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Qudaih, M., Engel, B., Truijen, D. et al (2020). The Contribution of Low-Head Pumped Hydro Storage to a successful Energy Transition. Proceedings of the Virtual 19th Wind Integration Workshop

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The Contribution of Low-head Pumped Hydro Storage to a successful Energy Transition

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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. Today's grid is reliant on synchronous generators. In case of sudden 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 an inverter-dominated system, these must also be able to replicate this characteristic. Therefore, Energy Storage Systems (ESS) are needed along the VRE. Among the different ESS, Pumped Hydro Storage (PHS) can be identified as particularly convenient, given its cost-effective implementation and considerable lifespan, in comparison to other technologies. PHS is reliant on difference in altitudes, which makes this technology only available if suitable topographic conditions exist. The ALPHEUS project will introduce a low-head PHS for a relatively flat topography. In this paper, a grid-forming controlled inverter 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 synthetic system inertia, as well as fast Frequency Containment Reserves (fFCR).**

I. Introduction

Following up on the Paris agreement, the parties in the European Green Deal are committed to make the European Union the world's first 'climate-neutral bloc' by 2050 [1]. The traditional electricity production sector in Germany is the largest single contributor to the release of CO_2 with approximately 37% of total emissions [2]. For this reason, the most highlighted alternatives to the traditional electricity production are the VRE, such as wind and solar power plants. As these plants are intermittent by nature and non-dispatchable, in order to integrate more VRE, new energy storage in bigger dimensions will be an important asset in furthering the energy transition in the future. Moreover, 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 [3]. Therefore, energy storage is essential for providing the balancing reserves and other AS which are needed for grid stability and security of supply. One of the most traditional energy storage systems are battery systems, which can be used wherever they are needed. One disadvantage, however, is their durability; a battery system today is expected to last around 15-20 years. The oldest hydroelectric power plant in Norway, on the other hand, has been in operation for over 120 years [4]. Despite the major advances in battery research in terms of efficiency and initial costs, lithium-ion batteries are still not considered as an economical storage alternative. Their ratio of manufacturing effort to service life possesses a much worse ratio than PHS. These advantages of PHS over battery systems makes it one of the best options for the energy storage that will be needed in the near future. In these plants, water is pumped to a higher topography in storage reservoirs when there is excess electricity production; when electricity consumption increases, the water flows back down through turbines. This process 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. The energy reserve therefore consists almost exclusively of fossil fuels and thermal power plants. 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 adjusting civil structures needed to make PHS economically viable in shallow seas and coastal environments with flat topography. Moreover, a comprehensive assessment of the mechanical, electrical and structural components will allow the costs of these systems to be determined and the risks to be assessed. This RPT will be coupled with a grid-forming controlled inverter, which can directly control local voltage and frequency, thus contributing to stabilising the power grid. Information and decision support tools will be developed to transfer knowledge to society. Economic, social and environmental sustainability aspects such as fish friendliness, scenery, and land use well be considered. Scenarios for construction and energy supply and storage for energy islands located in shallow seas will be developed as well [5],[6]. This paper will illustrate the concept and rationale of the ALPHEUS project, as well as explain how ALPHEUS will contribute to grid stability and flexibility through low-head pumped hydro energy storage, together with emphasising the benefits of this technology regarding its ability to provide different Ancillary Service (AS), especially frequency control through the provision of synthetic system inertia, as well as fast Frequency Containment Reserves (fFCR).

II. Turbine design and Civil structure

Conventional mountainous PHS is a well-established energy storage technology. Typically, it uses Francis type turbines operating both as a pump and turbine. This technology can reach between 70–80% efficiency with some PHS claiming a round trip efficiency up to 87% [7]. Designing a Reversible Pump-Turbine (RPT) with high efficiencies in both modes is a challenging task. Aiming for high pump efficiencies will reduce turbine efficiency and vice versa. Usually, pump-turbines are designed from pump mode and are verified with turbine operation. Computational Fluid Dynamics (CFD) analysis is the most common design technique, but these are time-consuming and expensive tools [8]. Further research into the turbine-pump design is needed to increase the round-trip efficiencies. The work presented in [8] showed that with proper analysis the efficiencies in turbine mode can be increased, thus improving round trip efficiency. Similarly, [9] showed that the efficiency in turbine mode can be increased by using adjustable guide vanes that re-direct the flow. However, Francis' turbines have limited performance in low-head situations [10], which gives opportunities for new pump-turbine designs. ALPHEUS aims at developing new reversible pump-turbines that can reach an overall efficiency between 70 and 80% [6]. To that aim, the Contra-Rotating type Reversible Pump-Turbine (CR RPT) concept will be studied. Recent studies [11]-[15] have shown that CR technology improve overall efficiency. With this technology, one axial motor is able of driving two axes by the action and reaction principle [11]. This counter-balances rotational torque [12] and rotates an inner and outer armature in the motor-generator which increases the efficiency [13]. Another advantage of CR pump-turbines is that they improve the unstable pump performance at low discharges and suppress cavitation at higher discharges [13]. Besides, numerical simulations performed in [14] and experiments from [15], show that the contra-rotating type pump-turbine is effective for the power stabilisation system, thus improving the grid's flexibility. Three promising CR RPT technologies will be analysed in ALPHEUS:

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

The initial shaft and rim driven contra-rotating pump-turbines were designed by Advanced Design Technology Ltd (ADT), an industrial partner of the ALPHEUS project, by using the 3D inverse design method in TURBOdesign Suite. The designs are made in prototype scale and verified via CFD to make sure that the performance is according to the requirements. Both the shaft and the rim driven alternatives have a runner diameter of roughly 6m. The first runner contains 8 runner blades and the second 7 blades. CFD simulations of a sector model with one single blade per stage predict an efficiency of above 90% for heads 8-12m in pump mode and for heads larger than 9m in turbine mode for the shaft driven ditto. The rim driven design shows slightly better efficiency in turbine mode, but roughly 10 percentage points worse performance in pump mode than the shaft-driven.

Scaling laws are applied to the shaft-driven alternative to get an appropriate model scale suitable for the experimental tests to be carried out at the TU Braunschweig hydraulic laboratory [16]. The shaft and rim driven contra-rotating pump-turbines are optimised in model scale using a multi objective Design of Experiment (DoE) setup and response surface surrogate models [17]. The DoE is carried out to maximise efficiency in both pump and turbine mode for a wide range of operating conditions. The optimisation is based on steady state CFD simulations made on a sector model containing one blade per rotor and interfaces to mimic complete rotors. For the optimisation, the commercial CFD code ANSYS CFX is used. Unsteady and transient CFD simulations are carried out on a complete domain containing two full rotating rotors, hub, support struts, and contraction/expansion parts before and after the runners. The full simulations are made with the open source CFD software OpenFOAM, ESI version. A comparison of efficiency, power, head, and flow rate between the simplified sector model and the full unsteady simulations reveals that the simplified model is in good agreement with the more complex simulations.

The testing facilities are currently being constructed at the TU Braunschweig laboratory. The scaled runner will be tested for head differences ranging between 6.45 and 8.45 meters and discharges up to 500 litres per second. 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.

Civil structures for low-head pumped hydro technology in seawater have been rarely built in Europe. They are a very innovative concept, and only few studies have been performed [18],[19],[20]. The Lievense Plan [18] and Energy island [19] are similar in a way that they both consider a circular-like dike ring in the sea. The Lievense plan consists 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, huge dike structures would be needed to elevate the water level well above sea level. 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). Considering 40 km^2 of storage area, the expected power output was 1500 MW. On the other hand, the DELTA21 plan [20] 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. Currently considering a storage area between 15 – 20 km^2, the expected energy output is 1800 MW.

ALPHEUS will investigate several aspects related to the low-head PHS construction. The development of a site assessment methodology for decentralised energy storage will be included. It will consider aspects such as topography, sea conditions, proximity to other energy generation technologies, environmental constraints, and social aspects (among others). Social acceptance will be achieved by stakeholder analysis. ALPHEUS will communicate stakeholders its plans and will use stakeholder feedback as input for location selection and conceptual design. Regarding civil construction, important aspects to be decided include the use of seawater robust materials, fatigue analysis of materials, the decision on kind of civil structure for enclosing the pump-turbines (earthen vs. caisson dams), kind of plant (offshore energy plant vs. storm surge barrier integrated with an energy plant) and construction method (in situ vs. prefabricated). To avoid large expenditures in maintenance, life-cycle analysis of the structure will support the conceptual design.

III. Energy storage and turbine integration

Besides the provision of AS, balancing the mismatch between the energy supply of VRE and a fluctuating demand is the core purpose of the proposed solution. 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 balance within the timescale of minutes to days. One major parameter to evaluate its capability to do so is total storage capacity. However, with increasing land use as a significant disadvantage of many renewable technologies, energy density is an important factor to take into account. 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 preliminary results of round-trip efficiencies gained from initial simulation and considering a minimum operational head of two meter, a storage capacity of 21.5 MWh/km^2, 98.1 MWh/km^2 and 404.7 MWh/km^2 could potentially be achieved for maximum gross heads of 5 m, 10 m 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 in the range of 300 kW to 10 MW enabling 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 newly developed turbine runners and the independent control of the two contra-rotating drive shafts imposes at the same time challenges and potential for optimisation. The main aims include high efficiencies in both turbine and pump mode ensuring economic viability but also the reduction of the time required to switch between operational modes.

To ensure optimised balancing of VRE it is of great advantage to switch rapidly between supplying and consuming energy. Francis RPT machines can take between five and ten minutes to switch modes while being inefficient 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 highly efficient round-trip operation in low and ultra-low heads will effectively increase the regulation capabilities of the system.

Beyond economic and technical goals, attention is also paid to environmental factors such as fish mortality. 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% [21]. Three designs of the turbine – shaft-driven, rim-driven and a positive displacement version – are evaluated with the goal to reach a fish mortality of less than 10% in both operational modes and at optimum efficiency.

Validating 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.

IV. Power Take-Off system and control

A Power Take-Off (PTO) system for the RPT needs to be designed. Since dynamic operation is vital for the grid-balancing aims within ALPHEUS, the full powertrain will be optimised to best accommodate rapid mode switching. Furthermore, the two contra-rotating propellers are driven independently through two separate electrical machines. Therefore, special attention is drawn to the mechanical design of the drivetrain. A promising design is derived from propulsion technology that has matured within the aircraft- and maritime shipping industries [22],[23]. Fig. 1 represents the envisioned PTO concept which will be explored within the ALPHEUS project. Two coaxial shafts with opposite rotational motion provide the mechanical energy transmission. This structure allows the PTO to be on one side of the propellers and hence, only disturb flow on one side. In this mechanical structure, the electrical machine will be 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. A PTO with separate, non-concentric, shafts are also feasible [24], but have the disadvantage of increased flow disturbance in the water tube or increased frictional losses in bevel gears. Nevertheless, these concepts will be explored as well.

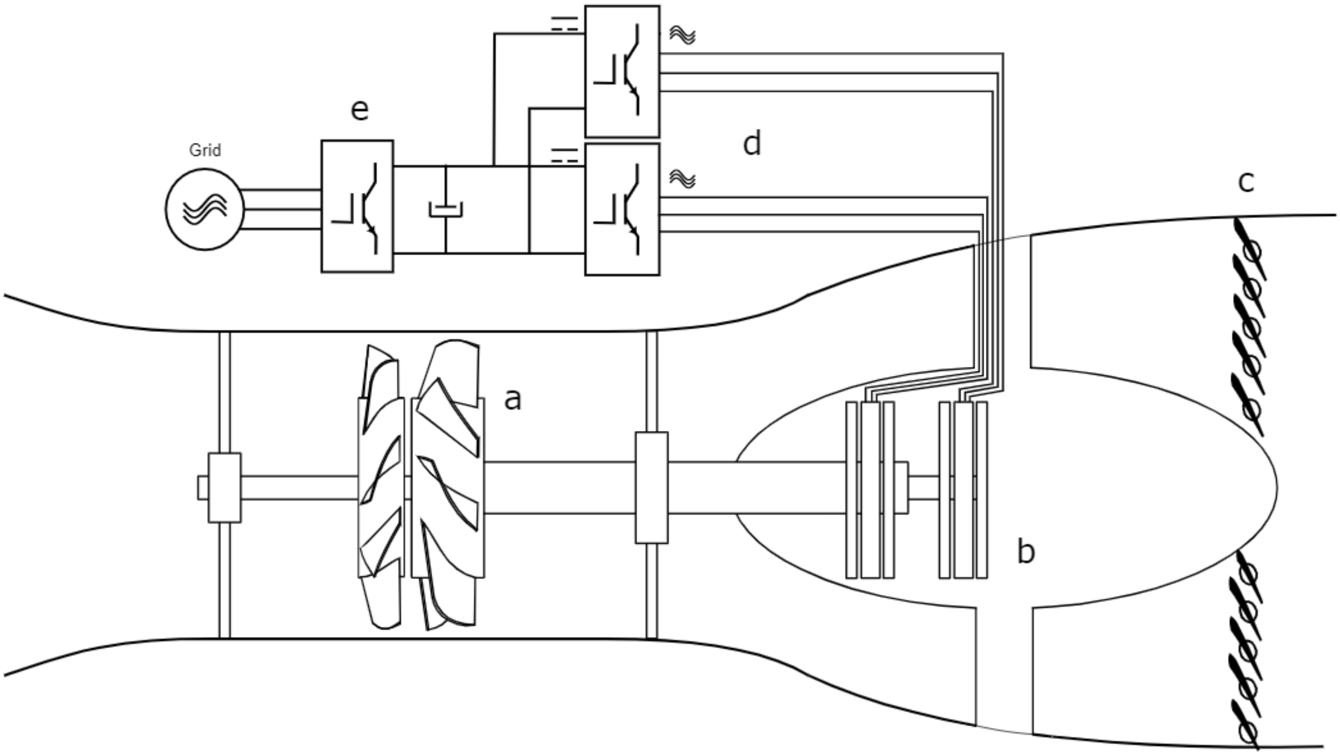

Fig. 1. Schematic of the PTO configuration with coaxial shafts and bulb. a) Contra-rotating propellers b) AF-PMSMs inside the bulb c) Inlet vanes d) Machine-side converters coupled to common DC-link e) Grid-side converter

For a coaxial shaft, the arrangement of bearings and seals needs to be carefully considered. Since the RPT is reversible, so are the axial forces exerted on the shafts. Due to the size of the shaft and fluctuating heat transfers, a high tolerance for expansion is needed. Combination of a locating double tapered bearing and a non-locating radial bearing seems suitable on account of their axial loadability and tolerance for shaft expansion. The radial bearings (one for each drivetrain) will be integrated in the electrical machines. Fig. 1 shows the location of the double tapered bearing of the outer shaft. Here, the exact axial position of the bearing will be the result of an interdisciplinary relation between influence of flow and moment load on the bearing, when placed either closer to, or further from, the actuator. Note that it is also possible for this thrust bearing to be located inside the bulb, as is also practiced in maritime crafts. Advantages include easier maintenance and less need for bearing sealing, at the cost of increased moment load. For the inner shaft bearing, a similar construction is evident and is thus shown in Fig. 1. Yet, an option to place this bearing in between the two coaxial shafts is being considered. This way flow disturbance is completely discarded on one side of the RPT. Drawbacks include increased mechanical friction, since the bearing experiences an increased relative speed, as well as increased load on the outer shaft.

Due to the low speed nature of water turbines, a multiple pole synchronous machine will be used. This averts the use of reduction gearing, which accounts for significant energy losses and reduced reliability in traditional slow turning systems [25]. In ALPHEUS, an Axial-Flux Permanent Magnet Synchronous Machine (AF-PMSM) is used for its high power density and suitability for low-speed-high-torque applications [26],[27]. 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. Further efficiency improvements are achieved by using segmented rotor magnets, concentrated pole windings and thin laminated grain-oriented material for the stator teeth [28]. The machine will be designed to have an efficiency >90% from 20% to 100% of nominal torque and speed, by accounting for cogging torque and torque ripple at low speeds during design. Fig. 2 shows the proposed machine topology with important design parameters indicated. The cooling method (air versus water) has a great effect on the allowable current, and thus on the machines torque. In existing hydropower installations, the water flow is used to cool the machines

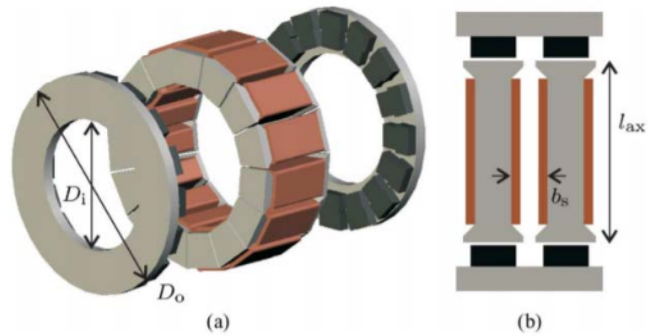

Fig. 2. YASA topology AF-PMSM. a) Overview b) Detailed view of tooth pitch [28]

through a simple air-water heat exchanger [29],[30]. Though this method is straightforward, using more complex cooling circuits for electrical components would require excessive filtering. The water flow can be used as a secondary cooling circuit, which collects heat from the primary closed cooling loop in a heat exchanger placed in the water tube.

As shown in Fig. 1, both AF-PMSMs are connected to a full-power active converter, e.g., a three-leg PWM-regulated inverter with six switches. These two inverters are coupled to a common DC-link, where also the grid-side inverter 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 inverter will be explained later in this paper.

The machine-side control is of great importance and will be optimized 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 productivity. For the low level machine-side control, Field Oriented Control (FOC) is most suited. In FOC, the current vector is regulated in the rotating reference frame to be aligned with the quadrature axis, i.e., 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 setpoints for the low level control of the two contra-rotating propellers are given by the high level control, which controls the power of the machines. Furthermore, the high level control can adjust the pitch of the inlet vanes and thus, control water flow. Conventionally, a Maximum Power Point Tracking system (MPPT) is used in wind- [31],[32] and hydropower [33] turbines. For a given water flow rate, the power versus speed curve of the turbine has a single maximum. So whenever water flow changes, the torque setpoint changes until the optimal rotational speed is achieved. The power curves used in MPPT, are obtained during the testing of the system. Here, the generator and converter should be taken into account. Their losses depend on the rotational speed, which causes the MPP to shift to a slightly lower speed [34]. In ALPHEUS, the RPT consists of two contra-rotating propellers, each adjusting action of one propeller has an effect on the other, complicating the effective use of MPPT. While MPPT can still be practiced with, e.g., a given speed ratio between the propellers, a more advanced control system seems worthwhile investigating.

One possible advanced control system is Model-based Predictive Control (MPC). MPC makes use of a detailed model of the full system, modelling the water flow, inlet vanes, propellers and all internal influences. During operation, the MPC calculates how the power would change, given changes in control parameters in the next few machine cycles. Thus it is excellent for reacting to power setpoints from the grid, since it already calculated what sequence of control parameter adjustments, would give a certain power output. While adjusting power flow, MPC makes the parameter changes within set boundary constraints, which account for the systems mechanical and electrical limitations, preventing wear and fatigue loads.

Instead of limiting the propellers speed to their optimal efficiency ratio, the two propellers can be operated modularly, to increase reaction speed to grid needs. The challenge here is to accurately model the flow influence between the two propellers. Next to MPC, other advanced control options such as machine learning, AI or even fuzzy logic could be applied.

V. Grid Integration

Most of the grid-connected inverters nowadays are based on grid-following control, where the controlled inverter behaves as a current source that synchronises to the grid voltage and feeds in current to meet its active and reactive power set point. Grid-following control is therefore bound to a Phase-Locked Loop (PLL) in order to keep synchronised with the grid. Using only grid-following, the energy transition goal to base a great part of electric energy generation on renewable energy sources would not be possible without losing grid stability [35],[36]. For this matter, a grid-forming control mode is currently being discussed. Here, the controlled inverter acts as an AC voltage source with stated voltage, phase and frequency. By controlling the voltage magnitude and frequency, the behaviour of the inverter 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 [36]. Therefore, an inverter controlled using grid-forming coupled with an energy storage system is currently being discussed as viable alternative to imitate the synchronous generator behaviour regarding frequency control. Especially its ability to provide ‘synthetic inertia’, which is the capability to react instantaneously to shifts in frequency with power support, is seen as capable of replacing the rotational inertia of a synchronous power-generating module to a prescribed level of performance. This ability to provide synthetic inertia together with fast Frequency Containment Reserves (fFCR), which is a control reserve located in the time frame between FCR and inertia [37], will augment the grid stability. By providing these vital ancillary services, the grid-forming controlled inverter would enable the grid towards an energy supply largely based on renewable energy sources unlike the grid-following[35],[38].

In the ALPHEUS project, an appropriate control method, which will act to provide synthetic inertia and fFCR by controlling the DC- and generator-side of the plant will be studied. Moreover this control system has to be designed and studied for the grid-side-inverter 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 the directive (EU) 2019/944 on common rules for the internal market for electricity [39] and commission regulation (EU) on requirements for grid connection of generators [38].

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 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.

One important issue that will be examined as well, is the contribution of low-head pumped storage to grid stability. This will be done in close collaboration with project partners from Ghent University, who study the machine-side control. In a first step, historic frequency measurement are collected, imported, and evaluated in MATLAB to verify data integrity and completeness. This data will be used to form profiles for expected loads on devices providing Frequency Containment Reserves (FCR). Furthermore, this data set will be utilised in the design of the PTO system to determine operation profiles and technical characteristics of the proposed plant setup that fuel the further studies on grid stability of the plant. The considered effects will be twofold. On the one hand, the proposed setup will be capable of long-term energy provision with several applications of interest. For instance, the plant could be enabled for peak shaving local offshore wind energy sources output - otherwise overstraining grid transport capacity - can be compensated such that the combined hybrid wind and hydro plants operate their mainland grid connection to maximise energy output. On the other hand, the plant is capable of providing support on the short-term range, which involves major grid support and stabilisation in reaction to any failures and emergency situations within the European transmission grid.

Based upon an assessment of the abilities of the plant, such as the capability of the proposed setup to provide flexibility in varying gradients and durations, the capability of the plant to serve as provider of the relevant operational reserves (FCR, Frequency Restoration Reserves (FRR), Replacement Reserves (RR)) are evaluated. Furthermore, since the plant inherently serves as an energy storage system, promising features of an expanded control concept would involve black-start capability and grid-forming behaviour. The former would enable the plant to serve as an independent voltage reference used to restart the grid after a major power outage. For this capability, grid-forming behaviour is a requirement. As mentioned before, this mode of control would also permit the provision of inertia, which is currently discussed as a requirement of a grid deemed to operate in a stable fashion with severely reduced shares of fossil generation. On the basis of the results from the other plant design results, the requirements for a grid-forming control system are given for the pumped storage power plant will be evaluated to test if this control can be used in the ALPHEUS project. If this is the case, a suitable control system is implemented and its contribution to inertia and black start capability will be examined. Besides grid-forming, different possibilities to provide synthetic inertia will be discussed, such as using the energy of the DC-link if the pumped storage is not fast enough. one more possibility is using the rotation of the turbines to provide inertia similar to a control concept currently discussed for wind turbines [40],[41], taking in consideration the differences between air and water hydrodynamics.

Moreover, as shown in Fig. 3; a time-domain simulation environment, using the historic frequency data, taking in consideration the time constants of ALPHEUS low-head PHS will give initial indication on the reaction speed of the plant and whether it is able to provide the required synthetic inertia, fFCR and other balancing reserve.

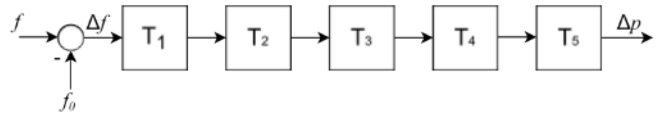

Fig. 3. Time constants of low-head PHS

Where,

f: Measured frequency (historical frequency data in this case)

f_0: Grid fundamental frequency (50Hz)

T_1: Time constant describes the time needed to open the valves and to build pressure

T_2: Time constant describes the time needed for the water flow from the higher basin to the lower

T_3: RPT take-off time constant (in turbine mode in this case)

T_4: Machine side converter time constant

T_5: Grid-side converter time constant

Δp: Balancing reserve

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 constrains in the EU countries will be considered during the project, e.g. 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, 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 of market-based-inertia is required [42],[39]. Such important regulatory constraints are to be followed up in ALPHEUS.

VI. Conclusion

With the new concept of low-head PHS, including the integrated and highly efficient RPT, PTO, DC-link and power electronics, along with grid-side inverter control equipped with functions for EU standard compliant operation, the project ALPHEUS 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 AS, 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 AF-PMSMs will provide 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 need to be able to withstand prolonged exposure to open sea conditions and seawater corrosion while storing potential energy. Several different sites will be proposed for the construction of the low-head PHS.

Acknowledgment

The project ALPHEUS presented in this paper has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 883553. The authors would like to thank the European Union for funding this project.

References

[1] UNITED NATIONS. United Nations Framework Convention on Climate Change. *Paris agreement*. 2015.

[2] Öko-Institut und Prognos, "Zukunft stromsystem kohleausstieg 2035," 2017.

[3] EUROPEAN COMMISSION, "METIS Technical Note T4 Overview of European Electricity Markets," 2016.

[4] Statkraft Markets GmbH, "Speicherlösungen für den Energiemarkt der Zukunft," 2020. [Online]. Available: https://www.statkraftdirektvermarktung.de/pioniergeist/Stromspeicher/.

[5] Technische Universität Braunschweig, "Energie aus Windkraft speichern und Stomnetze stabilisieren," 2020. [Online]. Available: https://magazin.tu-braunschweig.de/pi-post/energie-aus-windkraft-speichern-und-stomnetze-stabilisieren/.

[6] ALPHEUS. ALPHEUS's official website. Augmenting Grid Stability Through Low Head Pumped Hydro Energy Utilization and Storage. https://alpheus-h2020.eu/.

[7] S. Rehman, L. M. Al-Hadhrami and M. M. Alam, "Pumped hydro energy storage system: A technological review," in *Renewable and Sustainable Energy Reviews*, vol. 44, pp. 586-598, Apr. 2015, doi: 10.1016/j.rser.2014.12.040.

[8] B. Zhu, X. Wang, L. Tan, D. Zhou, Y. Zhao, and S. Cao, "Optimization design of a reversible pump–turbine runner with high efficiency and stability," in *Renewable Energy*, vol. 81, pp. 366-376, Sept. 2015, doi: 10.1016/j.renene.2015.03.050.

[9] Z. Qian, F. Wang, Z. Guo, and J. Lu, "Performance evaluation of an axial-flow pump with adjustable guide vanes in turbine mode," in *Renewable Energy*, vol. 99, pp. 1146-1152, Dec. 2016, doi: 10.1016/j.renene.2016.08.020.

[10] D. Hart and D. Whale, "A review of cavitation-erosion resistant weld surfacing alloys for hydroturbines," in *Eutectic Australia Pty. Ltd.*, Sydney 8, pp. 180-187, 2007.

[11] Kim, Joon-Hyung, et al. "Design technique to improve the energy efficiency of a counter-rotating type pump-turbine," in *Renewable Energy,* vol. 101, pp. 647-659, Feb. 2017, doi: 10.1016/j.renene.2016.09.026.

[12] T. Kanemoto, S. Kimura, S. Oba, and M. Satoh, "Smart Control of Axial Flow Pump Performance by Means of Counter-Rotation," in *JSME International Journal Series B Fluids and Thermal Engineering*, vol. 45, no. 2, pp. 293-300, May 2002, doi:10.1299/jsmeb.45.293.

[13] T. Kanemoto, and S. Oba, "Proposition of unique pumping system with counter-rotating mechanism," in *International Journal of Rotating Machinery*, vol. 10, July 2004, doi: 10.1080/10236210490447494.

[14] T. Murakami, and T. Kanemoto, "Counter-rotating type pump-turbine unit cooperating with wind power unit," in *Journal of Thermal Science*, vol. 22, no. 1, pp. 7-12, 2013, doi: 10.1007/s11630-013-0585-2.

[15] T. Kanemoto, R. Kasahara, H. Honda, T. Miyaji and J-H. Kim, "Counter-rotating type pump-turbine unit stabilizing momentarily fluctuating power from renewable energy resources," in *ASME International Mechanical Engineering Congress and Exposition*, vol. 56284, p. V06AT07A093. American Society of Mechanical Engineers, Nov. 2013, doi: 10.1115/IMECE2013-66000.

[16] S.L. Dixon, C.A. Hall, "Fluid Mechanics and Thermodynamics of Turbomachinery (7th edition)" *Butterworth-Heinemann*, 2013.

[17] C. Gatti, "Design of Experiments for Reinforcement Learning" in *Springer International Publishing*, 2015, doi: 10.1007/978-3-319-12197-0

[18] Rijkswaterstaat, Hollandsche Beton Groep NV, Ballast Nedam Groep NV, & Raadg. Ing. Bur. Lievense. *Pomp accumulatie centrale Noordzeekust (Hoofdrapportage fase 1)*, 1985.

[19] De Boer,W.W., Verheij,F.J., Moldovan,N., Van der Veen,W., Groeman,F., Schrijner,M., ... Zwemmer,D. *Energie-eiland, de haalbaarheid van drie verschillende opties van energieopslag voor Nederland.*, KEMA Consulting/Lievense, 2007.

[20] Delta21 report "Update 2019: DELTA21 Een actualisering van het plan." [Online]. Available: https://www.delta21.nl/wp-content/uploads/2019/09/UPDATE-DELTA21-29-7-2019.pdf

[21] B. M. Pracheil, C. R. DeRolph, M. P. Schramm, M. S. Bevelhimer, "A fish-eye view of riverine hydropower systems: the current understanding of the biological response to turbine passage," in *Reviews in Fish Biology and Fisheries* vol. 26, pp. 157-158, 2016, doi: 10.1007/s11160-015-9416-8.

[22] Coaxial helicopter, by E. F. Rock. U.S. Patent US6886777B2 [Online]. Available: https://patents.google.com/patent/US6886777B2/en

[23] Contra-rotating propller propulsion system for ships, by A. R. Lago *et al.*. European Patent EP2202143A1 [Online]. Available: https://patents.google.com/patent/EP2202143A1/en

[24] F. Kutt, K. Blecharz, D. Karkosiński. "Axial-Flux Permanent-Magnet Dual-Rotor Generator for a Counter-Rotating Wind Turbine". *Energies 2020*, 13, 2833.

[25] G. Dubrovskiy, A. Mikerov, V. Dzhankhotov and J. Pyrhonen, "General comparison of direct and geared drives for control applications," *2014 16th European Conference on Power Electronics and Applications*, Lappeenranta, 2014, pp. 1-6, doi: 10.1109/EPE.2014.6910754.

[26] S. Huang, J. Luo, F. Leonardi and T. A. Lipo, "A comparison of power density for axial flux machines based on general purpose sizing equations," in *IEEE Transactions on Energy Conversion*, vol. 14, no. 2, pp. 185-192, June 1999, doi: 10.1109/60.766982.

[27] A. Cavagnino, M. Lazzari, F. Profumo and A. Tenconi, "A comparison between the axial flux and the radial flux structures for PM synchronous motors," in *IEEE Transactions on Industry Applications*, vol. 38, no. 6, pp. 1517-1524, Nov.-Dec. 2002, doi: 10.1109/TIA.2002.805572.

[28] H. Vansompel, P. Sergeant and L. Dupré, "Optimized Design Considering the Mass Influence of an Axial Flux Permanent-Magnet Synchronous Generator With Concentrated Pole Windings," in *IEEE Transactions on Magnetics*, vol. 46, no. 12, pp. 4101-4107, Dec. 2010, doi: 10.1109/TMAG.2010.2070075.

[29] S. Georgescu, D. M. Bucur, G. Dunca, A. Georgescu, A. A. Nicolae and P. Ciuc, "Hydraulic balancing of the cooling water system of a pumped storage power plant," *2017 International Conference on ENERGY and ENVIRONMENT (CIEM)*, Bucharest, 2017, pp. 246-250, doi: 10.1109/CIEM.2017.8120766.

[30] W. Qu, X. Zhang and X. Lu, "Numerical Simulation of Cooling Water of Yangluo Power Plant," *2009 Asia-Pacific Power and Energy Engineering Conference*, Wuhan, 2009, pp. 1-4, doi: 10.1109/APPEEC.2009.4918536.

[31] V. K. Sharma and L. Gidwani, "Performance Analysis of PMSG for Wind Turbine Using Optimum Torque Control and D-Axis Current Control," 2018 8th *IEEE India International Conference on*

Power Electronics (IICPE), JAIPUR, India, 2018, pp. 1-5, doi: 10.1109/IICPE.2018.8709484.

[32] K. Han and G. Z. Chen, "A novel control strategy of wind turbine MPPT implementation for direct-drive PMSG wind generation imitation platform," *2009 IEEE 6th International Power Electronics and Motion Control Conference*, Wuhan, 2009, pp. 2255-2259, doi: 10.1109/IPEMC.2009.5157778.

[33] L. Belhadji, S. Bacha, I. Munteanu, A. Rumeau and D. Roye, "Adaptive MPPT Applied to Variable-Speed Microhydropower Plant," in *IEEE Transactions on Energy Conversion*, vol. 28, no. 1, pp. 34-43, March 2013. doi: 10.1109/TEC.2012.2220776

[34] J. De Kooning, T. Vandoorn, J. Van de Vyver, B. Meersman and L. Vandevelde, "Displacement of the maximum power point caused by losses in wind turbine systems," in *Renewable Energy*, 85. pp. 273-280, Jan. 2016 doi: 10.1016/j.renene.2015.06.052

[35] P. Roos, "A Comparison of Grid-Forming and Grid-Following Control of VSCs," Uppsala University, 2020.

[36] S. Laudahn, J.Seidel, B.Engel, T.Bülo, and D. Premm, "Substitution of Synchronous Generator Based Instantaneous Frequency Control Utilizing Invertercoupled DER" in *2016 IEEE 7th International Symposium on Power Electronics for Distributed Generation Systems (PEDG)*, Vancouver, BC, 2016, pp. 1-8, doi: 10.1109/PEDG.2016.7527020.

[37] J.Seidel, B.Engel, "Contribution of Photovoltaic Power Systems to Frequency Control" in *8th Solar Integration Workshop, 16.-17. Oktober 2018*, Stockholm, Schweden, 2018.

[38] COMMISSION REGULATION (EU) 2016/631 of 14 April 2016, "Establishing a network code on requirements for grid connection of generators" in *Official Journal of the European Union*,2016.

[39] Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU (Text with EEA relevance.)" in *Official Journal of the European Union*,2019.

[40] Z. Wu, W. Gao, T. Gao, W. Yan, H. Zhang, S. Yan and X. Wang, "State-of-the-art review on frequency response of wind power plants in power systems," in *Journal of Modern Power Systems and Clean Energy*, vol. 6, no. 1, pp. 1-16, 2018, doi: 10.1007/s40565-017-0315-y

[41] P. Denholm, T. Mai, R. Wallace Kenyon, B. Kroposki, and M. O'Malley, "Inertia and the Power Grid: A Guide Without the Spin," Golden, CO: National Renewable Energy Laboratory. NREL/TP-6120-73856, 2020.

[42] The German Federal Ministry of Justice and for Consumer Protection, German Energy Act"§ *12 Aufgaben der Betreiber von Elektrizitätsversorgungsnetzen, Verordnungsermächtigung*,2020.