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Review on Simulation of Hydraulic Turbine Regulation System

Yongkang Fu, Yiqiang Yang

School of Automation and Information Engineering, Sichuan University of Science & Engineering, Zigong 643000, China

Abstract

This paper presents a comprehensive review of simulation studies on hydroturbine control systems. The hydroturbine serves as a crucial component for harnessing hydroelectric energy, and its control system plays a central role in maintaining the stability of hydroelectric units and ensuring the production of high-quality electrical energy. The importance of hydroelectric energy, the current status of simulation studies on hydroturbine control system models, parameter identification research, and the state of control strategy research are introduced in this paper. Through an exploration of these topics, this study aims to provide diverse perspectives and methodologies for the simulation research of hydroturbine control systems.

Keywords

Hydraulic Turbine Regulation System; Hydropower Energy; Parameter Identification; Control Strategy.

1. Introduction

The hydroturbine generator unit is an integral component of hydroelectric stations, converting water energy into electrical energy to meet the energy demands of production and daily life[1]. Electric power consumers not only have high requirements for power supply safety and reliability but also demand superior power quality to ensure safe production and living conditions. This necessitates maintaining grid frequency within a narrow range. According to regulations set by the power sector in our country, the rated frequency of the power grid is 50Hz, with a permissible deviation of no more than 0.2Hz.However, the continuous fluctuation in power loads can lead to frequent variations in grid frequency. Therefore, the hydroturbine control system, as the core component of hydroturbine generator units, plays a crucial role in adjusting the output power of the hydroturbine generator unit in real-time, based on the constantly changing power load of the power system, to maintain the unit frequency within the specified range. The hydroturbine control system is a comprehensive automation system that includes a governor and a controlled system. As a key control device ensuring the safe and stable operation of hydroturbine units, the control accuracy and response speed of this system are directly related to the electrical energy quality of hydroelectric power generation, thereby influencing the stable operation of the power system[2].

2. Importance of Hydropower Energy

Energy serves as the foundation and driving force for the survival and development of human society. It is crucial for the prosperity and development of nations, the improvement of people's lives, and the long-term stability of societies. With the further development of modern industrialization, the demand for energy in society is increasing. The decrease in fossil coal energy and the growing demand for energy pose a significant contradiction, hindering social development and the well-being of the people.As modern technology advances, there is a push for the rapid development of new energy sources. In the past five years, renewable energy has contributed to approximately 60% of the world's newly added electricity generation capacity. The world has embarked on a new journey to address climate change, with over 130 countries and regions committing to carbon neutrality goals. Accelerating the transition to low-carbon energy has become a global consensus.In China, the optimization of the energy structure has been ongoing, with the proportion of non-fossil energy consumption reaching around 16.6%. The '14th Five-Year Plan' period is a critical and urgent window for achieving carbon peaking. The transformation of energy development is more pressing than ever, as countries worldwide recognize the need for a low-carbon transition in response to the challenges of climate change.

In the realm of electrical power energy, hydroelectric power is increasingly becoming the preferred choice in many countries' energy development plans due to its cleanliness, ease of development, and low operational costs. Since the beginning of the '14th Five-Year Plan,' China's hydropower industry has made significant strides. Large-scale conventional hydropower projects such as Wudongde, Baihetan, and Lianghekou, as well as a series of pumped storage projects including Fengning, Changlongshan, Dunhua, Meizhou, Yangjiang, Huanggou, Zhouning, and Yimeng, have been put into operation. Especially in 2021, the national newly added hydropower grid-connected capacity reached 23.49 million kilowatts, marking the highest annual figure since the '13th Five-Year Plan.' As of now, the total installed hydropower capacity in the country has reached 400 million kilowatts, maintaining its position as the world's number one for 17 consecutive years, with pumped storage exceeding 40 million kilowatts. Hydropower, as a high-quality and clean renewable energy source, holds an exceptionally important position in China's energy development strategic layout.

3. Research Significance

The hydroturbine control system is a complex nonlinear control system that integrates hydraulic, electrical, and mechanical subsystems. It mainly consists of subsystems such as the governor, servo system, hydroturbine, water intake system, and generator. Due to the constraints of objective conditions in hydropower stations, conducting actual experiments on the hydroturbine control system poses significant challenges. Therefore, modeling and simulation for theoretical analysis of the system are essential.In traditional power system analysis, an ideal hydroturbine model under rigid water hammer conditions is often used. While this model partially reflects certain characteristics of the hydroturbine, it cannot meet the requirements for fine-grained simulation of Hydroturbine Regulation Systems (HTRS). When there are changes in system operating conditions, significant external disturbances, or large load fluctuations, the traditional hydroturbine model fails to capture the dynamic changes in the system. This necessitates a more refined Hydroturbine Governor System (HTGS) model.An accurate system model is the foundation and prerequisite for optimizing control parameters, designing, and applying advanced control systems. Therefore, constructing a hydroturbine control system model and conducting parameter identification for the model are crucial aspects.

The hydroturbine governor serves as a crucial component for achieving the efficient and orderly operation of the hydroturbine control system, playing an integral role in ensuring the safe and stable operation of the unit. PID control, known for its simplicity and robustness, is widely applied in hydroturbine control systems. Consequently, the effectiveness of PID control parameters in hydroturbine regulation systems significantly influences the quality of electrical energy output and the stable operation of hydroelectric units.However, traditional PID control faces challenges when the unit's operating state deviates from the set operating point. It struggles to restore the system to a stable state, requiring manual parameter tuning based on experience. Therefore, researching PID parameter optimization methods for hydroturbine regulation systems to enhance the governor's control performance holds paramount significance for the efficient and stable output of hydroelectric units.

With the continuous expansion of the scale and increasing interconnection of power systems, as well as the large-scale integration of intermittent energy sources such as wind and photovoltaics, the

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structure of power systems has become more complex. The operating modes of dispatch have undergone profound changes, and the uncertainty of the system has intensified, leading to a growing risk in the secure and stable operation of the power grid. Hydropower is a high-quality and economical peak-load and frequency-regulating power source. Hydropower units possess characteristics such as rapid start-stop capabilities, flexible operational transitions, and a wide adjustment range, playing a crucial role in the safe and economical operation of power systems.Additionally, with the widespread deployment of pumped storage in the power grid, it has gradually become irreplaceable in aspects such as peak shaving, frequency and phase regulation, and emergency backup in power systems. With the introduction of the concept of "building a strong smart grid" and the implementation of related policies, there is an increasing demand from power production departments, power supply companies, and users for higher levels of automation in power equipment, improved stability in power systems, and enhanced power quality.As a vital component of the power system, hydropower units are complex and exhibit non-minimum phase characteristics and hydraulic-mechanical-electrical coupling nonlinearities. Advanced control research on hydropower units is of paramount importance for addressing key scientific issues such as achieving efficient and economic unit operation, maintaining the safety and stability of power systems, and enhancing power quality.

4. Research Status of Hydraulic Turbine Regulation System Model

Due to constraints in on-site conditions at hydroelectric stations, conducting real-machine experiments on hydroturbine control systems is often impractical. As a result, researchers frequently resort to system mechanism analysis and utilize computer simulation software to model and simulate hydroturbine control systems. Analyzing the operational mechanisms of hydropower units and establishing comprehensive and detailed simulation models for hydroturbine control systems hold significant importance. This approach is commonly adopted by modern researchers for understanding the dynamic characteristics of hydroturbine control systems and enhancing the control performance of the system.

The hydroturbine control system can be divided into two main components: the controller and the controlled object. Currently, controllers mostly adopt parallel PID control. The controlled object encompasses the servo system, pressure pipeline, water intake pipeline, hydroturbine, and generator, among other parts. The governor, composed of the controller and the servo system, is the core component of the hydroturbine control system. It adjusts the opening of the hydroturbine's guide vanes based on the different operating modes of the hydroturbine and the current values of parameters such as unit speed, generated power, gate opening, and load, aiming to control the hydropower unit to output a stable desired speed and power.As the capacity of units and the scale of the power grid continue to expand, the control algorithms of governors need constant innovation. From PI algorithms, PID algorithms, variable-parameter PID algorithms to modern intelligent control algorithms such as predictive control[3], fuzzy control[4], sliding mode control, and neural network control[5], the introduction of these new control methods provides fresh perspectives for the control of hydroturbine regulation systems. It opens up new feasible directions for the more efficient control of hydropower units.

Generator models commonly used in simulation experiments for hydroturbine control systems include first-order, second-order, third-order, fifth-order, and seventh-order models. Among these, the first-order generator model is the most frequently employed in hydroturbine control system simulations[6]. However, with the further development of interconnected power grids and the need for detailed system analysis, the first-order generator model is no longer sufficient to meet the requirements of hydroturbine control system simulation experiments.To address this, scholars have explored higher-order generator models for simulation research. For instance, in references [7] and [8], second-order generator models were utilized, while references [9] and [10] employed third-order generator models.

Within the water intake pipeline, the water hammer effect arising from the inertia of the water flow exerts a significant and unavoidable influence on the analysis of system dynamic characteristics. In most cases, the water intake pipeline neglects elasticity and adopts a rigid water hammer model.The modeling research of hydroturbines is a crucial prerequisite for the control and optimization of hydroturbine regulation systems, and it can be broadly categorized into linear and nonlinear models. Linear models include rational models, 6-coefficient hydroturbine models, transfer function models, and others. Nonlinear models encompass analytical nonlinear models, comprehensive characteristic curve models, inner characteristic models, and nonlinear models based on neural networks.

5. Research Status of Parameter Identification of Hydraulic Turbine Regulation System

Obtaining an accurate mathematical model and parameter values for the hydroturbine control system is fundamental for further control optimization. Therefore, the parameter identification of the governing system is crucial. Researchers have explored identification methods, and the parameter identification approaches for the hydroturbine control system can be classified into the following three categories.

(1) Least Squares Method

The least squares method, as a classical approach in system identification, possesses advantages such as simple principles, fast convergence, and ease of implementation. Due to these characteristics, it is widely applied in the parameter identification of hydroturbine control systems.

(2) Neural Network Identification

Neural networks, by simulating the connections of neurons in the human brain, possess advantages such as autonomous learning, associative storage, and high-speed optimization. These characteristics make neural networks suitable for nonlinear system identification in hydroturbine control systems. The identification process involves optimizing the neural network model based on input-output data and error criteria to approximate the system under identification.

(3) Intelligent Algorithm Identification

Intelligent optimization algorithms, by imitating the behavioral patterns of certain intelligent organisms or physical phenomena, engage in random searches to seek optimal solutions. These algorithms exhibit strengths in adaptability and short convergence time, making them suitable for handling complex optimization problems that traditional optimization techniques may struggle with. In recent years, swarm intelligence algorithms have been frequently introduced into the parameter identification of hydroturbine control systems, achieving notable results.

Model Predictive Control (MPC) is a closed-loop optimization control strategy developed based on predictive models and has been widely applied in complex industrial processes. MPC comprises three fundamental characteristics: predictive models, rolling optimization, and feedback correction. This algorithm has a low requirement for the accuracy of mathematical model building, primarily relying on predictive models. It introduces feedback correction strategies, correcting the actual output based on the error between the measured output and the predicted output. MPC utilizes a rolling local optimization instead of traditional global optimization, to some extent overcoming the impact of system modeling errors and certain uncertainties.Moreover, MPC can effectively handle model mismatch situations and multi-constraint control problems. It achieves optimization control for multiple objectives and exhibits good control performance for pure lag systems, non-minimum phase systems, and nonlinear control processes. Therefore, MPC methods partially address the challenge of nonlinear and precise modeling in hydroturbine regulation systems. Additionally, MPC meets the high requirements for real-time monitoring of the state of hydroturbine regulation systems.

6. Research Status of Control Strategy of Turbine Regulation System

With the continuous expansion of the power grid scale, increasing interconnection, and the large-scale integration of intermittent energy sources such as wind and photovoltaics, the requirements for the control performance of hydroturbine regulation systems in the power sector are also escalating. Consequently, researchers have explored various novel control strategies.

(1) PID Control

PID control is widely applied in the control field due to its clear structure and good stability. However, conventional PID control may fall short in meeting the demands for control precision and responsiveness when dealing with complex characteristics such as time variation and nonlinearity in the controlled objects. In response to this, experts have proposed various optimization methods to improve conventional PID control.There are two categories of PID parameter tuning methods:1)Traditional methods, such as the Ziegler-Nichols algorithm, pole placement method, optimization test method, gradient search algorithm, orthogonal experiment method, etc. These methods have rigorous logic and clear calculation processes. However, they are inefficient, and their effectiveness is compromised for hydroturbine regulation systems with severe nonlinear characteristics.2)Intelligent optimization algorithms, including Genetic Algorithm (GA), Gravitational Search Algorithm (GSA), Differential Evolution Algorithm (DE), Particle Swarm Optimization (PSO), etc. These algorithms essentially optimize the objective function and are not dependent on the structure of the optimization object. They can effectively handle nonlinear problems and are suitable for optimizing parameters in hydroturbine regulation systems.

(2) Intelligent Control

Intelligent control is a control approach characterized by intelligent information processing, feedback, and decision-making. It is utilized to address control problems in complex systems that traditional control methods may struggle with, such as systems with uncertain mathematical models or high nonlinearity. Intelligent control mainly includes neural network control, fuzzy control, and expert control.

(3) Nonlinear Control

As the demand for control precision continues to increase, nonlinear control has emerged and experienced significant development in the 21st century. Nonlinear control primarily includes robust control, predictive control, sliding mode control, and others. These nonlinear control methods are also widely applied in the control of hydroturbine regulation systems.

7. Conclusion

With the continuous expansion of the power grid and the large-scale integration of intermittent energy sources such as wind and photovoltaics, there has been a growing demand in the power sector for enhanced control performance of hydroturbine regulation systems. To meet this challenge, researchers have actively explored various novel control strategies.

Firstly, PID control, as a classical method, is widely used due to its clear structure and stability. However, traditional PID control may face challenges in control precision and responsiveness when dealing with complex systems. To improve PID control, experts have proposed various optimization methods, including traditional parameter tuning methods and intelligent optimization algorithms.Secondly, intelligent control methods, such as neural network control, fuzzy control, and expert control, utilize intelligent information processing and decision-making to address control problems in complex systems with uncertain mathematical models and high nonlinearity. These methods provide flexible control approaches for hydroturbine regulation systems.Lastly, nonlinear control methods, including robust control, predictive control, and sliding mode control, have gained widespread application, especially in response to the increasing demand for control precision. These methods have found practical applications in hydroturbine regulation systems, offering new directions for improving control performance.

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In conclusion, in response to the elevated requirements for control performance in hydroturbine regulation systems in the power sector, researchers have provided diverse solutions through the optimization of PID control, the application of intelligent control methods, and the development of nonlinear control methods.

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