Assessing the mileage reduction of a Kaplan turbine hybridized with a battery using digital twins

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Abstract. Kaplan turbines are well suited for the provision of frequency containment reserve (FCR) to the electrical power system thanks to their adjustable guide vanes and runner blades, allowing to quickly regulate its power output while maintaining high efficiency for different volumetric flow rates and heads. However, continuous power regulation, induces a heavy load on the actuator mechanism of the moving parts, leading to a significant increase of the wear and tear. The integration of batteries with hydropower turbines has gained attention as a promising approach to reduce the amount of movements in the regulation servomotors by advantageously splitting the load between the Battery Energy Storage System (BESS) and the hydraulic unit when providing FCR service. To demonstrate this approach, one of the four Kaplan units of Vogelgrun Run-of-River (RoR) power plant which has been hybridized with a small size battery within the frame of the XFLEX HYDRO H2020 European research. The battery is used to compensate for small fluctuations in the frequency of the power network by supplying or absorbing active power while working in tandem with the hydro unit through a dedicated control algorithm. However, assessing the actual mileage reduction of the hybridized Kaplan turbine is challenging due to the constantly changing operating conditions and grid frequency, such that comparing between days with and without the BESS in operation proved to be inappropriate. In this study, the use of digital twins for mileage reduction assessment is presented. Several 1D SIMSEN numerical models of the hydropower plant were created, including the hydraulic system dynamics and the turbine governor system. These models were then run in real time, using the grid frequency and reservoir levels of the real unit, to accurately simulate the behaviour and performance of the hydro unit in different operating modes, such as standalone, hybrid, or without FCR. This allowed an effective comparison of the performance of the hybrid mode and the associated control algorithm. In addition, digital twins can also be used to predict the system dynamics and performance, enabling a more efficient and cost-effective optimization of the regulator parameters as well as benchmarking of different hybrid control strategies.

1. Introduction

Kaplan turbines are well suited for the provision of Frequency Containment Reserve (FCR) to the electrical power system thanks to their adjustable guide vanes and runner blades, which enable rapid power regulation while maintaining high efficiency for different volumetric flow rates (discharges) and heads. However, continuous power regulation, induces a heavy load on the actuator mechanism of the moving parts, leading to a significant increase of the wear and tear In particular, shorter maintenance intervals, increased outage time and reduced lifetime (wear and tear) are the main associated consequences of providing FCR with Kaplan units [1] [2]. This is particularly true for runner blade mechanism of Kaplan turbines where the difficulty of access results in prolonged outages and costly repairs in the event of failure.

As part of the XFLEX HYDRO project [3], the Vogelgrun Run-of-River (RoR) power plant serves as one of the seven demonstrators to showcase how hydro power plants can provide more flexibility to the power systems. The focus of Vogelgrun is to enhance the FCR provision while at the same time reduce the wear & tear of the Kaplan turbine, by hybridizing one turbine with a minimally sized Battery Energy Storage System (BESS). The idea is to advantageously split the load between the BESS and the hydraulic unit when providing FCR service, in order to reduce the amount of movements in the regulation servomotors. This is achieved through a dedicated control algorithm that allows the battery to compensate for small frequency fluctuations in the power network by supplying or absorbing active power, working in tandem with the hydro unit. However, assessing the actual mileage reduction of the hybridized Kaplan turbine is challenging due to the constantly changing operating conditions and grid frequency, such that comparing between days with and without the BESS in operation proved to be inappropriate. Similarly, the use of the neighbouring stand-alone unit as a reference was inconclusive due to inherent differences in unit behaviour and differences in controller settings.

To overcome these difficulties, this paper presents the use of digital twins to evaluate the reduction in mileage attributable to BESS. A set of SIMSEN 1D numerical models were developed to represent various aspects of the hydropower plant, including the dynamics of the hydraulic system and the turbine control system. Real-time simulations were carried out using actual input data from the unit's turbine regulator, i.e. the frequency and water level to be regulated, to accurately reproduce the behavior and performance of the hydroelectric unit in different operating modes, such as stand-alone, hybridization or without FCR. This enabled a full performance comparison between the hybrid mode and the corresponding control algorithm.

2. Description of the XFLEX HYDRO Vogelgrun demonstrator

The Vogelgrun RoR power plant is situated on the Grand Canal d'Alsace, which channels the Rhine river, approximately 80km south of Strasbourg. The plant consists of four 35 MW Kaplan turbine units and is operated by Electricité de France (EDF). The objective of this demonstrator is to enhance the provision and dynamics of Frequency Containment Reserve (FCR) through the utilization of a hybrid system. Simultaneously, it aims to increase flexibility capability while reducing wear and tear by 90% compared to a non-hybrid turbine-generator-unit (TG-unit). Moreover, the intention is to use a BESS with minimal capacity, while the existing speed governor of the hybridized TG-unit remains unchanged. To do so, the hybridization of one TG-unit with a battery energy storage system (BESS) of 650 kW/370 kWh is assessed. Details about the technical and economical constraints in the optimization of the BESS size can be found in [4][5].

An overview of the Vogelgrun demonstrator with the setup of the hybrid unit is shown in Figure 1, and a more complete description can be found in [6]. To achieve a response time of 30 seconds for FCR provision at the Vogelgrun demonstrator, a hybrid controller and a dedicated algorithm are employed. The algorithm splits the active power setpoint between the BESS and the TG-unit, with the BESS responding more rapidly. Sensors were installed on both the hybridized TG-unit and a non-hybridized TG-unit to validate the success of the hybridization. Additionally, digital twins were employed to compare real-time behavior with expected results. This allowed for the validation of digital tools against measurements and facilitated the simulation of "What-if" scenarios to estimate the expected lifetime under different operating modes for the same grid frequency time series. Consequently, mileage and sign changes, which are a good indicator of wear and tear [7], were obtained for the following operating scenarios: discharge control (without FCR provision), stand-alone FCR provision (TG-unit without BESS), FCR provision in hybrid mode (TG-unit + BESS), and benchmarking of different hybrid control strategies.

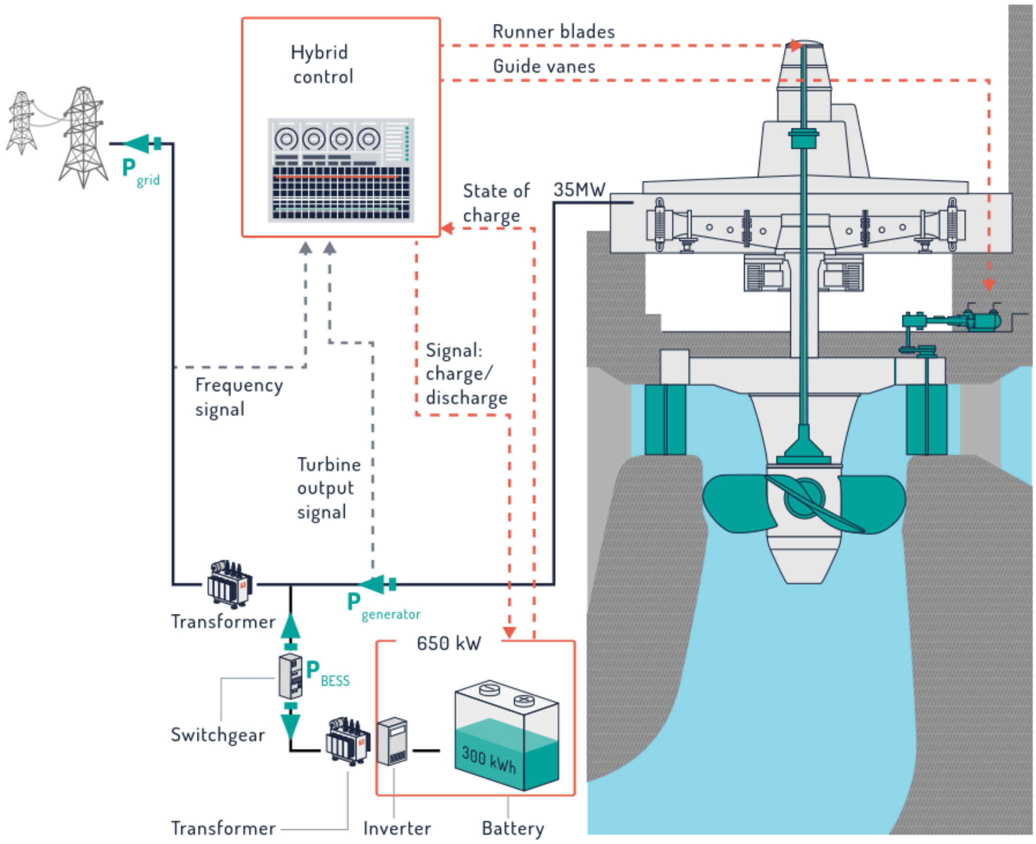


Figure 1 Overview of the Vogelgrun demonstrator with the hybrid unit setup.

3. Hydro-Clones description

Hydro-Clone® is an advanced Real-Time Simulation Monitoring System (RTSM) that relies on a meticulously calibrated and validated digital model of the hydropower plant. This system can accurately replicate any dynamic behavior of the plant in real-time by utilizing the boundary conditions measured on-site, effectively functioning as a digital twin. It enables ongoing health diagnostics of a hydropower plant (HPP) by digitally replicating the main hydraulic and electrical components of the plant using SIMSEN software [8][9][10]. The Hydro-Clone general concept is illustrated in Figure 2. It is essentially a software suite that manages the tasks of real-time acquisition and transfer of boundary conditions and measured quantities to a SIMSEN model of the HPP, as well as data processing and diagnosis of the HPP health status. A custom-built archival storage system and an associated database facilitate the display and analysis of historical results. Consequently, the digital twin can detect abnormal events when there is a discrepancy between measurements and simulations [11].

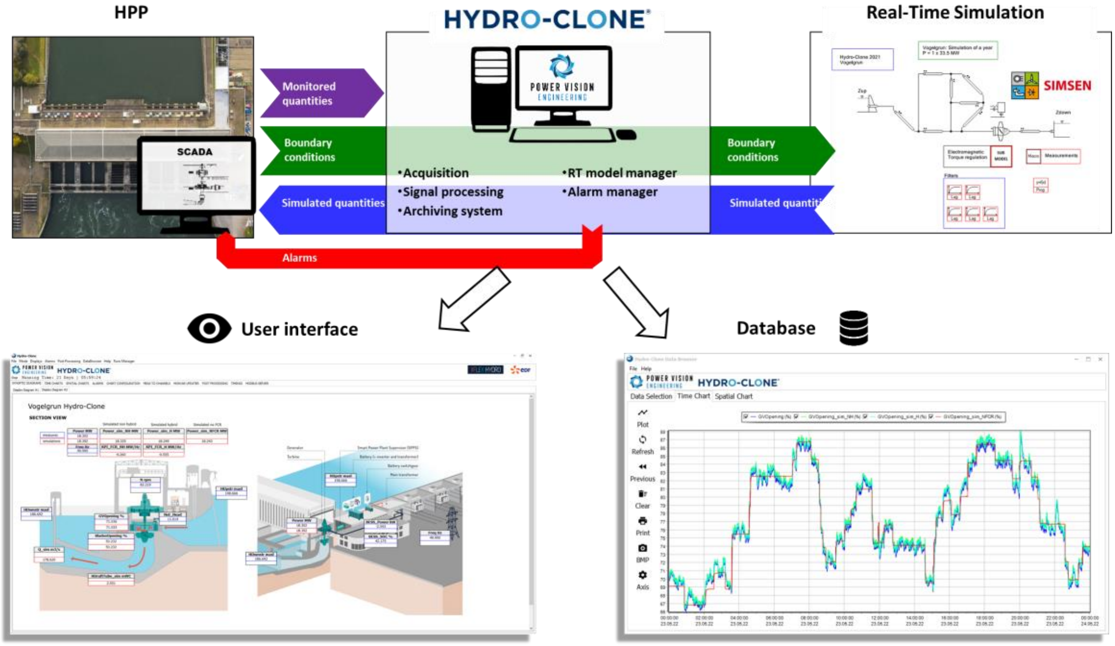


Figure 2 General concept of Hydro-Clone system based on real-time simulation.

The core of Hydro-Clone is built around a detailed hydraulic model of the hydropower plant. For this purpose, a SIMSEN model of Unit 1 of Vogelgrun HPP was developed, encompassing the water intake, Kaplan turbine, and draft tube. Special attention was given to modeling the spiral case to account for the evolution of the cross-sectional area and the distribution of discharge. The hydraulic component of the numerical model was validated by comparing simulation results with time series data of static pressure in the spiral case and the rotational speed of the Kaplan turbine measured during an emergency shutdown in 2015, see [5]. The SIMSEN model also incorporates the turbine governor, which combines the control of the Rhine River's volumetric flow rate (discharge) and FCR control. This controller considers both the grid frequency (or the frequency generated by the hybrid controller algorithm) and a discharge setpoint (essentially a guide vane opening setpoint) that regulates the water level. These parameters are used to calculate the appropriate opening position for the guide vane. The turbine governor operates in guide vane position control mode and utilizes an on-cam look-up table to determine the blade angle setpoint based on the head and guide vane position.

A dedicated Programmable Logic Controller (PLC) is used to provide the necessary signals for the Hydro-Clone process. For this purpose, a 32-channel MVX Oneprod monitoring system is used to collect data from the sensors as described in [12]. The MVX system collects measurement data from both Unit 1 and Unit 3, as well as specific signals from the BESS, which are then distributed to the Hydro-Clone system. In order to comply with cyber security standards, all the transmitted signals are in analogue form. Consequently, there is no digital connection between the Hydro-Clone PC and the rest of the power plant network. The Figure 3 shows a snapshot of the Hydro-Clone interface for Vogelgrun HPP. It includes historical data of measured and simulated quantities, along with synoptic diagrams displaying instant values of monitored parameters. As it can be observed, with the appropriate boundary conditions, the digital twin is able to accurately replicate in real-time the power generation and guide vane positions of the actual unit. This confirms the ability and relevance of using such a digital twin to emulate the HPP behaviour when operating in different modes, in order to benchmark the different hybrid control strategies.

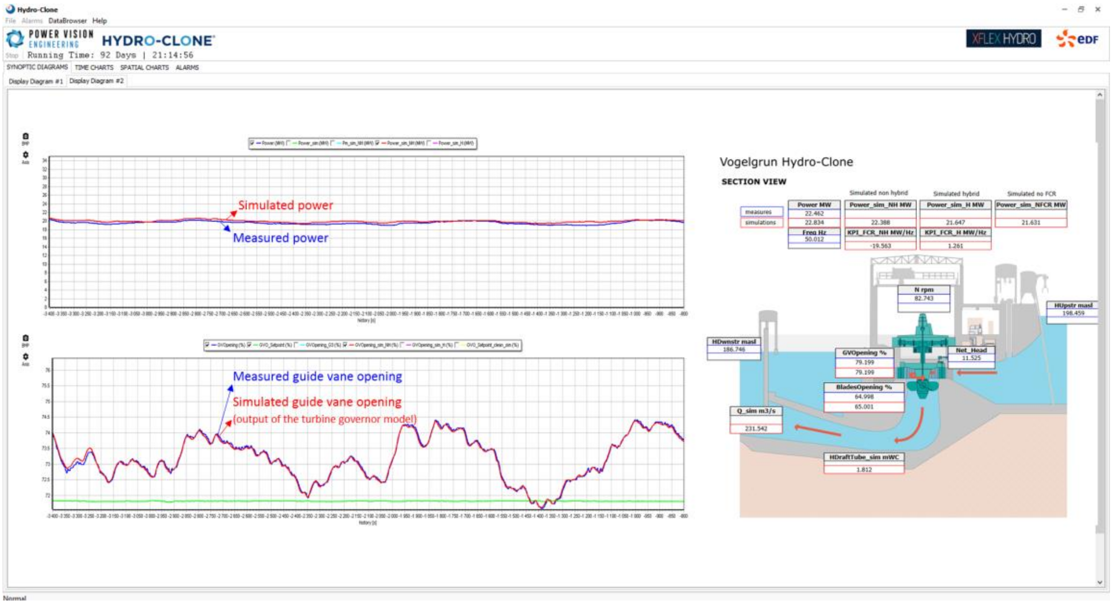


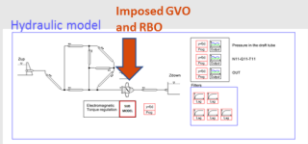
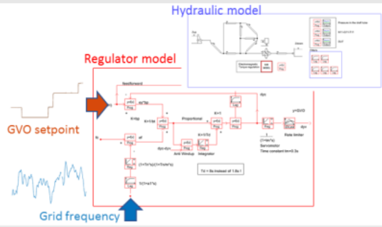
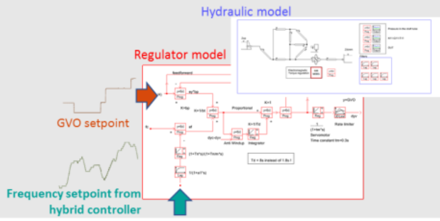
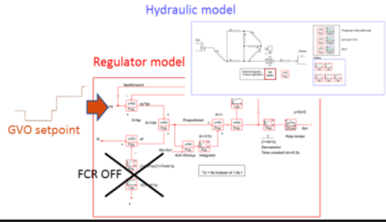
Figure 3 Snapshot of the Hydro-Clone interface for Vogelgrun HPP, featuring the history of measured and simulated quantities, as well as synoptic diagrams showing the instantaneous values of measured and simulated monitored quantities.

One of the main advantage of this digitalization is the ability to monitor non-measured or non-measurable quantities at any time without needing to install additional physical sensors. For the Vogelgrun HPP, this digitalization approach was utilized to assess the impact of the BESS on the movements of the guide vane opening (GVO) and runner blade opening (RBO). To this end, several real-time models were deployed in parallel in Hydro-Clone, in order to simulate the behaviour of the unit in different operating modes (e.g. hybrid, stand-alone, etc.), under the same hydraulic and network conditions. The characteristics and goals of each model, listed in Table 1, can be summarized as such:

- Clone model #1 is the classic monitoring, which replicates the behavior of the real unit by imposing the measured guide vane openings and runner blade opening in the simulation. Consequently, this model ignores the turbine controller and is specifically used to monitor hydraulic transients;
- Clone model #2 includes the turbine governor model, with the guide vane opening set point, which controls the discharge, and grid frequency as inputs. In this mode, the movements of the guide vanes and blades are therefore a result of the turbine governor model. This clone enables to emulate the behavior of the unit 1 without the BESS regardless of the mode of operation of the real unit (stand-alone mode);
- Clone model #3 follows the same philosophy as the model #2 except that the input is the frequency setpoint derived by the hardware hybrid controller, cf. [6] for a detailed explanation of the hybrid unit control strategy. This allows to replicate the behavior of the hybridized unit 1 with the same control structure as when the BESS is activated (hybrid mode);
- Clone model #4 simulates the behavior of the unit when the FCR provision is disabled and the unit operates in discharge control mode. This makes it possible to isolate the contribution of level regulation to the movement of GVO and RBO.

These different versions of the digital twins, integrated with the unit controller, provide a foundation for comparing hybrid and non-hybrid modes under identical operating conditions. It was confirmed that the behavior of clones #2 and #3 accurately mirrors that of the real unit when the BESS is either deactivated or activated, respectively. Conducting a comparison among numerical models offers the additional benefit of mitigating the issue of noise present in measured signals. When examining the measured signals of servomotor displacement to calculate the overall mileage, it became evident that distinguishing between movements attributed to power regulation and those originating from noise was imperative. This noise interference can introduce inaccuracies in assessing the actual effectiveness of the hybridized Kaplan turbine's mileage reduction. By relying on numerical simulations through digital twins, this source of error is effectively bypassed, ensuring a more accurate evaluation of the impact of the hybrid mode and its associated control algorithm on reducing wear and tear on the turbine's actuator mechanism.

Table 1 Summary and characteristics of the four real-time models deployed in Hydro-Clone.

Clone #	Description and goal	Boundary conditions	Schematic view of the model
1	**Digital twin of the real unit** without regulator / measured GVO and RBO imposed in the simulation	• Reservoir water levels • Guide vanes opening • Blade pitch angle	
2	Digital twin with regulator replicating the **stand-alone mode** (non hybrid)	• Reservoir water levels • Grid frequency • GVO setpoint (eq. to discharge setpoint)	
3	Digital twin with regulator replicating the **hybrid mode**	• Reservoir water levels • Frequency setpoint from hybrid controller • GVO setpoint (eq. to discharge setpoint)	
4	Digital twin with regulator replicating the discharge control **without FCR provision**	• Reservoir water levels • GVO setpoint (eq. to discharge setpoint)	

4. Outcome of digital twins

The various instances of the digital twins discussed in the previous section enable the assessment of the reduction in the mileage of the guide vane and runner blade movements attributable to the BESS during daily operation. Figure 4 illustrates the comparison of the simulated guide vane openings and runner blade openings in hybrid and non-hybrid modes over one day of operation. As previously described, the non-hybrid mode involves using the grid frequency as the input for the turbine governor, whereas the hybrid mode employs the "HPP frequency set point," which, in this case, is a low-pass filtered version of the grid frequency, to control the turbine speed governor, see [6]. As a result, the hybrid mode responds to a smoother frequency signal, leading to reduced movements of the GVO and RBO, as shown on the right side of Figure 4.

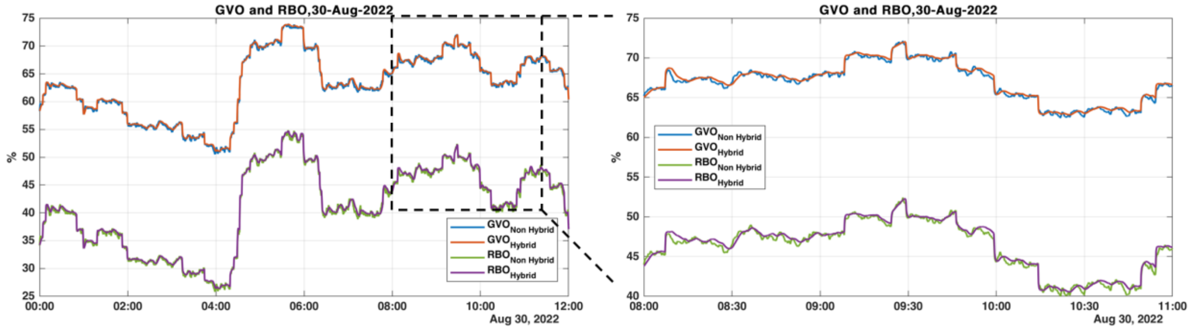


Figure 4 Example of real-time simulation of guide vane opening (GVO) and runner blade opening (RBO), in hybrid and non-hybrid modes.

Mileage reduction with low-pass filtering of grid frequency

The Figure 5 shows the histogram of the GVO and RBO variation for a typical day, both in hybrid and non-hybrid modes, where the hybridisation algorithm consists of filtering the actual grid frequency with a time constant set to 100s, as detailed in [6]. The filtered frequency leads to smoother and more gradual adjustments in response to grid frequency variations, resulting in fewer and smaller amplitude movements. As observed, the hybrid mode significantly reduces the number of small amplitude movements for both the GVO and RBO, while the number of large-amplitude motions (>5mm) remains unaffected by the presence of the BESS. This is expected since large amplitude movements are driven by discharge control, whereas the BESS is designed to mitigate movements resulting from FCR provision. Despite their small scale, these movements substantially impact the total mileage of the GVO and RBO. Consequently, on this particular day, the hybrid mode reduced the total mileage of the guide vanes by 57.6% and the runner blade openings by 55.3%. It is noteworthy that level regulation accounts for 22.4% of GVO mileage and 28.2% of RBO mileage. Additionally, the BESS significantly decreases the number of sign changes in the movements of the GVO and RBO.

This analysis can be repeated over several days to determine the average mileage reduction resulting from this hybridization algorithm. As shown in Table 2, the low pass filter of the grid frequency with a 100s time constant reduces the total mileage of the guide vanes by 55% on average, while the runner blade opening movement are reduced by 52%. In addition, the number of sign changes is reduced by 80% for guide vane openings and 74% for runner blades openings. This type of result is encouraging in terms of reducing the fatigue load on mechanisms by reducing the number of cycles to which they are subjected. Nevertheless, the proportion of mileage in hybrid mode remains around twice as high as that resulting from level regulation only (without FCR), demonstrating further potential for improvement.

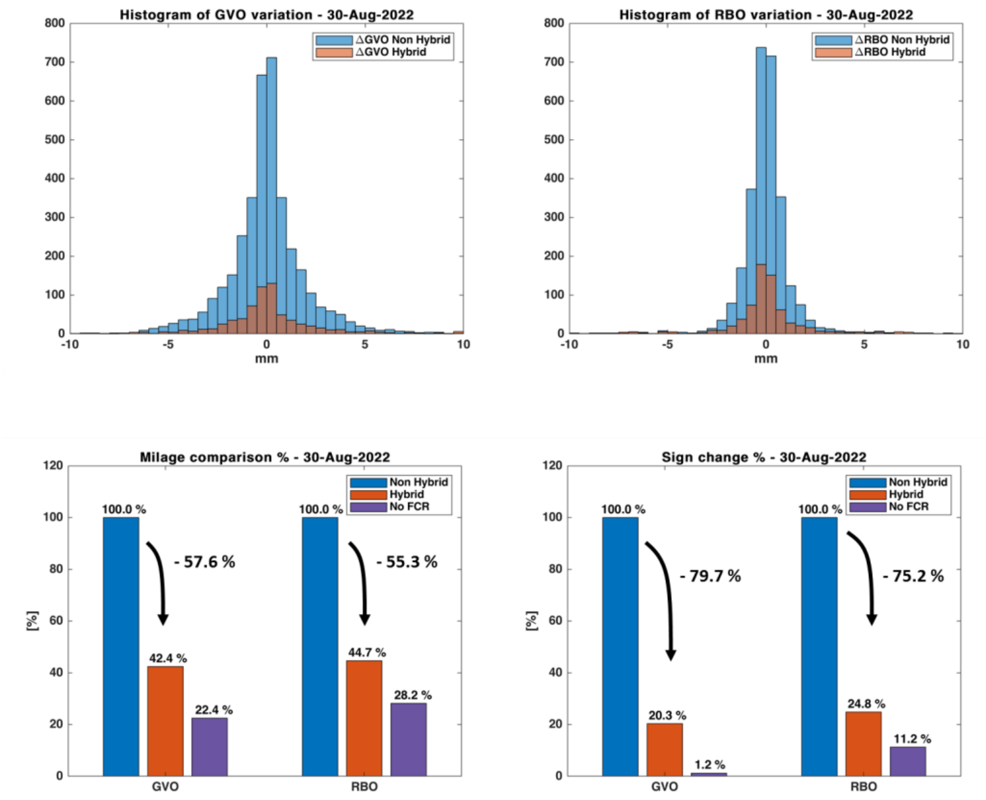


Figure 5: Assessment of the reduction in mileage and number of sign changes for the guide vane opening (GVO), and runner blade opening (RBO), in hybrid mode using the 100s low-pass filtering control algorithm.

Table 2 Summary of mileage and sign changes reduction hybridization using the 100s low-pass filtering control algorithm.

Date	**GVO mileage**	**RBO mileage**	**GVO sign changes**	**RBO sign changes**
29.08.2022	-57.3%	-55.4%	-80.0%	-75.0%
30.08.2022	-57.6%	-55.3%	-80.0%	-75.0%
31.08.2022	-49.1%	-44.8%	-80.0%	-71.0%
Average	**-54.7%**	**-51.8%**	**-80.0%**	**-73.7%**

Mileage reduction with fuzzy logic reasoning

Following the same hybrid controller architecture used for the low-pass filtering of the grid frequency as described in [6], Andritz Hydro and the Commissariat à l'énergie atomique et aux énergies alternatives (CEA), both involved in the XFLEX HYDRO Vogelgrun project, have implemented on site another approach based on a fuzzy logic reasoning algorithm. Figure 6 shows an extract from a real-time simulation illustrating the behaviour of the GVO and RBO in hybrid and non-hybrid modes, when fuzzy logic reasoning is used to calculate the frequency setpoint input to the turbine controller. This figure clearly highlights the high efficiency of the fuzzy logic reasoning approach to significantly reduce the number of movements of GVO and RBO compared to the non-hybrid mode. This tendency is confirmed on the histograms in Figure 7 for the GVO and RBO variation during a typical day of operation. As it can be observed, this hybridisation algorithm is very efficient in eliminating small movements and minimizing unnecessary adjustments, indicating that the BESS effectively assumes the responsibility of most of the frequency control as long as its capacity allows. The hybrid mode with fuzzy logic reasoning reduces the total mileage of the guide vanes by 83% on average, while the runner blade opening movement are reduced by 77%, as shown in Table 3. In addition, the number of sign changes is reduced by 95% for guide vane openings and 74% for runner blades openings.

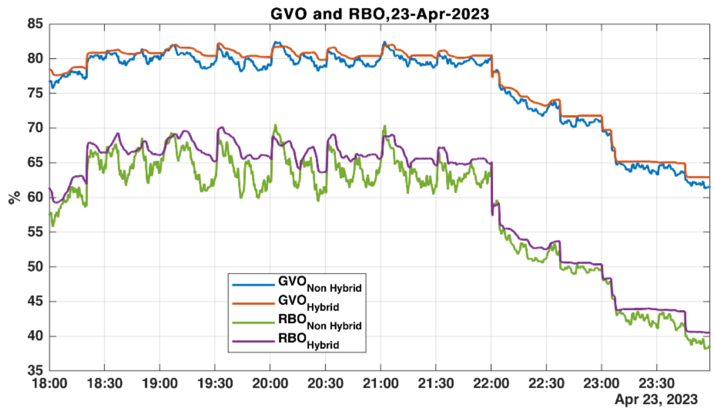


Figure 6 Extract of real-time simulation of GVO and RBO in hybrid and non-hybrid modes, with the fuzzy logic reasoning to determine the frequency setpoint sent to the turbine governor.

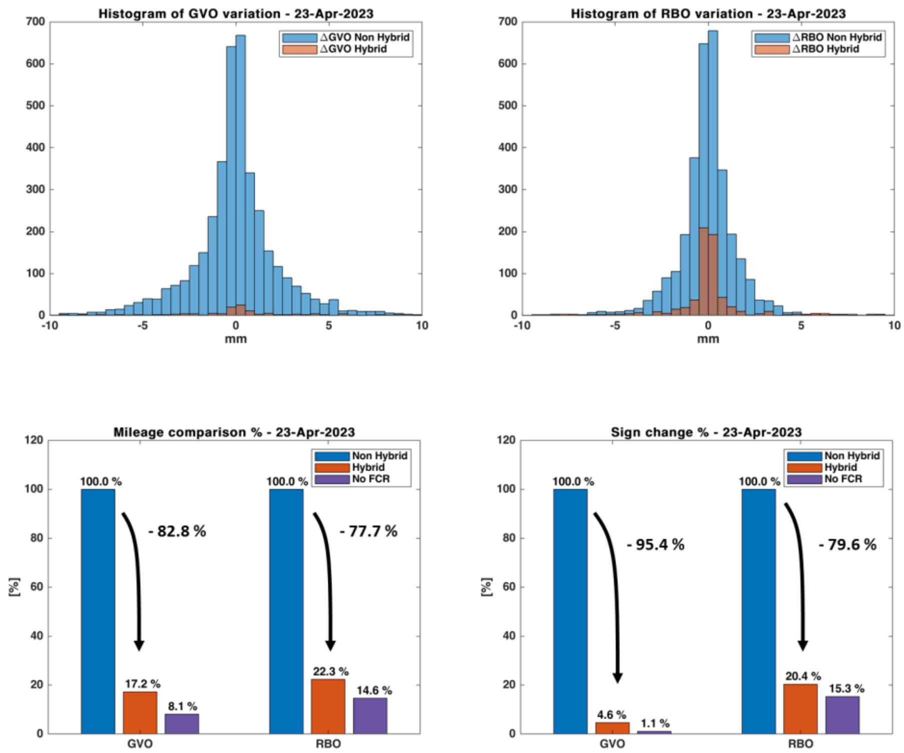


Figure 7 Assessment of the reduction in mileage and number of sign changes for GVO and RBO in hybrid mode using the fuzzy logic reasoning control algorithm.

Table 3 Summary of mileage and sign changes reduction hybridization using the fuzzy logic reasoning control algorithm.

Date	GVO mileage	RBO mileage	GVO sign changes	RBO sign changes
23.04.2023	-82.8%	-77.7%	-95.0%	-80.0%
24.04.2023	-83.0%	-76.1%	-95.0%	-68.0%
Average	**-82.9%**	**-76.9%**	**-95.0%**	**-74.0%**

5. Conclusions

This study aimed to evaluate the mileage reduction of the mechanism of Kaplan turbine achieved through the integration of a Battery Energy Storage System (BESS) to provide part of the frequency containment reserve. However, quantifying the exact mileage reduction proved a significant challenge due to the dynamic nature of operational conditions and the constant fluctuations in network frequencies. Overcoming these challenges was imperative to comprehensively understand and quantify the BESS's impact on the longevity and operational efficiency of the turbine.

In this context, the application of digital twins emerged as a key solution. The limitations of traditional methods were overcome through the use of real-time 1D SIMSEN numerical models that accurately simulate various operating scenarios, such as discharge control (without FCR provision), stand-alone FCR provision (TG-unit without BESS), FCR provision in hybrid mode (TG-unit + BESS), and benchmarking of different hybrid control strategies. By relying on numerical simulations through digital twins, the inherent uncertainties stemming from varying operational conditions and measured signal noise were effectively mitigated. This approach ensured a more precise assessment of the effectiveness of the hybrid mode, along with its associated control algorithm, in reducing wear and tear on the turbine's actuator mechanism. As a result, the integration of batteries with Kaplan turbines gains credibility as a viable strategy for increasing operational life, while providing valuable ancillary services to ensure grid stability.

Acknowledgements

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