Renewable Energy 199 (2022) 35–43

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Benefits of battery hybridization in hydraulic turbines. Wear and tear evaluation in a Kaplan prototype

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ARTICLE INFO

Keywords:
Hydropower
Frequency containment reserve
Wear and tear
Hybridization

ABSTRACT

Kaplan turbines are nowadays used to provide Frequency Containment Reserve (FCR) to the grid due to their fast capacity to regulate their power maintaining high efficiency. However, this continuous power regulation increases the wear and tear of the regulation system considerably. To reduce the amount of movements in the regulation servomotors, and thus their wear and tear, a new technology is being investigated within the frame of the European project XFLEX Hydro. This new technology is based on hybridizing the hydro unit with a small size battery in parallel, this one being in charge of compensating the small frequency fluctuations in the grid by providing or absorbing power. In this paper, the benefits of the implementation of this new technology are evaluated. A Kaplan turbine prototype located in Vogelgrun, France, has been hybridized and different parameters have been monitored while the unit was working in hybrid mode and in normal standalone hydro mode. Wear and tear of the regulation system have been compared for both hybrid and standalone hydro modes. A reduction of about 25% in servomotors mileage and of 50% in fatigue damage have been obtained by hybridizing the unit.

1. Introduction

Hydropower is today the largest renewable source in the world, generating more electricity that all the rest renewable sources together, about 15% of the world's electricity [1]. In order to transition energy systems and limit the global temperature rise, it is expected that hydropower will double its capacity by 2050 [2]. However, it is not only about installing more hydropower capacity but hydro units will have to provide flexibility to the grid by balancing the power generation as well as providing Frequency Containment Reserve (FCR) [3,4]. This means that hydropower has to be able to compensate frequency deviations in the grid with a fast response. For that, the hydraulic unit increases the power if the frequency grid goes below 50 Hz and decreases the power if the frequency grid goes over 50 Hz (50 Hz in Europe, according to ENTSO-E (European association for the cooperation of transmission system operators for electricity)). For hydraulic turbines, increasing or decreasing the output power means increasing or decreasing the flow-rate passing through the unit, thus opening or closing the guide vanes in the distributor in the case of reaction type turbines, like Francis or Kaplan turbines [5]. Furthermore, in Kaplan turbines, the runner blades position is also adjusted to have the best efficiency for every guide vane opening, known as on cam curve [6]. The regulation system of guide vanes and runner blades are generally based on oil-powered servomotors that move the guide vanes or runner blades by means of different levers and links (see Fig. 1 and Fig. 2).

The large amount of movements of the servomotors when hydraulic turbines are providing FCR could lead to wear and tear problems in the regulation system [7–9]. This is even more important in Kaplan turbines, which have more critical components due to the blades regulation system. The guide vanes rotate using a shaft which is supported by different bearings. The shaft of every guide vane is connected to a regulating ring by means of levers and links. There can be one or more servomotors which are hydraulic pistons connected to the regulating ring. Controlling the oil pressure in both side of the pistons, the opening and closing position and velocity is controlled. The mechanism for the blade opening is similar but it consists of only one hydraulic piston inside the rotating shaft which moves different levers that change the blade angle. The blade is fitted with a shaft that also is supported by a bearing (see Figs. 1 and 2).

Analyzing the components of the regulation system of both guide vanes and runner blades, the components that are prone to have wear are the bearings or bushings and the hydraulic pistons. According to

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https://doi.org/10.1016/j.renene.2022.08.117
Received 15 March 2022; Received in revised form 1 July 2022; Accepted 23 August 2022

literature [10–12], the wear rate in this kind of components is dependent on the friction materials properties and proportional to the contact pressure in the surface and the sliding distance or the mileage of the servomotor. The contact pressure in the bearings of guide vanes and runner blades in Kaplan turbines is dependent of the operating point, therefore it is different for every generating power of the turbine. The mileage of the servomotors is the accumulated distance moved during a certain period of time. About the tear or fatigue in those components, the stress in the different components is proportional to the resulting forces in those components [13,14], thus their lifetime can be obtained by knowing the stress and number of cycles in every part of the regulation system [15]. Therefore, not only the mileage of the servomotor is important but also the number of maneuvers and duration of those maneuvers.

Hybridization of hydraulic turbines with batteries is trending topic in the field of hydropower [16–19]. The application of batteries in power systems are becoming of increasing focus thanks to their decreasing cost and high ramping duties compared to conventional generation systems. The most important application is on the provision of FCR but the battery can also help to respond to power set points in few seconds, much faster than the unit standalone [20]. Whereas previously known hybridization of hydro units has consisted in full transfer of FCR to a battery system, this novel battery hybrid approach splits the FCR burden between battery and hydro unit. Battery is only in charge of providing the small changes in power due to the small frequency changes while the hydro unit still contributes to FCR for deeper or long frequency deviation. Thanks to this smart hybrid solution using a small size battery, a fast FCR is provided while on hydro unit side, the guide vanes and runner blades are moving less. However, the battery size has to be selected accurately according to the unit power output in order to be able to provide or absorb all the power fluctuations, or at least, part of them.

In this paper, the benefits of hybridization of a Kaplan turbine prototype are studied. This study is part of the XFLEX Hydro [21] European Project, which aims to provide flexibility to the grid using new technologies in hydropower. A Kaplan turbine prototype in the power plant of Vogelgrun, France, has been selected for the study. A monitoring system including several sensors was installed to measure different parameters of the turbine in operation, including guide vanes and runner blades position, oil pressure in the servomotors, vibration and other operating parameters. A battery system was installed in parallel with the unit and it was commissioned in August 2021. Since that moment the unit has been working in hybrid mode. Moreover, different tests were performed with the machine providing FCR at a constant flow-rate and head in hybrid and standalone hydro modes. Mileage, number of maneuvers and forces in the servomotors have been analyzed in detail for both modes, hybrid and standalone hydro. The comparison of the results permits evaluating the benefits of hybridizing the unit in terms of wear and tear.

2. Experimental investigation

2.1. Prototype characteristics

The prototype is located in Vogelgrun power plant, which is a 142 MW run-of-river hydropower plant in the river Rhine. The unit has a maximum power of 35 MW and a rated head of 12 m. When the unit provides FCR to the grid, the maximum available power to do so is of 4 MW in case of 200 mHz frequency deviation. The runner has 4 blades and there are 24 guide vanes. The rotating speed of the turbine is 83.3 rpm (1.39 Hz). The geometry of the runner can be observed in Fig. 1 and the one of the guide vanes in Fig. 2. The machine has two radial bearings, in turbine and generator sides, and one thrust bearing in the generator side.

The guide vanes regulating system has two servomotors located at 180° to move the regulating ring (see Fig. 1). The oil is pumped to the servomotors using a constant speed oil pump and a proportional valve. Controlling the position of the valve, the oil pressure increases or decreases in both sides of the pistons, reaching the desired opening point in both guide vanes and runner blades.

2.2. Battery characteristics

The battery has been provided by Entech and it is installed in parallel with one Kaplan unit. The total power of the battery is 650 kW with an effective capacity of 300 kWh and with voltage connection to grid of 10.3 kV. The battery size represents the 16.25% of the maximum balancing power of the hydro unit (4 MW) when providing FCR. This means that in this case, the battery will be only in charge of providing part of the power fluctuations but not the totality. This solution is rather

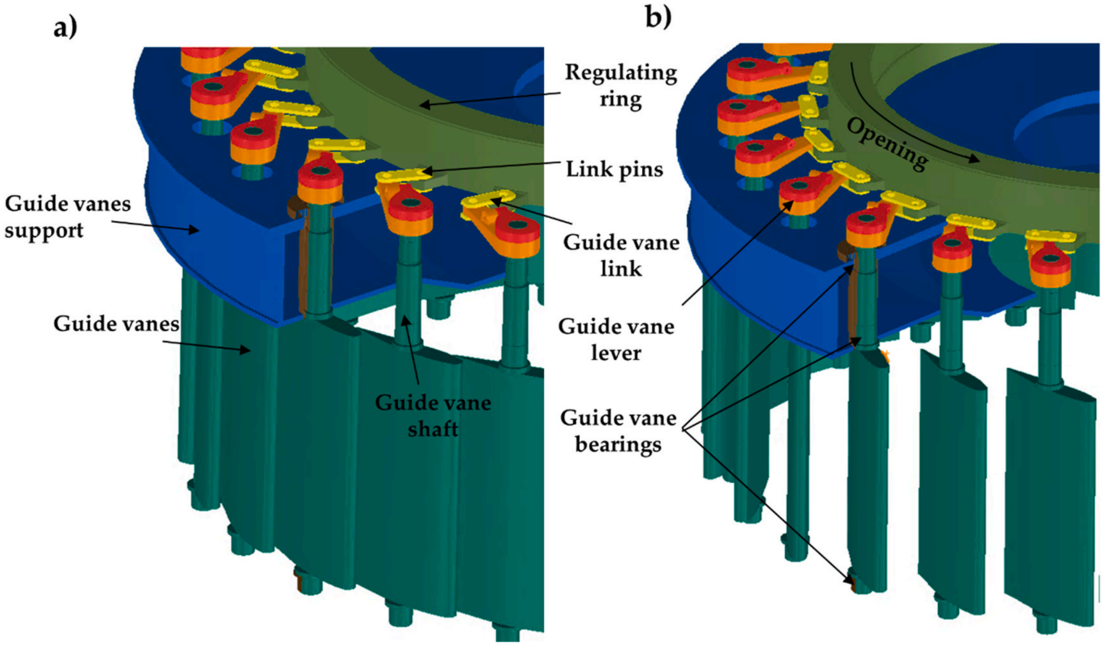

Fig. 1. Guide vanes regulation system in a Kaplan turbine. a) Maximum closing. b) Maximum opening. Geometry and CAD provided by Andritz.

less expensive than considering a battery that can absorb the totality of all the frequency fluctuations.

2.3. Instrumentation

A total of 32 sensors are installed along the unit to monitor its behavior. There are vibration sensors (9 accelerometers in the bearings, oil pumps and draft tube wall, 2 displacement sensors in the turbine bearing), pressure sensors (4 in the regulation system, 1 in the draft tube), angular displacement in one guide vane, linear displacement in the servomotors, and operating signals such as active power, current, voltage, frequency grid, water levels, battery power, battery state of charge.

2.4. Monitoring system

An MVX Oneprod monitoring system with 32 channels is used for the acquisition of the sensors. Two different acquisition strategies are programmed: one periodical every 1 h with all of the sensors and acquiring time series, frequency spectra, overall vales and band values, and other continuously in time with only the sensors related with the regulation system. For the continuous acquisition, a sample rate of 128 Hz is used.

2.5. Tests description

The machine was working continuously in standalone hydro mode since September 2020 to August 2021 and in hybrid mode since August 2021 to the present. However, during all this time, the machine was not only providing FCR but it was also providing flow regulation as needed. This fact made very difficult to separate the servomotors movements due to the flow regulation from those coming from the FCR provision. For this, it was decided to do a one-day test with the unit 4 h in hybrid mode and 4 h in standalone hydro mode with the flow and the head set to constant. In that way, the responsible of almost all of the servomotors' movements will be the FCR and the comparison between hybrid and standalone hydro will be clearer. Fig. 3 shows an overview of the tests done in standalone hydro and hybrid modes. Guide vanes, runner blades openings, head and frequency grid are shown in the plots.

3. Comparison methodology

3.1. Signal treatment

When analyzing the signals of the servomotors displacement it is important to select the best sampling frequency and to filter those movements that are not due to the power regulation. According to Gawarkiewicz and Wasilczuk [10], most of the tiny movements of the servomotors are due to external vibrations or the regulation system pumps. In this case, it is only interesting to compare those movements that are due to an actual power change in FCR mode. For this, a previous signal analysis has been perform using a power step of −4 MW (the maximum that can be found when providing FCR) and comparing different sampling frequency. In Fig. 4 one can see this step of −4 MW in terms of servomotors openings. The original sampling frequency (fs = 128 Hz) is used as a reference, and the signals have been downsampled to 10 Hz and 1 Hz. It is clearly seen in the zoom of the signals that there are very small fluctuations with an amplitude of about 0.02% and a frequency of 25 Hz. These small fluctuations are coming from the rotation of the oil pump providing the oil pressure. Therefore, for our present study, these tiny fluctuations need to be deleted to not overestimate the mileage of the servomotors. Fig. 5 shows the accumulated servomotor stroke for the time signal presented in Fig. 4. It is observed that with the sampling frequencies of 10 Hz and 1 Hz, the tiny movements are deleted and they both present the same results. Thus, the fs = 1 Hz is selected for the present study.

3.2. Mileage calculation

With the sampling frequency of 1 Hz, the mileage of the servomotors is calculated with the expression shown in Eq. (1), where x is the variable (guide vanes or runner blades openings), t the time (t_1 initial time and t_2 final time selected) and M is the mileage with the x units. The original signal coming from the servomotors lineal displacement is in %, but it can be converted to degrees or meters using the corresponding conversion. The angular displacement and linear displacement relationship with the servomotor stroke are obtained with the CAD model of the regulation system (Figs. 1 and 2).

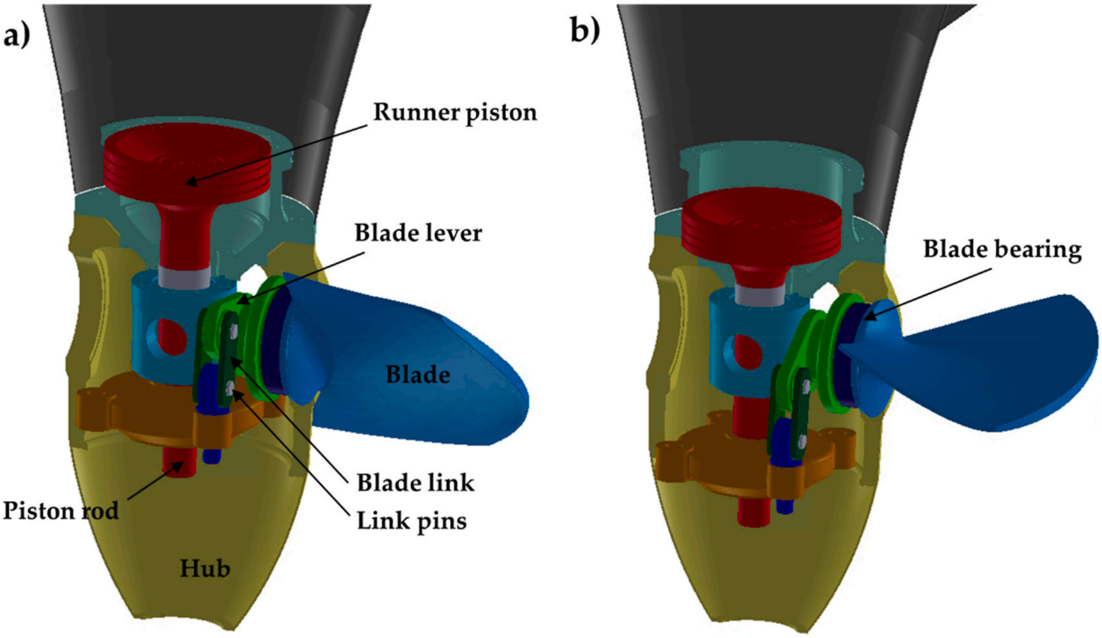

Fig. 2. Blade regulation system in a Kaplan turbine. a) Maximum opening. b) Maximum closing. Geometry and CAD provided by Andritz.

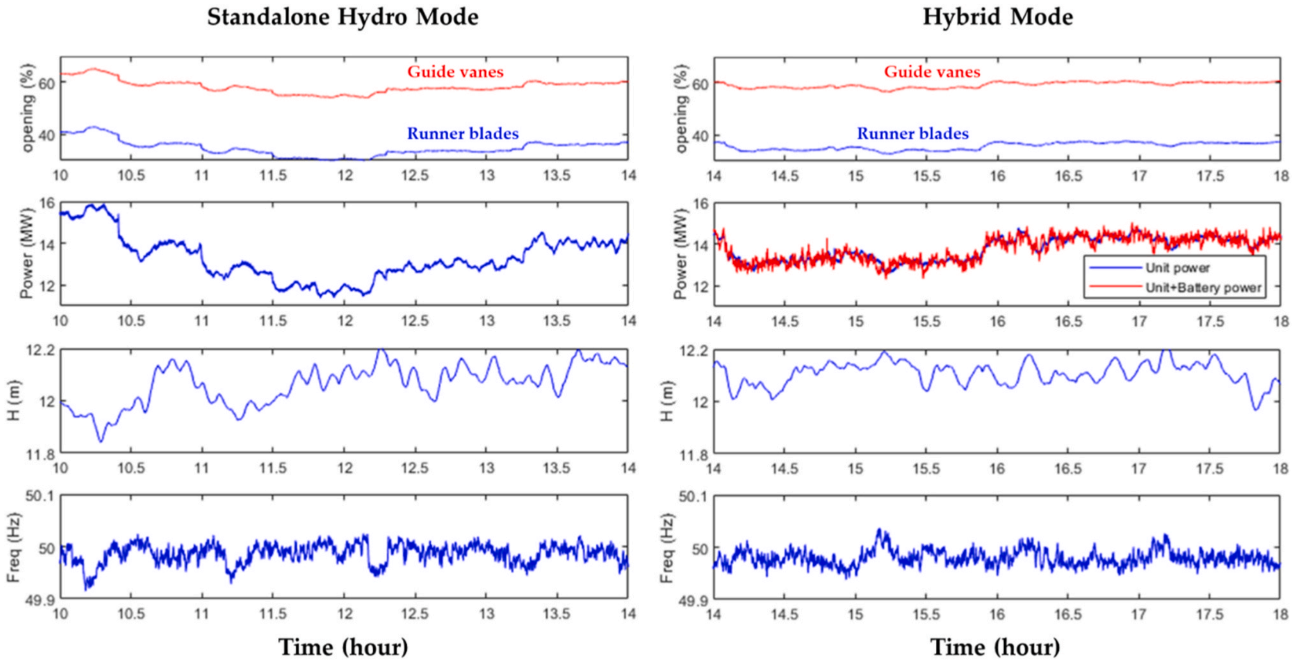

Fig. 3. Tests performed with the Kaplan turbine providing FCR to the grid in standalone hydro mode (left) and hybrid mode (right).

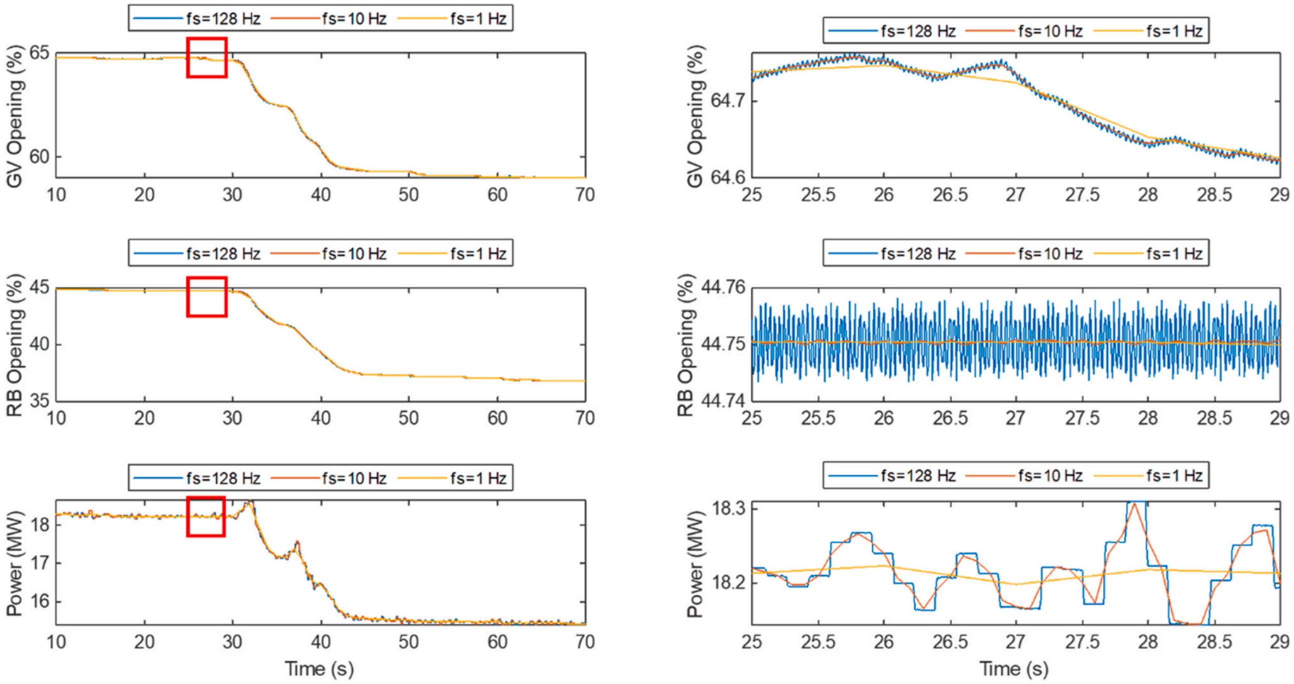

Fig. 4. Selection of the best sampling frequency for analysis. Right plots are the zoom of the red square marked in every left plot.

$$M = \sum_{t=t_1}^{t=t_2} abs(x_t - x_{t-1}) \tag{1}$$

3.3. Forces calculation

The forces in the servomotors can be obtained from the pressure in both sides of the hydraulic pistons and their area. The guide vanes are moved with two servomotors at 180° as it is seen in Fig. 6. There is one pressure used to open the guide vanes (PGVOpen) and one to close them (PGVClose). These pressures come from the regulation system oil pump and the servovalve. Therefore, the total force to move the regulating ring can be calculated as in Eq. (2). Furthermore, the averaged torque in every guide vane can be obtained by multiplying this force by the servomotor piston distance (d) and dividing by the number of guide vanes (24) (Eq. (3)). For the runner servomotor, as it is only one servomotor, the expression to calculate the force is simpler (Eq. (4)).

$$F_{GV} = PGVOpen{\cdot}A_1 - PGVClose{\cdot}A_2 - PGVClose{\cdot}A_1 + PGVOpen{\cdot}A_2 \tag{2}$$

$$T_{GV} = \frac{F_{GV}\, d}{24} \tag{3}$$

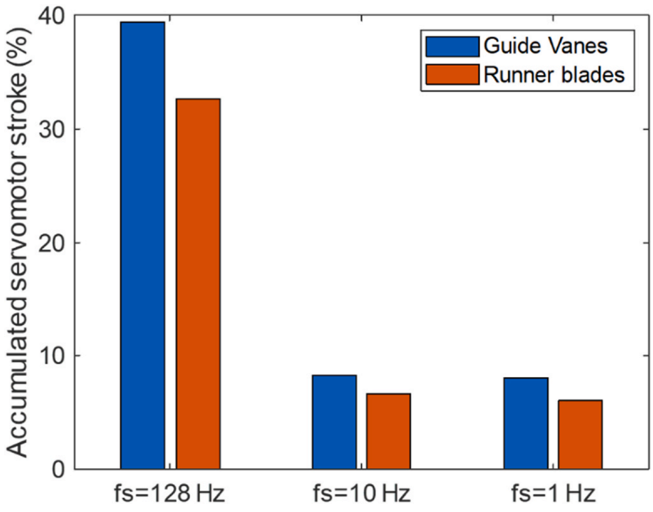

Fig. 5. Selection of the best sampling frequency for analysis. Accumulated servomotor stroke for the time-signals shown in Fig. 4.

$$F_{RB} = PRBClose \cdot A_1 - PRBOpen \cdot A_2 \tag{4}$$

3.4. Wear and tear assessment

To estimate the wear in the bearings of the regulation system, the formula presented in Ref. [11] is used, which can be summarized as in Eq. (5), where W is the wear in (μm), P is the bearing contact pressure, K is a coefficient dependent on the friction material and M is the mileage of the servomotor. In this case, K is considered as 1 (μm/(MPa*km)) according to Ref. [11] and the actual material characteristics. The P can be calculated by applying the torque in the guide vane obtained with the pressures in the servomotors (Eq. (3)) in a FEM (Finite Element Method) model and obtaining the contact pressure in the bearing surfaces. For this case, this contact pressure is estimated to be between 7 and 15 MPa depending on the operating condition and if the maneuver is to open or close the guide vane. Therefore, as a rough estimation, it can be assumed that the wear is proportional to the mileage of the servomotors.

$$W = KPM \tag{5}$$

For the tear assessment, the fatigue lifetime in the different components of the regulation system has to be determined. In a linear model of this kind, the stress of the regulating system components is proportional to the servomotor forces in the way shown in Eq. (6). a and b are constants that can be obtained by using a FEM model and they are different for the different components. According to numerical simulations of the runner blade regulating system, the most critical component is the link pin than joints the blade lever and blade link (see Fig. 2). For the guide vane regulating system, the link pins are also the critical components (see Fig. 1).

$$\sigma = a \cdot F + b \tag{6}$$

With the forces obtained measuring the servomotor pressures (Eq. (2) and (4)), the stress in the link pin of both runner and guide vanes regulating system can be calculated as shown in Fig. 7. Once the stress time history is obtained, the remaining useful life of the component can be calculated by performing a fatigue analysis. A rainflow counting algorithm [22] is used to obtain the number of cycles and their associated alternate stresses. The Goodman-Haigh correction [23] is applied to correct the mean stress and compression effects. The accumulated damage (D) in the component is calculated as in Eq. (7), where N is the number of cycles to failure and n_i the number of cycles at a certain stress amplitude s_i. Both N and ni are obtained using the SN curve of the link material, which in this case, it is obtained from the ASME Boiler & Pressure Vessel Code [24]. The remaining useful life is the inverse of the damage (D) for the studied period of time.

$$D = \sum_{i=1}^{N} \frac{n_i}{N} \tag{7}$$

4. Results

The tests presented in section 2.5 have been analyzed in detail calculating the mileage and the accumulated damage according to section 3. Four hours of hybrid mode operation and 4 h of standalone hydro (non-hybrid) have been analyzed. The results obtained are presented in the following subsections.

4.1. Mileage

The mileage of the servomotors is reduced in the hybrid mode with respect to the standalone hydro mode as it can be seen in Fig. 8. There is a reduction of about 25% for the runner servomotor and about 28% for the guide vane servomotor. The reduction is greater in the guide vanes because are the first to move when regulating, and some small power fluctuations are done by only moving the guide vanes and not the runner blades.

To check the duration of the maneuvers, histograms have been plotted in Fig. 9. It is observed that the majority of the maneuvers are of

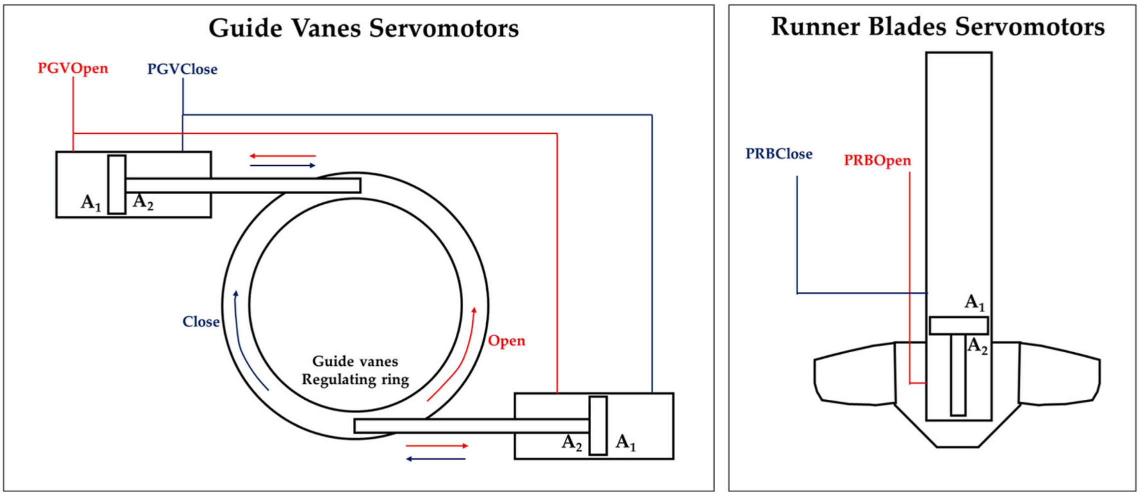

Fig. 6. Schematic of servomotors.

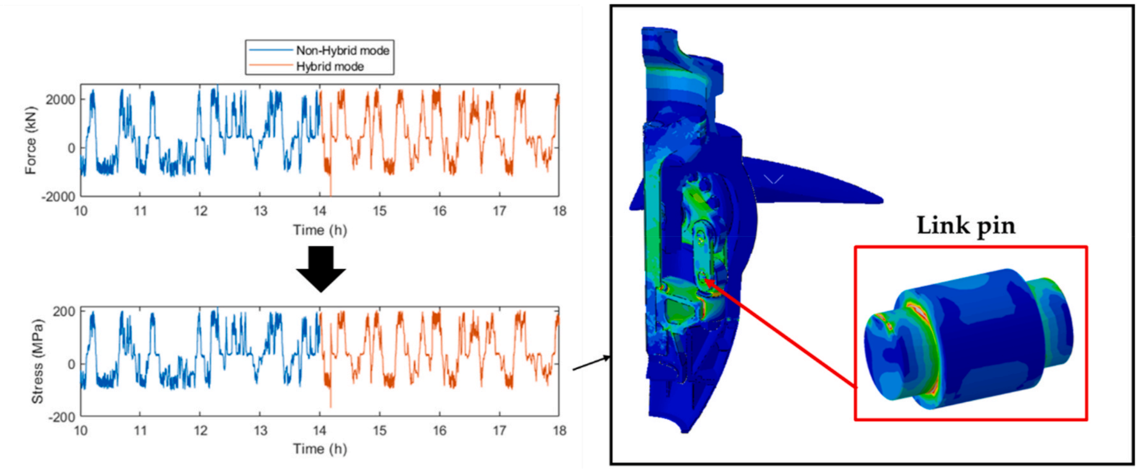

Fig. 7. Stress in the blade link pin calculated with the servomotor forces. Simulation results provided by Andritz (Colors scale: red maximum stress, blue minimum stress).

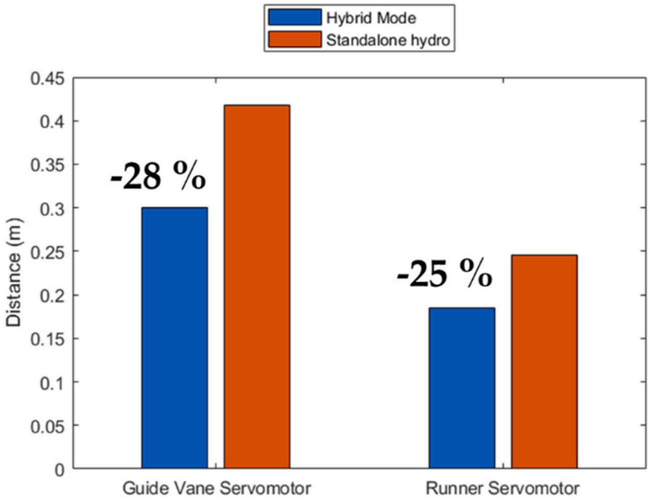

Fig. 8. Servomotors mileage for hybrid and non-hybrid mode (standalone hydro).

a short duration, between 0 and 10 s. Comparing the hybrid mode with the standalone hydro mode (non-hybrid) it is observed that there are shorter maneuvers (from 0 to 10 s) and less from 10 to 20 s or 20–30 s. The average time per maneuver it is also smaller for the hybrid mode, as well as the standard deviation. This confirms that there are more or less the same number of maneuvers in hybrid and non-hybrid mode but in hybrid mode they are of a shorter duration. This is explained by the size of the battery, which is not able to compensate completely the frequency fluctuations but it is able to reduce the mileage and time duration of the maneuvers.

4.2. Fatigue damage

The forces in the servomotors have been calculated according to Eqs. (2) and (4). Fig. 10a shows the servomotor forces against the opening. It is observed that the forces in the runner servomotor go from −1000 kN to 2500 kN for openings between 30% and 42%. For the guide vane, the forces go from 150 kN to 300 kN for openings between 54% and 65%. There is not a clear difference between hybrid mode and standalone hydro mode (non-hybrid). In fact, the maximum and minimum of the forces are exactly the same for both modes. This is because the maximum and minimum values are reached at the very initial moment of starting every maneuver, and as there are similar number of maneuvers in both modes, those values remain the same.

To assess the fatigue lifetime of the regulation systems, the procedure explained in section 3.4 has been followed. Fig. 11 shows the Goodman plots for the critical component (link pin) of both runner and guide vanes regulating system. In these graphs, the relationship mean-alternate stress is shown at the same time than the mean correction is also plotted. All the corrected points that are below the Goodman line represent very large fatigue life, whereas the ones that are above are the ones that produce the most damage. In this sense, it is seen that the runner link pin is more prone to fatigue failure than the guide vane link pin, where the stress amplitudes are smaller.

The accumulated damages for both components are shown in Fig. 12. The accumulated damage has been divided by the accumulated damage in non-hybrid mode, in that way, a relative value is shown. A reduction of 7% in damage is obtained in the guide vane critical component and a 50% reduction is obtained for the runner link pin. As shown in Fig. 11, the runner link pin stress amplitudes are higher that the ones in the guide vanes, thus, the hybrid mode is able to reduce the fatigue damage considerably, especially in the runner regulation mechanism.

5. Summary of the hybrid mode benefits

5.1. Wear and tear benefits

The hybrid mode presents less servomotors mileage (about 25–28% less) and less accumulated damage (about 7–50% less) in the critical components of the regulating systems. However, in both periods of time the frequency fluctuations were not exactly the same since this is given by the electrical grid. The flow-set point was set to constant during the tests, but the frequency could not be controlled. Fig. 13 shows the frequency variations during the periods studied. It is seen that in the non-hybrid mode, the data is centered above 50 Hz, while in the hybrid mode it is centered below 50 Hz. Nevertheless, the fluctuations are very similar in both cases, even the number of fluctuations is slightly higher for the hybrid mode. In addition to the histogram, the accumulated frequency variations can be also counted using Eq. (1). In this case, the accumulated frequency is about 5% higher in the case of the hybrid mode than in the non-hybrid mode (see Fig. 14). This fact means that the benefits obtained for the hybrid mode could be even more important for periods with exactly the same frequency variation.

Furthermore, the Vogelgrun unit used for the demonstration embedded a fairly slow time response governor meaning that the servomotors did not move as fast as they could. For faster actuators it is expected to obtain bigger benefits in terms of wear and tear. Actually,

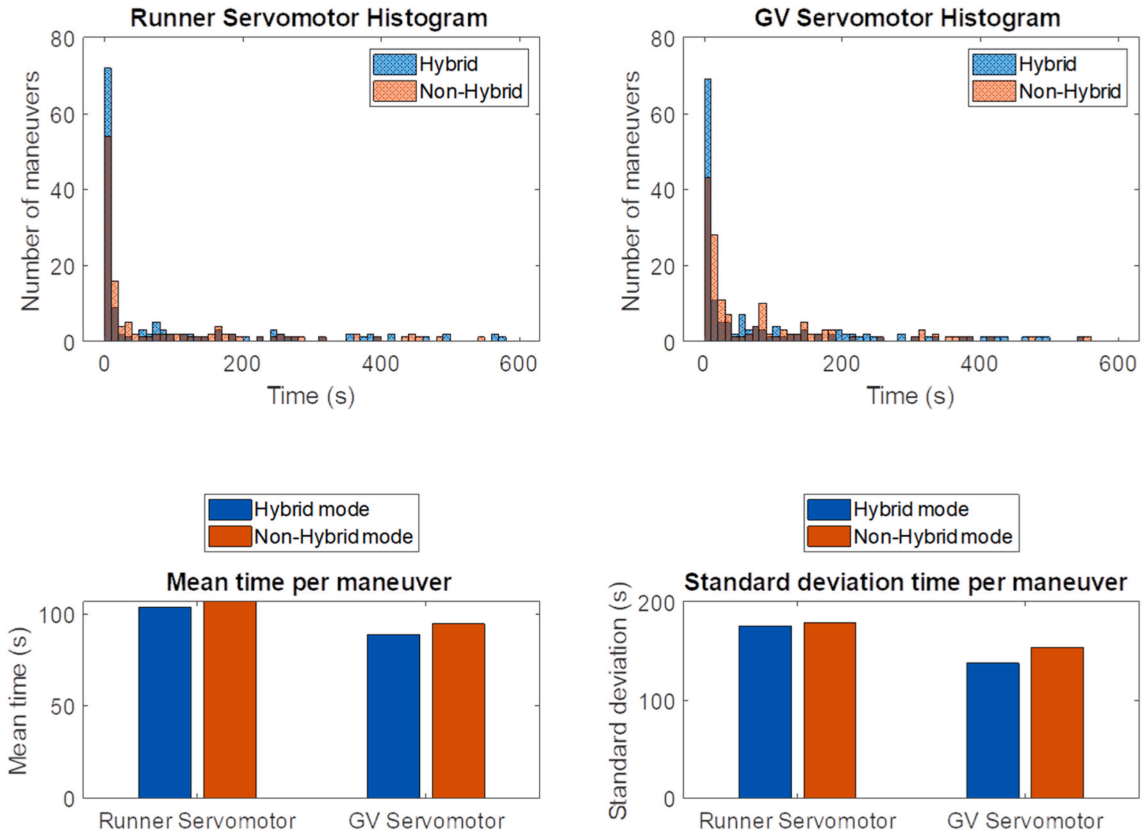

Fig. 9. Maneuvers duration statistics.

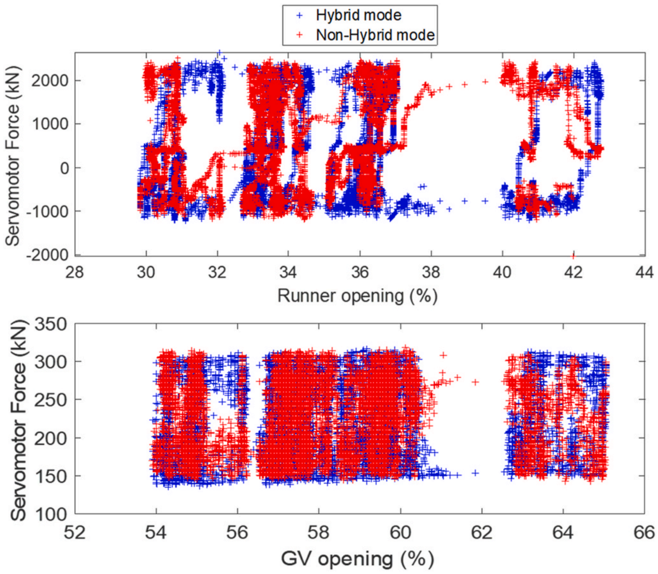

Fig. 10. Servomotor force range with respect to the opening.

the unit is running with faster response governor time since March 2022, exhibiting faster response when providing FCR.

5.2. Economic benefits

To hybridize the unit, it is necessary an initial investment which includes the battery cells, inverter, transformer, cabling, switches and other electrical equipment. In this case, the battery cells represent de 40% of the total cost of hybridizing the unit. For the purpose of helping to provide FCR to the grid, the battery capacity could be rather small, since it is charging and discharging continuously and its state of charge is almost constant at long period time. For that, one solution which is being implemented is to recycle old batteries from other applications, such as the ones of electric vehicles for example. In this way, the initial investment in the battery is rather small at the same time that technology is recycled.

The economic benefits of hybridizing hydro units are basically two: the first one is the studied in this paper, which is related with the reduction in wear and tear of the components. This implies reduction in maintenance of the unit, and at the end, less time with the unit stopped without generating electricity. The other economic benefit comes from the possibility to provide the FCR service faster. Some units are not able to provide FCR in the time needed by the regulation, and the battery can help to do that, since its response is instantaneous. This is translated in economic earnings, since providing FCR it is well paid.

In the XFLEX Project, it has been estimated a pay back of the initial investment done to install the battery of about 4–5 years. In this calculation, it has been included the wear and tear reduction obtained with the results in this paper as well as the response improvement of the battery to the FCR service.

6. Conclusions

The benefits of hybridizing hydraulic turbines with a small size battery are studied in this paper. This is a trending topic in hydraulic turbines, especially when they provide FCR to the grid. When a hydraulic turbine is providing FCR, it has to constantly regulate power to compensate the frequency fluctuations. Thus, the regulation systems of the hydraulic turbine, i.e. servomotors of the guide vanes and runner blades if the unit is Kaplan, are constantly moving, which causes wear and tear in their components. A battery in parallel helps to provide power fluctuations faster that the unit standalone and reduces the

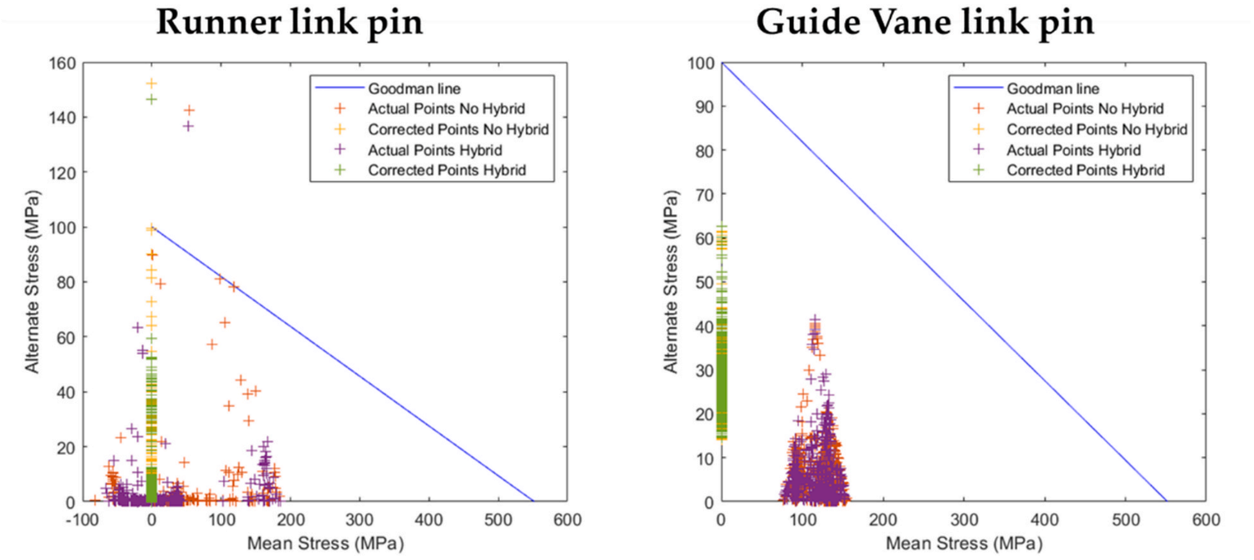

Fig. 11. Goodman plots for the critical components (link pin) of the regulating system.

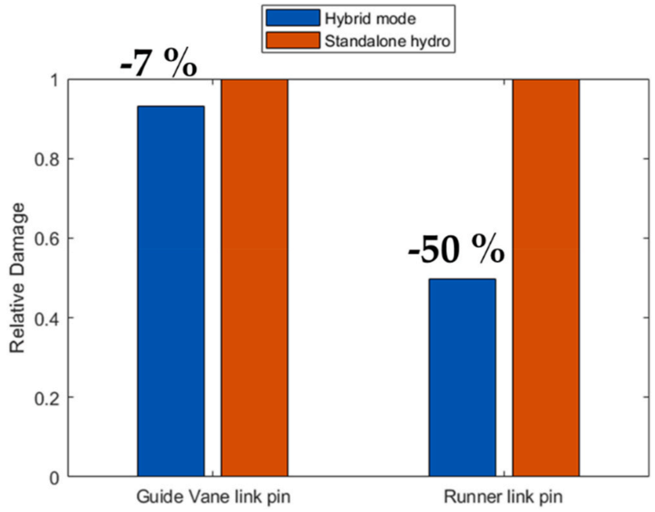

Fig. 12. Relative damage of the guide vane and runner link pins for both hybrid and non-hybrid (standalone hydro) modes.

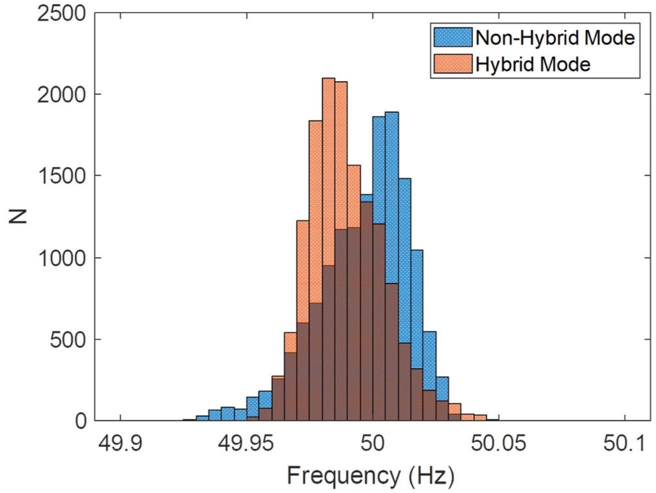

Fig. 13. Histogram of the frequency grid during the hybrid mode and the non-hybrid mode. Bars width = 5 mHz.

movements of the regulation systems, therefore reducing too the wear and tear in their components.

Within the scope of the European project XFLEX Hydro, this new technology based on hybridizing the unit with a battery is implemented. A prototype Kaplan turbine located in Vogelgrun, France have been hybridized and tested in hybrid and conventional standalone hybrid mode. To quantify the benefits of the battery, a test with constant flow rate and head with the unit providing FCR in hybrid and non-hybrid mode was performed. Servomotors mileage and fatigue damage have been analyzed and compared in detail in both modes. A comparison methodology has been developed to be sure that the differences between the measured quantities are significant.

It is observed a reduction of about 25% in the runner servomotor mileage and about 28% in the guide vane servomotor mileage, these values are considered as base values and greater benefit is to be expected with more dynamic hydro units. The number of maneuvers in both modes is very similar but they present a shorter duration and length in the hybrid mode. This is due to the fact that the battery size only represents the 16.25% of the total power that this unit is able to provide in FCR, so the battery only helps doing shorter maneuvers but not reducing

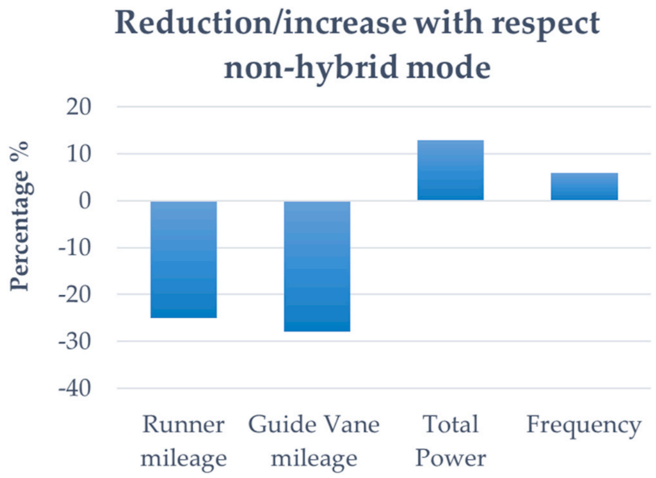

Fig. 14. Reduction of different quantities between the hybrid and non-hybrid modes.

the number of them.

A fatigue analysis has been performed for the critical components of both runner and guide vanes regulating system. The pressures in the servomotors have been used to calculate the forces in the pistons and afterwards the stress in the critical components using a numerical simulation model. A 50% of damage reduction is obtained for the critical component of the runner regulating system, which is a link pin that joints the runner lever and link. For the guide vane components, this is not that high, since the forces that they receive are smaller and so the stresses. In this case, the reduction in damage it is about 7% for the critical component.

Therefore, with the results presented in this paper it is confirmed that the battery helps to reduce the wear and tear of the turbine components when the machine is providing FCR to the grid. Furthermore, the wear and tear have been quantified with the mileage and fatigue damage reductions. In future works, the long-term wear and tear of the regulation system of this prototype will be studied, since the machine is currently working in hybrid mode since August 2021, and with faster governor response (faster servomotors movements) since March 2022.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Monica Egusquiza reports financial support was provided by Horizon 2020.

Acknowledgements

Authors would like to acknowledge XFLEX Hydro [21]. This study is a direct output implementing the new technologies that are being studied in this project. Special thanks to all the EDF staff for the help in the monitoring and instrumentation installation and to Andritz for the geometry construction, FEM calculations and technical assessment. Authors would like to acknowledge too to all the WP9 partners of the XFLEX Hydro project. David Valentín and Alexandre Presas acknowledge the Serra Húnter program.

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