Novel Hydraulic Turbine Governing System

Based on Digital Cartridge Valve Technology

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Abstract. Digital cartridge governor, as a new direction of hydraulic turbine governor control, has been applied in engineering practice, but its relative theory and engineering application research are few. The engineering application of novel hydraulic turbine governing system based on digital cartridge valve technology is taken as the research object in this paper. Combining theory with engineering application, control strategies and rules of the digital cartridge turbine governor in key concerns of engineering applications such as closed-loop power regulation, isolated grid operation, the low-frequency de-excitation and the over-speed of load rejection of bulb turbine units are discussed, and engineering applications of digital cartridge turbine governor are summarized, which can be used for reference to solve some problems in the application of governor.

Keywords: microcomputer governor; turbine; cartridge valve; high-speed switching valve;

1. Introduction

As an important equipment for controlling hydro-generating units [1], the hydraulic turbine governing system undertakes a very important control task and plays a very important role in the hydropower regulating system. Since the birth of hydraulic turbine governor, its development history has undergone great changes, including mechanical hydraulic speed governor at the beginning of the 20th century, electrical hydraulic governor widely used in the 1950s [2] and the microcomputer governor that is universally applied at the present stage [3]. With the wide application of programmable logic controller (PLC) and programmable computer controller (PCC) [4] in the industrial automation industry since the 1990s, PLC or PCC is applied as the core controller by the relevant research and manufacturing units to the turbine governor control, which promotes the development of the microcomputer governor and obtains a wide range of engineering applications in the hydropower plant.

The traditional classical microcomputer governor is the governor with this structure model, where the microcomputer governor mainly takes the medium and small-sized PLC or PCC as the core controller, the hydraulic servo system generally uses the main distribution, and the electrical and mechanical connection makes the conversion device. The biggest difference of the microcomputer governor which uses traditional structural mode is to use different electrical/mechanical, electrical/hydraulic conversion elements as their electrical/mechanical conversion devices, and usually adopt proportional valves, servo valves, stepper motors and other hydraulic components. The static and dynamic performance of the conventional microcomputer governor have been greatly improved by the upgrade of the electric/machine conversion components. The main control valve commonly uses main distribution valve, whose slide valve structure easily causes the frequent start and stop of oil pump due to block and large leakage caused by maintenance cumbersome and oily deterioration.

The quality of the hydraulic turbine governor is largely determined by the control strategy of the microcomputer controller [5], the response speed of the hydraulic servo system and the adjustment accuracy. The main control strategy of governor mainly includes conventional PID control, which is intelligent control strategy represented by artificial neural network, fuzzy control, genetic algorithm [6,7]. At present, the conventional PID variable parameter control is the main application of the governor project, and the intelligent control strategy is mainly applied to the simulation analysis and
theoretical research. However, since the successful development of the microcomputer governor, the hydraulic servo system has been using the main distribution valve and the electric/machine conversion device structure mode [8], and the problem that the structure of main distribution valve restricts the development of governor has not been solved well.

Research team of hydro-turbine governor at China Institute of Water Resources and Hydropower Research has analyzed the problems of traditional microcomputer governors according to a large number of field tests of hydropower stations. The digital cartridge turbine governor prototype [9], which takes high-speed switching valves and cartridge valves as the main hydraulic components, was successfully developed using advanced hydraulic, automation and other technology in 1999, and successfully applied in the 2×18MW Francis turbine units of the Xigou hydropower station in Heilongjiang Province in May 2001 [10]. For more than 20 years from the success of research and development to the market popularization, the research results have obtained a wide range of engineering applications around the world, and achieved good results in engineering applications. However, it is found according to the relevant literatures at home and abroad that the theoretical research and engineering application analysis of application of cartridge valve technology to the microcomputer speed governor is less. Most of the literatures are based on the test of hydraulic turbine governor in a hydropower plant to discuss its engineering application effect and test results, without in-depth analysis and discussion of the principle, structure and engineering application of the digital cartridge turbine governor.

It is hoped that this paper will further expand the basic theory and engineering application of hydraulic turbine governor based digital cartridge valve technology. The closed-loop power antiregulation, the unstable operation of the isolated grid, the low-frequency de-excitation and overspeed of load rejection of bulb turbine unit during the operation of the hydropower plant have successfully been solved by the related control strategies and laws adopted, which can be used for reference to solve the key problems in the operation of governor in hydropower plant at present.

2. The Digital cartridge turbine governor

2.1. Overall structure

The general structure of digital cartridge turbine governor is basically the same as that of the traditional type of microcomputer governor. Two types of governors mainly include two main parts: the microcomputer regulator and the hydraulic servo system. However, digital cartridge turbine governor is essentially different from the traditional governor. The traditional governor mainly uses the analog quantity outputted by the microcomputer regulator to control the pilot valve of the hydraulic servo system, so as to drive the main distribution pressure valve, while the digital cartridge turbine governor mainly adopts pulse width modulation (PWM) control method. The high-speed switching valve or solenoid valve is controlled by the output pulse of the microcomputer regulator, so as to drive the hydraulic valve or the cartridge valve. The main difference between the two structures is the hydraulic servo system. The cartridge governor mainly takes the high-speed switching valve as the pilot control valve, the hydraulic reversing valve and the two-pass cartridge valve as the main control valve. The traditional microcomputer governor at this stage mainly takes the proportional servo valve, servo motor and other conversion elements as the pilot valve, the main distribution pressure valve as main control valve.
The traditional microcomputer governor generally adopts the analog quantity after D/A conversion by the regulator, and then amplifies it at the pilot control valve, so as to control the main motor relay. And the digital cartridge turbine governor uses the pulse quantity directly outputted by the regulator through the PWM control method. The electrical control output cancels the conversion module between the digital quantity and the analog quantity, which can directly affect the mechanical hydraulic part. According to the liquid resistance theory [11], the mechanical hydraulic part discretizes the function of direction and the size of oil flow of control relay of main distribution. This kind of design idea and the control way have broken the mode that the main control valve of traditional microcomputer governor adopts the main distribution.

2.2. Basic Principles

The cartridge technology used in the digital cartridge turbine governor is usually based on the principle of pilot control, seat main stage, cartridge connection [10], where different integrated structures are designed to meet the control performance according to the control objects and requirements. The calculation is guaranteed according to the requirements of the hydraulic turbine control performance and the hydropower station regulation, and the cartridge valve integration block which satisfies the requirement is designed. The hydraulic components, such as cartridge valve, hydrodynamic directional valve and high speed switch valve, are constructed into hydraulic servo system by means of inserting and integrating. The pilot valve is mainly used to control hydraulic directional valve and cartridge valve, and the pilot valve can accept the analog quantity, digital quantity, and other control signals outputted by regulator, so its pilot valve can adopt switch valves, proportional valves, digital valves and so on. If the pilot valve is controlled by analog signal, the control function of proportional valve or servo valve can be realized to form the hydraulic servo system of proportional cartridge valve; if the pilot valve adopts a high speed switch valve or solenoid valve, the digital quantity and switch quantity outputted by the regulator can be directly used to control, thus forming a direct digital mechanical hydraulic system.

From the principle, cartridge valve is a single control liquid resistance [11], different control functions and effects can be obtained using different pilot control valve. The operating principle of the cartridge valve is shown in Fig. 2. K is the control oil cavity on the control lid. A and B are the oil ports on the working oil circuit. Oil pressures of K, A, B are respectively defined as the hydraulic $P_K$, $P_A$ and $P_B$, three effective working areas are $P_K$, $P_A$, $P_B$, where

$$S_K = S_A + S_B \quad (1)$$

The join forces and direction of the valve core are used to determine switching of cartridge valve circuit. According to the mechanics of the principle, the resultant force $\sum F$ applied to the valve core:

$$\sum F = P_K \ast S_K - P_A \ast S_A - P_B \ast S_B + F_1 + F_2 \quad (2)$$
In the formula: $F_1$ is cartridge valve spring elasticity, $F_2$ is the fluid power of the valve core.

According to formula (1) and (2), it can be known that oil circuit at A cavity and B cavity are disconnected when $\Sigma F > 0$. When $\Sigma F < 0$, the valve element is opened, A cavity and B cavity circuit are implemented. The opening and closing of pressure control valve core of oil cavity K by the pilot control valve, so as to achieve switching of the oil circuit at A cavity and B cavity.

![Diagram of cartridge valve control principle](image)

**Fig. 2.** the control principle of cartridge valve

If the port k=1 when the pressure oil is passed by the controlling oil port, then port A and port B are cut off. On the contrary, if the port k=0 when the pressure oil is interdicted by the controlling oil port, then port A and port B are connected, so as to drive servomotor.

As a new type of digital hydraulic component, the high-speed switching valve adopts pulse control mode to directly switch according to a series of pulse signals. Different from the continuous control mode of servo valve and proportional valve, the high-speed switch valve mainly adopts the PWM method to perform high-speed switching operation, so as to control the average flow rate through the valve. Used in the hydraulic control system, the high-speed switching valve mainly uses the width and frequency of the pulse outputted by the controller to control the average flow of the hydraulic system. Without D/A conversion, the interface of controller can be directly connected, which simplifies the entire system structure and effectively reduces manufacturing costs. However, due to the high operating frequency and small flow capacity, the high-speed switching valve can not directly drive the hydraulic control system in some hydraulic controls with large flow and high power [12]. The hydraulic valve and the cartridge valve have large flow and high power drive capability that can be adjusted. Therefore, the high-speed switching valve can be taken as a pilot valve to drive a hydraulic valve or a cartridge valve, achieving high flow and power control requirements, as well as smooth control of flow. For hydraulically operated reversing valves or cartridge valves with high requirement for reversing performance, sudden braking or starting of the load will cause pressure spikes and shocks throughout the hydraulic system under high inertia and high speed motion. Therefore, an adjustable throttle (damper) can be provided between the hydraulic valve and the pilot valve to adjust the movement speed of the main spool of the hydraulic valve, reducing the commutation shock and noise [13].
The selection of the main control valve of digital cartridge turbine governor, that is the cartridge valve, is basically the same as that of the traditional microcomputer governor. The maximum flow capacity must be considered at the rated pressure to meet the turbine adjustment, so as to guarantee calculation. Due to the flexible combination of the cartridge valve and the selectivity of the pilot control valve, the designing of the hydraulic control system is more complicated than the traditional hydraulic system. At the same time, it is necessary to consider the maximum flow capacity of the pilot control valve and the hydraulic directional control valve in the design process, otherwise the adjustment accuracy and response speed of the whole system will be affected. Generally, high-speed switching valves, proportional valves, etc. can be selected as the pilot valve to control the main valve, so as to meet the requirements of adjustment accuracy and response speed; the ordinary solenoid valves can be used for pilot valves that only need to be reversed, such as open stop valves, emergency stop valves, accidental pressure regulating valves. In the turbine governing system, some requirements are put forward for the control of the water guiding mechanism, the response speed, adjustment accuracy and stability of the large fluctuations and small fluctuations of the turbine during operation. The time and control accuracy of the hydraulic system adjustment meet the requirements, the water guiding mechanism moves smoothly, and the pressure impulse of the entire hydraulic control circuit is small. Therefore, considering the particularity and complexity of the turbine adjustment, the appropriate pilot control valve should be selected to drive the hydraulic directional control valve or the cartridge valve, which is very important for the digital cartridge turbine governor. Since the proportional valve and the high-speed switching valve can be used as the pilot valve to realize the continuous control of the pressure/flow of the control chamber of the cartridge valve, the opening degree of the main spool of the cartridge valve can be adjusted proportionally, which solves the problems of motion stability and pressure shock.

3. Application of digital cartridge turbine governor
Since the successful development, the digital cartridge turbine governor has been applied in various types of hydro-generators, covering the reaction turbine and impulse turbine unit and the pump storage unit, and applied to 700 hydroelectric units of more than 300 hydropower stations at the world. Problems such as the adjustment of precision and speed for primary frequency regulation and closed-loop power regulation of large-scale unit Francis turbine, the co-efficient control of Kaplan turbine, the low-frequency deexcitation and load rejection overspeed of the tubular unit, the isolated net regulation of impulse have been successfully solved.
3.1. Application situation of domestic engineering

The engineering application of digital cartridge turbine governor in domestic hydropower station has already formed watershed, whole-plant, large-scale application. The digital cartridge turbine governor has been adopted by large units such as 2*250MW Francis unit at Zhexi Hydropower plant in Hunan province, 7*200MW Kaplan unit at Fujian Shuikou power Plant and 6 MW tubular units at Honghua hydropower plant at Guangxi Autonomous Region. The 3*80MW Francis unit at Wannmipo hydropower station in Hunan Province adopts digital closed-loop power regulation and pulse regulation back-up control, which not only improves AGC control efficiency, but also ensures the coordination of primary frequency regulation (PFR) and automatic generation control (AGC). For tubular units, the moment of Inertia is small, and the inertia of the flow is significant to the fluctuation of the unit and the speed of flight. The regulation performance of the governor and the safe and stable operation of the unit in the process of wave transition should be comprehensively considered for the problems caused by the combination of hydraulic, mechanical and electrical factors in the process of wave transition, therefore, the control strategy needs to be optimized. Speeding up the closing time of blades is generally used in engineering applications, and some strategies such as increasing no-load limit opening and segmented closing are adopted in the process of program control, which solves the problems such as low-frequency deexcitation and over speed during load rejection of tubular unit. The control strategy above is adopted by the tubular unit of the Honghua hydropower station in Guangxi to successfully solve the problem of its long running.

3.2. Application situation of foreign engineering

The digital cartridge turbine governor not only obtains a lot of successful engineering application in China, but also obtains a lot of engineering applications abroad, which are exported to Honduras, Pakistan, Vietnam, Burma, Syria, Zambia, Belarus, Panama and other countries. From the connected power line of Zambia Lenzo hydropower Station, the shortest is 30 Km, and the longest is 220 Km. The field load type is basically lighting electricity, that is, pure resistive load. For the pure resistive load, the dynamic transition process is very complicated, involving the complex coupling relation of hydraulic-mechanical-electric power system. And the pure resistive load power system essentially provides 0 damping or negative damping, so the isolated network system is inherently difficult to stabilize. The impulse unit of Lenzo hydropower station in Zambia effectively solves its isolated network operation of the Northern power grid using digital cartridge turbine governor. The rapid and accurate judgment of the isolated network operation, the timely switching of control mode and parameters, and the fast and stable regulation process plays a very good stabilizing effect for solving the easy formation of the isolated power system in northern Zambia [14,15]. Local control unit (LCU) and governor of a hydroelectric power station in Panama use IEC61850 communication [16]. As the digital cartridge turbine governor adopts digital direct hydraulic control system, the IEC61850 standard and related technology is one of the methods used in intelligent hydropower plant [16]. Therefore, the successful application of digital cartridge turbine governor based on the IEC61850
communication protocol at a power station in Panama is a useful attempt for the application of intelligent hydropower plant.

4. Conclusions and discussions
(1). A large number of engineering applications of digital cartridge turbine governor show that it has the advantage of good application value as a new direction of governor control. The relevant control strategies and rules are of significance to solve the practical problems in the operation of the hydroelectric generating unit.
(2). Digital cartridge turbine governor adopts high speed switching valve and cartridge valve as the pilot valve and main control valve of hydraulic servo system, which improves the speed and stability of regulation to some extent. The structure characteristics of the ball valve and the cartridge valve determine the small internal discharge of the hydraulic system and prolong the interval of the oil pump start-up and stop, so it has beneficial advantages in the engineering application.
(3). The further research about digital cartridge turbine governor should focus on analyzing quantitatively with model simulation and test analysis, and formulating the principles and standards of design and manufacture.

5. Acknowledgments
The work presented in this paper was funded by the IWHR Research & Development Support Program AU0145B202018 and AU0145B202020.

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