frontiers | Frontiers in Energy Research

TYPE Mini Review
PUBLISHED 13 September 2024
DOI 10.3389/fenrg.2024.1478072

OPEN ACCESS

EDITED BY
Ming Liu,
The University of Tokyo, Japan

REVIEWED BY
Yadong Han,
University of Oxford, United Kingdom
Haoru Zhao,
Tsinghua University, China

*CORRESPONDENCE
Zhangbin Yang,
yang_zhangbin@ctg.com.cn

RECEIVED 09 August 2024
ACCEPTED 30 August 2024
PUBLISHED 13 September 2024

CITATION
Yang Z, Yuan H, Cai X, Lian X, Mao J and Shi X (2024) Monitoring technology of hydroturbines in pumped storage power stations: a mini review.
Front. Energy Res. 12:1478072.
doi: 10.3389/fenrg.2024.1478072

Monitoring technology of hydroturbines in pumped storage power stations: a mini review

Zhangbin Yang[1]*, Hongping Yuan[2], Xi Cai[1], Xueguang Lian[1], Jiang Mao[1] and Xiangjian Shi[2]

[1]China Three Gorges Construction Engineering Corporation, Chengdu, China, [2]NR Engineering Co., Ltd., Nanjing, China

Regarding the monitoring and control technology of pumped storage power stations, the monitoring methods for the operating parameters of the turbines in pumped storage power stations were first analyzed, including the monitoring locations and methods for pressure and vibration, as well as the analysis of the reasons for special operating conditions; Secondly, the operation monitoring and fault diagnosis system of pumped storage power stations was summarized and introduced, including the commonly used monitoring systems, fault diagnosis principles, and application situations. Finally, the development trend of turbine monitoring technology and fault diagnosis was discussed.

KEYWORDS

pumped storage power station, monitoring technology, hydroturbine, vibration, fault diagnosis

1 Introduction

In the context of global energy structure transformation, pumped storage power plants play a crucial role in the power system (Zhang et al., 2024a). As renewable energies such as wind and solar power become more widely used, the balance between supply and demand in the power system faces unprecedented challenges (Jia et al., 2024). With their unique ability to shift loads and generate power, pumped storage plants not only effectively mitigate the impact of intermittency and volatility associated with renewable energy sources but also provide quick-response reserve capacity to ensure grid stability and reliability (Zhou et al., 2024).

The pump-turbine, as the core equipment of pumped storage plants, plays a vital role in ensuring the plant's overall performance through its efficient and stable operation. The development of monitoring technologies not only allows for real-time monitoring of equipment status and prevention of failures but also optimizes operational strategies through data analysis, thereby improving the efficiency of the plant (Xiang et al., 2024). Currently, both pumped storage technology and monitoring technologies have made significant progress. Digital and intelligent monitoring systems are becoming more prevalent, including vibration monitoring, real-time analysis of performance parameters, and fault diagnosis, which greatly enhance the plant's maintenance and operation capabilities (Wang, 2024; Xu et al., 2024). However, technical bottlenecks still exist, such as resonance issues under extreme operating conditions, untimely detection and control during operations, and the effective mining and application of monitoring data.

This article aims to discuss the monitoring and control technologies of pumped storage plants. It begins by analyzing the monitoring of parameters such as pressure and vibration.

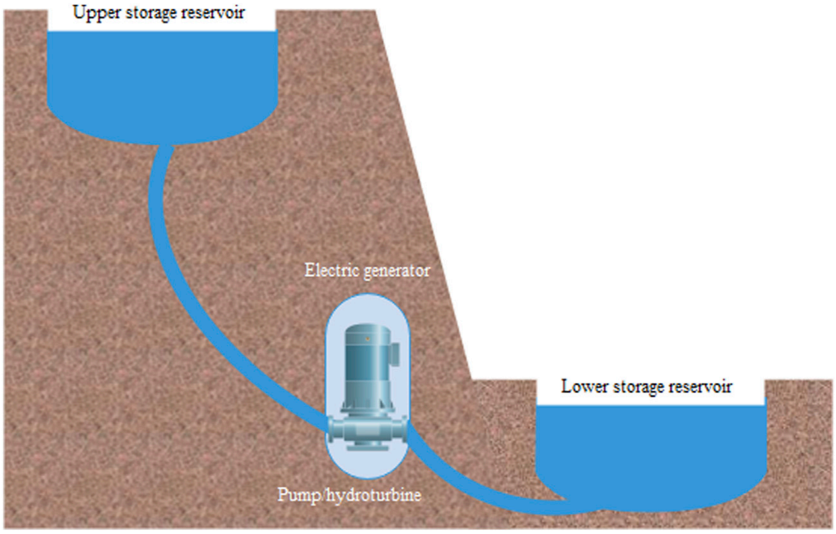

FIGURE 1
Schematic diagram of pumped storage power station.

Subsequently, it introduces the monitoring systems for these data and the forms of fault diagnosis. Finally, it explores the development trends of turbine monitoring technologies and fault diagnosis.

2 Pumped storage hydropower plants and pump-turbines

Pumped storage hydropower plants employ a clever mechanism for energy conversion and storage, with their basic operation mode consisting of two phases: pumping and power generation, as illustrated in Figure 1. During periods of low electricity demand or surplus power, the plant uses this excess power to pump water from the lower reservoir to the upper reservoir, converting electrical energy into potential energy stored in the water. When electricity demand increases, the water is released back to the lower reservoir, flowing through turbines to generate electricity, thus converting the stored potential energy back into electrical energy for use by consumers. This mechanism endows pumped storage hydropower plants with excellent peak-load regulation capabilities, enabling them to respond quickly to changes in grid loads, particularly in grids with high proportions of renewable energy sources. It plays a significant role in enhancing grid stability and promoting the transition to a more sustainable energy mix.

3 Pump-turbine operation monitoring technology

3.1 Vibration monitoring

Pump-turbine operation monitoring technology is crucial for the maintenance and predictive diagnostics of hydropower station equipment (Li et al., 2024a). The vibration monitoring of pump-turbines is a key aspect as the characteristics of vibration can reflect the health status of the internal structure of the turbine. During the startup phase of pumping operations at the Yixing power station (Jiangsu province, China), abnormal vibrations occurred in the guide vanes, leading to damage. The core issue was related to slippage in the friction device connecting the upper and lower arms, weakening control over the guide vane and causing one of them to lose control and collide with the stationary guide vane (Nennemann and Parkinson, 2010). Similarly, during the startup process for power generation at the Tianhuangping power station (Zhejiang province, China), the unit faced significant challenges, including severe vibrations in the top cover and abnormal high-pressure pulsations in the bladeless area, which directly led to the failure of grid connection attempts (Hao et al., 2024; Xu et al., 2021; Liao et al., 2022). In the Zhanghewan power station (Hebei province, China), the power station building floor experienced unusually intense vibrations accompanied by significant noise. Further investigation revealed that the vibrations were due to dynamic interference between the bladeless area of the pump-turbine and the building structure, causing resonance effects (Yu et al., 2024a; Wang et al., 2024).

Vibration monitoring includes the monitoring of parameters such as acceleration, velocity, and displacement, which reflect the vibration condition of the unit in real time (Yu et al., 2024b). For pumped storage power stations that frequently switch between energy storage and power generation modes, Li et al. (2019) used the Zhanghewan pumped storage power station as an example to discuss the causes and impacts of local structural vibrations. Force balance type sensor, piezoelectric sensor and pressure fluctuation sensor were placed at the vertical directions of vaneless area, inlet of spiral case, and under the head cover to monitor major excitation sources and the natural frequencies of the structure. It was concluded that during the design phase, it is necessary to ensure that there is no overall structural resonance or resonance between local structures and excitation sources to guarantee the stable operation of the hydropower station.

To study the vibration conditions at different locations within the power station more intuitively, Lian et al. (2024) studied the vibration of the units at the Changlong Pumped Storage Power Station (Zhejiang province, China). The sensors were placed at upper reservoir, near the horizontal and lower flat tunnel, and near the units. The results indicate that the vibration acceleration under pumping conditions was greater than that under power generation conditions, and the vibration acceleration increased with the increase of power.

3.2 Pressure monitoring

Pressure monitoring is another key method for assessing the operational status of pump-turbine equipment through the measurement of pressure distribution within the turbine (Zhang et al., 2024b; Khalfaoui et al., 2024). Pressure distribution measurements typically utilize pressure sensors (such as pressure gauges, transducers, etc.) to collect real-time pressure data at critical points of the equipment, such as the inlet, outlet, and blade gaps, to analyze the operational state of the pump-turbine (Fang et al., 2023). Previous studies have shown that the magnitude of pressure pulsations is closely related to the tongue gap (Parrondo-Gayo et al., 2002). Long et al. (2024) set up a micro pumped storage test platform equipped with inlet and outlet pressure monitors. The pressure measurement range was 0–1.6 MPa with an accuracy of 0.2% full scale (FS). The system can display pressure values in real time. Guo et al. (2024) studied the pressure fluctuations in the turbine by installing six pressure sensors from the spiral inlet to the tailrace outlet. Pressure measurements were taken under four different load conditions. The signals for pressure measurement were sampled at a frequency of 1,200 Hz to capture some high-frequency components. Furthermore, based on numerical simulation results, previous studies have found that the frequency amplitude of volute pressure pulsations increases due to cavitation in centrifugal pumps (Tan et al., 2013; Wang et al., 2015).

3.3 Remote monitoring and fault diagnosis systems

Remote monitoring and fault diagnosis systems for pump-turbines are an essential part of modern management in hydropower plants. Bently Nevada's Data Manager 2000 is an advanced data management system that can achieve remote monitoring of hydroelectric station equipment operation data through its network module. ALARM's monitoring system, which has been applied in multiple projects, features intelligent alarm functionality. This system can monitor changes in key parameters and automatically trigger alarm mechanisms when preset thresholds are exceeded. Siemens' SIMATIC PCS 7 is an advanced process control system that integrates data acquisition, process control, and alarm management, providing a comprehensive remote monitoring solution. Schneider Electric's EcoStruxure Power Monitoring Expert supports remote monitoring and data analysis, helping users optimize the performance of their power systems and promptly identify potential issues. ABB's 800xA DCS can integrate multiple subsystems to enable centralized monitoring and control of all critical processes in hydroelectric stations. GE Digital's Historian Software can efficiently collect and store large volumes of data and provides powerful analytical tools to help users gain insights into equipment operational status. Currently, the most widely used system remains the SCADA (Supervisory Control and Data Acquisition) system, due to its good applicability and maturity. It is widely used in various fields such as power and oil. The structure of the fourth-generation SCADA system is shown in Figure 2 (Borhani et al., 2024).

Fault diagnosis relies on steps such as data acquisition, feature extraction, and pattern recognition to assess the health status of the turbine and provide maintenance recommendations. Qualitative analysis for fault diagnosis, while relatively simple, has limited practicality. Zhang et al. (2020) coupled hydraulic systems with unit systems and proposed a transient model for multi-unit pumped storage systems. Analysis of the dynamic characteristics of the pumped storage system showed that transient performance could be improved by altering the movement patterns of guide vanes. With the maturation of artificial intelligence technologies, data-driven fault diagnosis methods have seen rapid development (Li et al., 2024b). Kumari and Rajchelliah (2024) employed MATLAB/Simulink establishing a model of 250 MW hydropower station and achieved fault detection and speed estimation. The effectiveness of the established model has also been verified through experiments. The fault diagnosis and control of the model can respond quickly within 20 m. Dao et al. (2024) proposed a water turbine fault diagnosis model based on Bayesian optimization (BO) and deep learning, which combines convolutional neural network (CNN) and long short-term memory (LSTM) methods. The experimental results show that the proposed BO-CNN-LSTM model achieves an accuracy of over 90% in the diagnosis of hydraulic turbine faults. Introducing the BO algorithm to optimize CNN-LSTM from the perspective of acoustic vibration signals can provide useful supplements to existing hydraulic turbine fault diagnosis. Sun et al. (2024) proposed a fault diagnosis method for hydraulic turbines based on Wasserstein Generative Adversarial Networks (WGAN). A case study using Unit 3 of the SK Power Station in China was conducted to validate the effectiveness of the fault diagnosis method. Liu et al. (2024) proposed a health condition assessment method for hydropower stations based on machine learning. The system collected vibration signals from critical components using the PSTA-2100. These signals were transmitted to the monitoring system via TCP/IP and Modbus 485 protocols. The effectiveness of this method was ultimately validated at Unit 6 of the upstream Dadu River Hydropower Station.

4 Future trends

With advancements in detection and artificial intelligence technologies, future turbine monitoring systems will become more intelligent.

1. Design Level: Big data, finite element analysis, and artificial intelligence (AI) will enhance system safety and stability. AI can assist in optimizing parameters like material selection and component dimensions, using historical data and predictive modeling.
2. Detection and Data Collection: Advanced and reliable measurement techniques will be developed, including

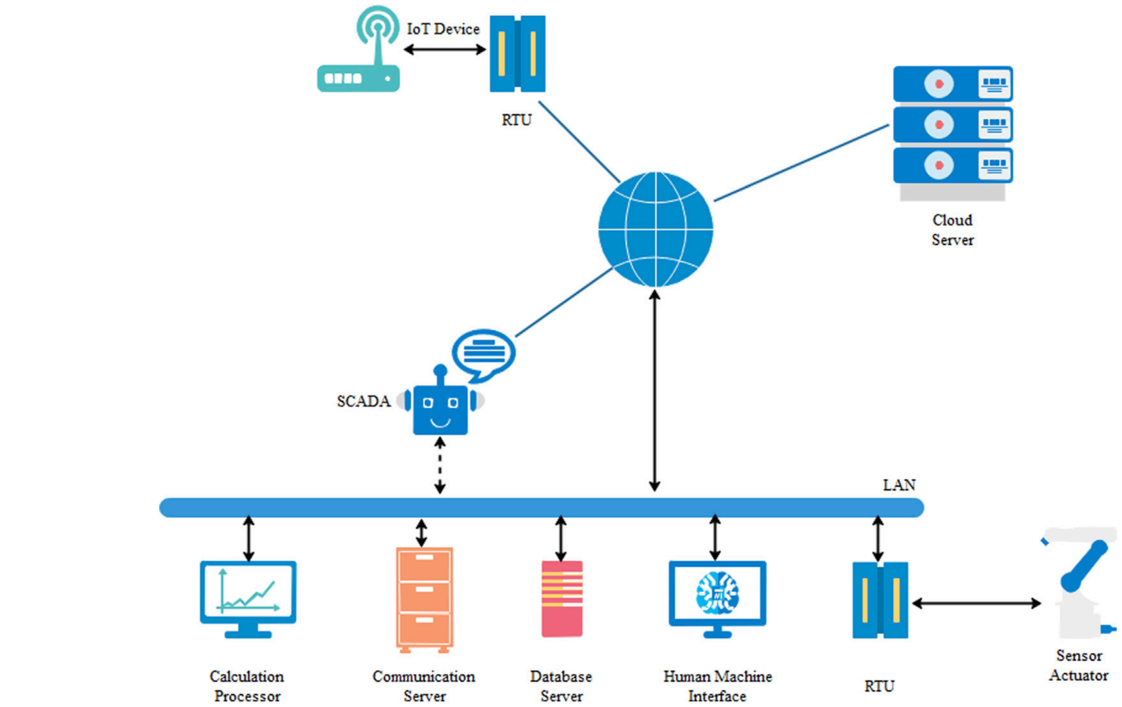

FIGURE 2
The structure of the fourth-generation SCADA system.

miniaturized, intelligent, and networked sensors such as laser and fiber optic sensors, which hold significant potential.

3. Monitoring Systems and Fault Diagnosis: The architecture and functions of intelligent monitoring systems based on the Internet of Things, big data, and artificial intelligence, along with their applications in fault prediction and performance evaluation, will become key areas of research. By integrating AI algorithms with IoT-generated data, these systems will provide advanced analytics, enabling early detection of potential failures and improving the overall performance of hydropower facilities.

5 Conclusion

With the large-scale construction of pumped storage power stations, their monitoring and fault diagnosis systems have attracted considerable attention. This paper provides an overview of turbine monitoring and fault diagnosis systems. Based on accurate monitor method and AI, faults could be predicted in advance, improving operational efficiency and ensuring safe operation of power plants.

Author contributions

ZY: Funding acquisition, Writing–original draft, Writing–review and editing. HY: Writing–original draft, Writing–review and editing. XC: Writing–original draft. XL: Writing–original draft. JM: Writing–original draft. XS: Writing–original draft, Writing–review and editing.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article.

Acknowledgments

This work was supported by Research funding from China Three Gorges Construction Engineering Corporation (No. JGJD0323010).

Conflict of interest

Authors ZY, XC, XL, and JM were employed by China Three Gorges Construction Engineering Corporation.

Authors HY and XS were employed by NR Engineering Co., Ltd.

The authors declare that this study received funding from China Three Gorges Construction Engineering Corporation. The funder had the following involvement in the study: the research, authorship, and publication of this article.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Borhani, M., Gaba, G. S., Basaez, J., Avgouleas, I., and Gurtov, A. (2024). A critical analysis of the industrial device scanners' potentials, risks, and preventives. *J. Industrial Inf. Integration* 41, 100623. doi:10.1016/j.jii.2024.100623

Dao, F., Zeng, Y., and Qian, J. (2024). Fault diagnosis of hydro-turbine via the incorporation of bayesian algorithm optimized CNN-LSTM neural network. *Energy* 290. doi:10.1016/j.energy.2024.130326

Fang, M., Zhang, F., Cao, Z., Tao, R., Xiao, W., Zhu, D., et al. (2023). Prediction accuracy improvement of pressure pulsation signals of reversible pump-turbine: a LSTM and VMD-based optimization approach. *Energy Sci. Eng.* 12 (1), 102–116. doi:10.1002/ese3.1620

Guo, B., Yu, R., Ye, Y., Li, X., and Xiao, Y. (2024). Experimental analysis of the pressure fluctuations for a prototype pump-turbine at different operating conditions. *J. Phys. Conf. Ser.* 2752 (1), 012039. doi:10.1088/1742-6596/2752/1/012039

Hao, Z. J., Wang, M. K., He, Q. Y., Shi, Q. H., Chen, H., and Ding, X. L. (2024). Redesign of adjustable guide vane cascades of pump turbine and its effect on self-excited vibrations at slight opening during pump mode's starting up process. *J. Phys. Conf. Ser.* 2752 (1), 012082. doi:10.1088/1742-6596/2752/1/012082

Jia, J., Zhang, G., Zhou, X., Shi, Z., Zhu, M., and Lv, X. (2024). Research on joint dispatch of wind, solar, hydro, and thermal power based on pumped storage power stations. *Front. Energy Res.* 12. doi:10.3389/fenrg.2024.1373588

Khalfaoui, K., Zorn, M., Ségoufin, C., André, F., Kerner, J., and Riedelbauch, S. (2024). Dynamic stress prediction for a Pump-Turbine in Low-Load Conditions: experimental validation and phenomenological analysis. *Eng. Fail. Anal.* 162, 108428. doi:10.1016/j.engfailanal.2024.108428

Kumari, R., and Raj Chelliah, T. (2024). Design and implementation of a redundant control system for variable speed hydro generators. *Int. J. Electr. Power & Energy Syst.* 156. doi:10.1016/j.ijepes.2023.109710

Li, J. W., Gu, Z. F., Zhu, H. F., Yu, J. X., and Ouyang, J. H. (2019). Study on intense vibration of local structures of Zhanghewan pumped-storage powerhouse. *IOP Conf. Ser. Earth Environ. Sci.* 240. doi:10.1088/1755-1315/240/8/082008

Lian, J., Zuo, L., Wang, X., and Yu, L. (2024). Ambient vibration analysis of diversion pipeline in mount Changlong pumped-storage power station. *Appl. Sci.* 14 (5), 2196. doi:10.3390/app14052196

Liao, W., Zhang, Y., Ding, T., Fang, J., Ju, P., Xie, D., et al. (2022). Performance and economy analysis of distributed small-scale pumped storage power station. *IOP Conf. Ser. Earth Environ. Sci.* 983 (1), 012014. doi:10.1088/1755-1315/983/1/012014

Liu, Y., Liu, J., Zhang, F., Gao, H., and Yuan, X. (2024). Data-model interactive health condition assessment for hydropower unit. *J. Phys. Conf. Ser.* 2752 (1), 012020. doi:10.1088/1742-6596/2752/1/012020

Li, X., Zhang, J., Xiao, B., Zeng, Y., Lv, S., Qian, J., et al. (2024b). Fault diagnosis of hydropower units based on gramian angular summation field and parallel CNN. *Energies* 17 (13), 3084. doi:10.3390/en17133084

Li, Z., Liu, F., Cai, G., Ding, J., and Chen, J. (2024a). Method of non-stationary random vibration reliability of hydro-turbine generator unit. *Acta Mech. Sin.* 40 (9), 523427. doi:10.1007/s10409-024-23427-x

Long, Z., Xu, R., Wu, J., Qian, T., and Shu, L. (2024). Experimental study on micro-pump turbine test bed and pump performance under working conditions. *J. Phys. Conf. Ser.* 2741 (1), 012034. doi:10.1088/1742-6596/2741/1/012034

Nennemann, B., and Parkinson, É. (2010). YiXing pump turbine guide vane vibrations: problem reso lution with advanced CFD analysis. *IOP Conf. Ser. Earth Environ. Sci.* 12, 012057. doi:10.1088/1755-1315/12/1/012057

Parrondo-Gayo, J. L., Gonzalez-Perez, J., and Fernandez-Francos, J. (2002). The effect of the operating point on the pressure fluctuations at the blade passage frequency in the volute of a centrifugal pump. *J. Fluids Eng. Trans. ASME* 124 (3), 784–790. doi:10.1115/1.1493814

Sun, W., Zou, Y., Wang, Y., Xiao, B., Zhang, H., and Xiao, Z. (2024). Fault diagnosis in hydroelectric units in small-sample state based on Wasserstein generative adversarial network. *Water* 16 (3), 454. doi:10.3390/w16030454

Tan, L. E. I., Zhu, Liang, C. S., Chuan, W. Y., and Bin, W. B. (2013). Numerical simulation of unsteady cavitation flow in a centrifugal pump at off-design conditions. *Proc. Institution Mech. Eng. Part C J. Mech. Eng. Sci.* 228, 1994–2006. doi:10.1177/0954406213514573

Wang, YUCHUAN, Tan, Cao, S., and Gui, S. (2015). Numerical study on characteristics of unsteady flow in a centrifugal pump volute at partial load condition. *Eng. Comput. Int. J. computer-aided Eng. Softw.* 32 (6), 1549–1566. doi:10.1108/ec-05-2014-0109

Wang, J., Min, L., Zhang, J., and Yan, B. (2024) "The characteristics and main building layout of pumped storage power stations in China in recent years," in *Proceedings of the 2024 7th international conference on structural engineering and industrial architecture (ICSEIA 2024)*, 428–440. doi:10.2991/978-94-6463-429-7_45

Wang, Z. (2024). A review of the application of neural networks and global optimization algorithms in hydroturbine optimization. *J. Simul.* 12 (1), 23.

Xiang, C., Xu, X., Zhang, S., Qian, H., and Duan, Z. (2024). Current situation of small and medium-sized pumped storage power stations in Zhejiang Province. *J. Energy Storage* 78, 110070. doi:10.1016/j.est.2023.110070

Xu, B., Zhang, L., Zhang, W., Deng, Y., and Wong, T. N. (2024). Data-driven modal decomposition methods as feature detection techniques for flow fields in hydraulic machinery: a mini review. *J. Mar. Sci. Eng.* 12 (5), 813. doi:10.3390/jmse12050813

Xu, L., Liu, Z., and Zheng, S. (2021). Exploration on planning and development of pumped storage power stations in China. *IOP Conf. Ser. Earth Environ. Sci.* 781 (4), 042058. doi:10.1088/1755-1315/781/4/042058

Yu, S., Zeng, Y., Dao, F., Li, X., Xu, Y., and Qian, J. (2024b). Calculation method for natural frequency and damping ratio of hydropower units based on motion model separation. *J. Phys. Conf. Ser.* 2752 (1), 012051. doi:10.1088/1742-6596/2752/1/012051

Yu, X., Zhang, S., Zhang, X., Yin, X., Qiu, W., Wang, Z., et al. (2024a). A review of the recent research on hydraulic excitation-induced vibration in hydropower plants. *J. Phys. Conf. Ser.* 2752 (1), 012093. doi:10.1088/1742-6596/2752/1/012093

Zhang, H., Guo, P., and Sun, L. (2020). Transient analysis of a multi-unit pumped storage system during load rejection process. *Renew. Energ.* 152, 34–43. doi:10.1016/j.renene.2019.12.111

Zhang, J., You, B., Li, X., Li, C., Chen, K., Peng, Y., et al. (2024a). MicroPSCal: a MicroStation package for storage calculation of pumped storage power station during planning and designing. *Energy Rep.* 11, 3005–3015. doi:10.1016/j.egyr.2024.02.057

Zhang, P., Cheng, Y., Liu, D., and Zheng, J. (2024b). Variations of flow patterns and pressure pulsations in variable speed pump-turbine during start-up process. *J. Phys. Conf. Ser.* 2752 (1), 012068. doi:10.1088/1742-6596/2752/1/012068

Zhou, Y., Zhu, Y., Luo, Q., Wei, Y., Mei, Y., and Chang, F.-J. (2024). Optimizing pumped-storage power station operation for boosting power grid absorbability to renewable energy. *Energy Convers. Manage* 299. doi:10.1016/j.enconman.2023.117827