to make low-head PHS feasible in the North Sea. Regarding turbine design, the project will investigate new contra-rotating reversible pump-turbines with an overall round-trip efficiency of 70–80%. A coaxial transmission linked to two separate double rotor axial-flux permanent magnet synchronous machines will pro- vide the power take-off. The devised new optimal machine-side control methods will make the energy flow highly efficient and dynamic. The civil structure will withstand prolonged exposure to open sea conditions and seawater corrosion while storing potential energy, which based on the current knowledge, the authors believe is feasible. Several different sites will be proposed for the construction of the low-head PHS, considering technical issues as well as social issues analysed via stakeholder analysis.

AUTHOR CONTRIBUTIONS

M.Q.: Conceptualization; Formal analysis; Investigation; Methodology; Software; Validation; Visualization; Writing – original draft; Writing – review & editing. B.E.: Conceptualization; Funding acquisition; Project administration; Resources;

Supervision; Writing – review & editing. D.P.K.T.: Conceptualization; Investigation; Visualization; Writing – original draft; Writing – review & editing. J.D.M.D.K.: Funding acquisition; Writing – review & editing. K.S.: Funding acquisition; Writing – review & editing. A.J.-L.: Conceptualization; Writing – review & editing. R.A.R.: Investigation; Writing – original draft; Writing – review & editing. N.G.: Conceptualization; Funding acquisition; Writing – review & editing. J.D.B.: Conceptualization; Funding acquisition; Writing – review & editing. M.J.: Visualization; Writing – original draft; Writing – review & editing. M.Z.: Writing – review & editing. K.T.: Conceptualization; Funding acquisition; Writing – review & editing.

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CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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