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Design of Hydraulic System for Pelton Turbine Governor

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Abstract. Bucket turbine is a device widely used in the development of high head and small flow hydraulic energy, which converts hydraulic energy into mechanical energy. The mechanical energy output by the water turbine is converted into electrical energy through a generator and then transmitted to the user end through the power grid for use. In order to ensure the quality of electrical energy and the controllability of energy conversion, bucket type water turbines need to be equipped with corresponding regulation and control mechanisms to achieve regulation and control during normal operation of the turbine and emergency shutdown of the turbine in case of accidents, while ensuring the safety of the hydropower station and unit. According to the requirements of hydraulic turbine regulation and control, a hydraulic control system scheme for the bucket type hydraulic turbine governor was designed, including the nozzle and deflector hydraulic control system, and the governor pressure oil station system scheme. The functions of various components of the hydraulic system and the regulation and control action process were analyzed in detail. The results have been applied in a high head hydropower station in Guangxi, China, with excellent performance and good results.

Keywords. Hydraulic turbine, governor, hydraulic system, needle

1. Introduction

Energy is the driving force for human civilization progress and socio-economic development. Water energy is a natural potential energy generated by solar radiation that causes the Earth's atmospheric circulation to form river runoff on the earth. It is cyclic and never exhausts, and is one of the earliest and most widely developed clean energy sources in the world.

The development and utilization of hydropower needs to be completed through water turbine generator sets. To ensure the quality of electrical energy, it is necessary to equip the hydraulic turbine generator unit with a high-performance regulation system. The hydraulic turbine regulation system responsible for controlling and regulating hydraulic energy is one of the most important regulation systems of the hydraulic turbine generator unit, playing a crucial role in stabilizing the unit frequency and changing the output electrical energy of the unit. Its composition is shown in figure 1.

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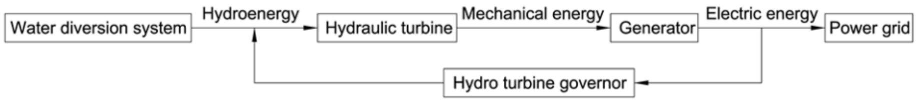


Figure 1. Composition of hydraulic turbine regulation system

The hydraulic turbine regulation system consists of five major parts: the water diversion system, the hydraulic turbine, the generator [1], the power grid, and the hydro turbine governor, forming a closed regulation system. The function of the water diversion system composed of the hydraulic turbine regulating system is to introduce the water from the upstream reservoir into the hydraulic turbine, which then converts it into rotating mechanical energy; The function of a generator is to convert mechanical energy into electrical energy [2]; The function of the power grid is to transmit electricity through transformation, transmission, and distribution to users for production and daily use; The function of the hydro turbine governor is to adjust the water energy entering the hydraulic turbine based on changes in unit frequency (closely related to changes in grid load during grid operation), ultimately changing the electrical energy output of the generator, balancing the power generation and consumption of the power system, and achieving stable operation of the power system.

The output power of a hydraulic turbine is related to its working head and flow rate, and its calculation formula is:

$$P = 9.81QH\eta \tag{1}$$

Among them: P - Hydraulic turbine output power, unit: kW

Q - Working flow rate of hydraulic turbine, unit: m^3/s

H - Working head of hydraulic turbine, unit: m

η- The working efficiency of hydraulic turbines can reach 90%~96% under optimal operating conditions [3].

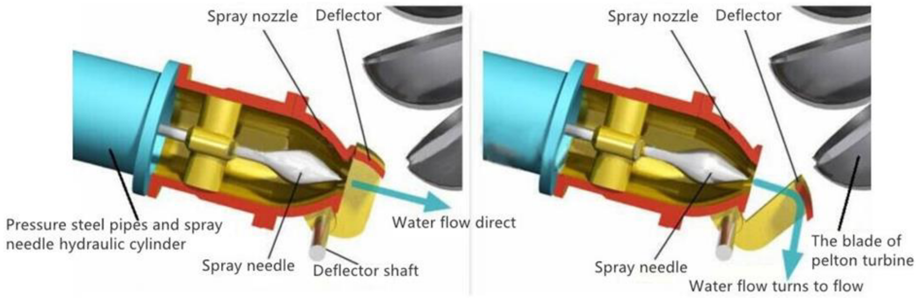
From equation (1), it can be seen that the most convenient and effective way to adjust the output power of a hydraulic turbine is to change the flow rate through the turbine.

According to the different characteristics of water energy utilization, hydraulic turbines can be divided into two types: reaction type hydraulic turbines and impulse type hydraulic turbines. Pelton type hydraulic turbines are a subdivision type of impulse type hydraulic turbines and are widely used in small and medium-sized hydropower stations with high head and small flow around the world. Currently, the highest applied head is 1772m.

2. Composition of Regulating Mechanism for Bucket Type Water Turbine

Figure 2 is a schematic diagram of the regulating mechanism of a pelton type hydraulic turbine, consisting of the turbine runner bucket blades, spray nozzles, spray needles, pressure steel pipes, spray needle operated hydraulic cylinder, deflectors, etc.

During the operation of the hydraulic turbine, the spray needle operated hydraulic cylinder controls the spray needle to move backwards, opens the spray nozzle, and high-pressure water flows directly from the spray nozzle towards the pelton blades of the hydraulic turbine, thereby driving the turbine runner to rotate, achieving the transformation of hydroenergy into rotating mechanical energy, as shown in figure 2 (a) [4].



(a) The deflector has exited operation (b) The deflector is put into operation

Figure 2. Schematic diagram of regulating mechanism for Pelton turbine.

The hydroenergy regulation of a pelton turbine is carried out by regulating the flow rate. In figure 2, the spray needle operated hydraulic cylinder controls the movement of the spray needle to change the opening of the spray nozzle, thereby changing the working flow rate of the hydraulic turbine. To overcome the forward thrust exerted by high-speed water flow on the spray needle during normal operation, the spray needle should be hydraulically controlled to obtain a larger operating force.

When the hydraulic turbine generator unit suddenly trips the motor outlet circuit breaker due to various faults, shedding all the load, and the generator output electrical energy suddenly drops to zero. At this time, the portion of water flow that exceeds the no-load opening flow rate of the nozzle (the corresponding energy can make the unit rotate to reach the rated speed) will cause the unit speed (proportional to frequency) to suddenly rise sharply, and the centrifugal force in the rotating part of the unit will increase, endangering the safety of the unit. To avoid excessively high unit speed, it is necessary to quickly reduce the opening of the spray nozzle. However, if the spray nozzle is closed too quickly, it will generate a large amount of water hammer pressure in the pressure steel pipe, and even lead to major accidents such as pressure steel pipe rupture, machine damage, and death. To this end, a deflector is installed at the spray nozzle outlet. When the spray needle quickly closes or normally closes the end section, the deflector is put into operation, as shown in figure 2 (b). It quickly cuts off the water flow directed towards the pelton blades of the turbine runner, and then slowly closes the spray needle fully, effectively solving the contradiction between high speed rise during unit load rejection and excessive water hammer pressure inside the pressure steel pipe when the spray needle quickly closes. Therefore, the hydraulic system of the pelton turbine governor should be able to control the coordinated operation of the spray nozzle and spray deflector components to achieve the regulation and control function of the hydraulic turbine.

3. Design Scheme for Hydraulic System of Pelton Turbine Governor

After experiencing the development of mechanical hydraulic governors and electrical hydraulic governors, with the continuous development of computer control technology, the microcomputer governor of hydraulic turbines using microcomputers as controllers has replaced the aforementioned two types of governors and become the mainstream equipment for regulating and controlling hydraulic turbines in hydropower stations.

Figure 3 is a schematic diagram of the microcomputer governor system for hydraulic turbines. The computer, as the regulating control core, is responsible for collecting the unit frequency, grid frequency, spray needle opening of the hydraulic turbine, and generator output power values. At the same time, PID calculation is performed based on the given values input by the operating personnel. The results are amplified by the hydraulic servo system, and the spray needle opening of the hydraulic turbine is controlled and changed to change the flow rate of the hydraulic turbine, thus achieving the purpose of regulating and controlling the hydraulic turbine. When closing the end stroke of the spray needle during emergency or normal shutdown, it is also necessary to control the engagement of the deflector and cut off the water flow directed towards the peiton blades of the turbine runner; Before starting up, it is necessary to control the deflector to exit in order for the hydraulic turbine to operate normally.

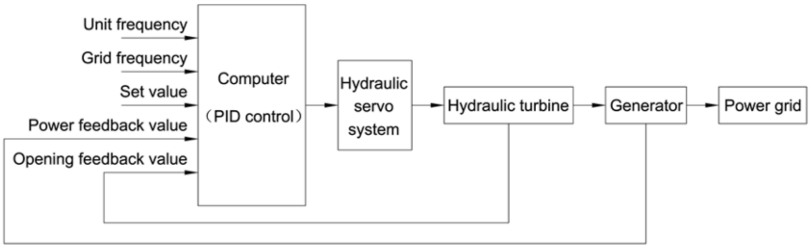


Figure 3. Schematic diagram of microcomputer governor system for hydraulic turbines.

The hydraulic servo system is an important actuator for the governor to achieve electro-hydraulic conversion and hydraulic amplification, and its reliability and stability directly affect the regulating performance and power quality of the hydroelectric generator set. Therefore, standardized hydraulic components should be used as much as possible to simplify the hydraulic system, reduce costs, and reduce subsequent maintenance workload while ensuring reliability.

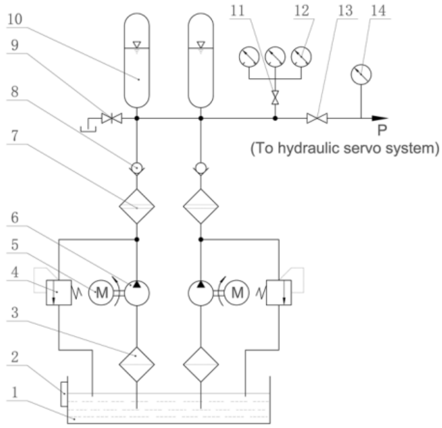
3.1. Design Scheme of Hydraulic Oil Source for Governor

To ensure the normal operation of the hydraulic servo system of the hydraulic turbine governor, it is necessary to equip the system with a highly reliable pressure oil station. Figure 4 is the pressure oil station system diagram of a high oil pressure governor (rated pressure 16MPa) for a pelton turbine in a certain power plant [5].

(1) Accumulator and its pressure control design scheme

Since the oil used for operating the spray needle and deflector is not continuous, but the oil consumption will change at any time, in order to meet the changing oil consumption and stable oil supply pressure of the hydraulic servo system at any time, the system is equipped with two bladder accumulators 10, with an air bag installed on the top of the inside, which uses the compressibility of the gas to achieve energy storage. When the hydraulic servo system uses a small amount of oil for a short time, the accumulator can ensure continuous oil supply to the system within the normal working pressure range. As the amount of oil used increases, when the oil pressure inside the accumulator drops to the lower limit of normal working oil pressure of 14MPa, the electric contact pressure gauge 12 acts to control the action of the oil pump motor 5, compressing the oil tank 1 into the accumulator for storage. When the oil pressure inside the accumulator reaches the upper limit of normal working oil pressure of 16MPa, the electric contact pressure gauge 12 acts and stops the oil pump from pumping. By using the electric contact pressure gauge 12, oil pump motor 5, oil pump 6, and corresponding electrical control circuits, the oil pressure in the accumulator can be maintained within the normal operating oil pressure range.

The accumulator is filled with inert gas - nitrogen gas, which is pressurized to 7-8MPa in an oil-free state, meeting the gas volume required for normal operation of the accumulator.



1. Oil tank;2. Liquid level gauge;3. Oil suction filter;4. Relief valve;5. Motor;6. Oil pump;7. Oil filter;8. One-way valve;9. Oil drain ball valve;10. Bladder accumulators;11. Ball valve;12. Electric contact pressure gauge;13. Oil supply ball valve;14. Pressure gauge

Figure 4. Governor Pressure Oil Station.

(2) Design scheme of hydraulic circuit for oil pump supply

The hydraulic circuit design scheme for oil pump supply includes oil tank 1, oil suction filter 3, oil pump 6, oil filter 7, one-way valve 8, and relief valve 4. When the oil pump motor 5 is working, it drives the oil pump 6 to suck the oil in the oil tank 1 into the oil suction filter 3. After coarse filtration, it is sent to the oil filter 7 for fine filtration, and finally sent to the bladder accumulator 10 through the one-way valve 8. Because the oil discharge of the hydraulic servo system is all discharged to oil tank 1, in order to protect the oil pump 6, the oil needs to be roughly filtered first; To ensure that the cleanliness of the pressure oil meets the requirements of the hydraulic servo system, the pressure oil after being pressurized by the oil pump must undergo fine filtration before being sent to the accumulator for storage. The function of one-way valve 8 is to prevent the pressure oil in the accumulator from flowing back to the tank through the oil pump when the oil pump 6 stops pumping. The function of relief valve 4 is to prevent oil pump 6 from stopping normally due to electrical control circuit faults.

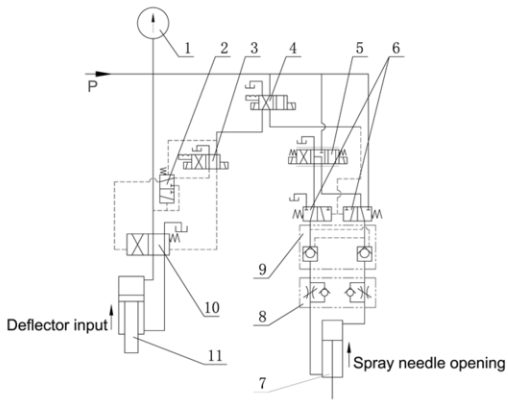
If oil pump 6 runs for a long time, the oil pressure at the outlet of the oil pump will continue to increase. When the oil pressure reaches a certain value, relief valve 4 opens to drain the oil at the outlet of the oil pump back to the oil tank, avoiding damage to the hydraulic system after the oil pump due to high oil pressure, thus protecting the safety of the hydraulic system.

Considering that the hydraulic servo system has a relatively large range of changes in oil consumption during operation, and also considering that the oil pump and its electrical control circuit may malfunction after long-term operation, which may prevent normal operation, two sets of oil pump devices are installed in the pressure oil station, one set as a working pump and the other set as a backup pump. The working pump maintains the oil pressure in the accumulator within the normal working oil pressure range. When the working pump is unable to start due to a malfunction or the system's oil consumption suddenly increases, and the pressure inside the accumulator drops to a certain value below the lower limit of normal working oil pressure, the standby pump starts and supplies oil to the accumulator. The working pump and standby pump can be manually switched, or they can be periodically rotated by the control system to ensure that the working hours of the two sets of oil pumps are similar during a certain stage.

When the oil consumption of the needle hydraulic cylinder and deflector hydraulic cylinder of the hydraulic turbine is relatively low, in order to save costs, a hydraulic oil source design scheme with a single accumulator and a single oil pump can also be adopted.

3.2. Design Scheme of Hydraulic Servo System for Governor

The regulating actuator of a pelton type hydraulic turbines consists of two parts: a nozzle and a deflector. Figure 5 shows the design scheme of the hydraulic servo system of the governor.



1. Pressure gage;2. Hydraulic valve for deflector;3. Solenoid valve for deflector;4. Emergency shutdown solenoid valve;5. Spray needle control proportional valve;6. Spray needle emergency shutdown hydraulic valve; 7. Needle hydraulic cylinder; 8. Bidirectional throttle valve; 9. Hydraulic control one-way valve;10. Hydraulic control directional valve for deflector; 11. Hydraulic cylinder for deflector operation

Figure 5. Design Scheme of Hydraulic Servo System.

(1) Needle hydraulic control system

The spray needle hydraulic control system consists of a spray needle hydraulic cylinder 7, a bidirectional throttle valve 8, a hydraulic control one-way valve 9, a spray needle emergency shutdown hydraulic valve 6, a spray needle control proportional valve 5, and an emergency stop solenoid valve 4.

Figure 5 shows the stable state of the spray needle at a certain opening, with the valve core of the spray needle control proportional valve 5 in the middle position, and the oil circuit of the switch chamber of the spray needle hydraulic cylinder being cut off. When the control signal of the computer is to increase the opening of the injection needle, the left coil of the injection needle control proportional valve 5 is energized, and the valve core moves to the right. The pressure oil P from the accumulator passes through the injection needle control proportional valve 5, the injection needle emergency shutdown hydraulic valve 6, the hydraulic control one-way valve 9, and the bidirectional throttle valve 8 to reach the startup chamber of the injection needle hydraulic cylinder 7. At the same time, the shutdown chamber of the injection needle hydraulic cylinder 7 passes through the bidirectional throttle valve 8, the hydraulic control one-way valve 9, and the injection needle emergency shutdown hydraulic valve 6 The injection needle controls the proportional valve 5 to turn on the oil discharge, thereby pushing the injection needle to move towards the larger opening direction. When the control signal of the computer is to turn down the opening of the injection needle, the action principle of the hydraulic servo system is opposite.

The purpose of setting a bidirectional throttle valve 8 is to adjust the fastest opening and closing time of the spray needle. During the process of increasing the opening of the spray needle mentioned above, when the pressure oil enters the opening chamber of the spray needle hydraulic cylinder through the bidirectional throttle valve 8, it can pass through two channels: the throttle valve and the one-way valve. However, the oil discharge from the closing chamber of the spray needle hydraulic cylinder can only pass through one channel of the throttle valve, which is equivalent to the oil discharge speed of the closing chamber of the spray needle hydraulic cylinder being controlled by the right throttle valve. Therefore, the fastest speed of the spray needle in the opening direction is achieved through the throttle valve on the right side of the bidirectional throttle valve 8, On the contrary, the throttle valve on the left side of bidirectional throttle valve 8 is used to regulate the fastest speed of the spray needle in the closing direction. The maximum speed of the spray needle switch cannot be determined arbitrarily, but should be determined by the calculation results of the hydraulic turbine adjustment guarantee. If the spray needle action speed is too fast, the water hammer pressure inside the pressure steel pipe is too large, and the pressure steel pipe may be difficult to withstand; The action speed of the spray needle is too slow, making it difficult for the regulating speed of the hydraulic turbine to meet the requirements. At the same time, during emergency shutdown, it may cause the unit to overspeed and endanger the safety of the unit.

After the emergency shutdown hydraulic valve 6 of the spray needle, a hydraulic control one-way valve 9 is installed in the hydraulic circuit. When there is a switch or a signal to adjust the opening of the spray needle, the pressure oil passes through the emergency shutdown hydraulic valve 6 of the spray needle. In addition to opening the one-way valve on this side, the pressure oil will also open the one-way valve on the opposite side, which does not affect the adjustment and control of the spray needle servo. When there is no signal for adjusting the opening of the spray needle, the hydraulic control one-way valve 9 closes on its own, cutting off the oil circuits on both sides of the spray needle hydraulic cylinder, to avoid internal oil leakage in the two chambers of the spray needle hydraulic cylinder through the emergency shutdown hydraulic valve 6 of the spray needle, which can cause the spray needle hydraulic cylinder to wriggle under external water thrust and cause the spray needle opening to lose control.

The needle emergency shutdown hydraulic valve 6 and emergency shutdown solenoid valve 4 are used together for emergency shutdown of the unit, fully closing the needle opening at the fastest speed. When an accident occurs in the unit that requires emergency shutdown, the coil of emergency shutdown solenoid valve 4 is energized, and the valve core moves to the left. Pressure oil flows from emergency shutdown solenoid valve 4 to spray needle emergency shutdown hydraulic valve 6, pushing the valve core of hydraulic valve 6 to move to the left and right. Pressure oil flows from the right hydraulic valve 6 to the shutdown chamber of the spray needle hydraulic cylinder through one-way valve 9 and throttle valve 8, while the startup chamber of the spray needle hydraulic cylinder is connected and drained through throttle valve 8, one-way valve 9, and left hydraulic valve 6, The needle hydraulic cylinder closes the needle opening to full close at the fastest closing speed set by throttle valve 8.

(2) Hydraulic control system for deflector

The hydraulic control system of the deflector consists of hydraulic valve 2, solenoid valve 3, emergency shutdown solenoid valve 4, hydraulic directional valve 10, and hydraulic cylinder 11.

When the hydraulic turbine is operating normally, the pressure oil flows from the emergency shutdown solenoid valve 4 and solenoid valve 3 to the right side of the hydraulic control directional valve 10. The left side of the hydraulic control directional valve 10 is connected and drained through the hydraulic valve 2 and solenoid valve 3. The pressure oil pushes the valve core of the hydraulic control directional valve 10 to move to the left position as shown in the diagram. At this time, the pressure oil directly enters the exit chamber of the deflector hydraulic cylinder through the hydraulic control directional valve 10, and the input chamber of the deflector hydraulic cylinder is directly connected and drained, and the deflector is in the exit position, As shown in figure 2 (a).

During the shutdown process of the unit, when the nozzle opening is closed to a certain degree, a control signal is sent out by the computer. The coil of solenoid valve 3 is energized, and the valve core moves to the right. The pressure oil flows from the emergency shutdown solenoid valve 4 through solenoid valve 3 and hydraulic valve 2 (both the upper and lower sides of the valve core are connected with pressure oil, and the valve core is in the position shown in the figure) to the left side of the hydraulic control directional valve 10. The right side of the hydraulic control directional valve 10 is connected and drained through solenoid valve 3, and the pressure oil pushes the valve core of the hydraulic control directional valve 10 to the right, The pressure oil directly enters the input chamber of the deflector hydraulic cylinder through the hydraulic control directional valve 10, while the outlet chamber of the deflector hydraulic cylinder is directly connected to the oil discharge through the hydraulic control directional valve 10. The deflector quickly switches from the exit position to the input position, as shown in figure 2 (b). The water sprayed from the nozzle is turned in the opposite direction, cutting off the water flow towards the blades of the turbine runner, and stopping the unit as soon as possible.

When the unit is shut down in an emergency, the coil of emergency shutdown solenoid valve 4 is energized, and the valve core moves to the left. The right side of hydraulic control directional valve 10 is connected and drained through solenoid valve 3 and emergency shutdown solenoid valve 4. At the same time, the upper side of hydraulic valve 2 valve core is also connected and drained through emergency shutdown solenoid valve 4. The valve core of hydraulic valve 2 moves up under the action of pressure oil on the lower side, and the pressure oil flows through hydraulic valve 2 to the left side of hydraulic control directional valve 10, pushing the valve core of hydraulic control directional valve 10 to move to the right, The pressure oil directly enters the input chamber of the deflector relay through the hydraulic control directional valve 10, while the outlet chamber of the deflector hydraulic cylinder is directly connected to the oil discharge through the hydraulic control directional valve 10. The deflector quickly switches from the exit position to the input position, urgently cutting off the water flow towards the water bucket blades of the turbine runner, and achieving emergency shutdown of the unit.

4. Concluding Remarks

The governor of a pelton type hydraulic turbine needs to accurately control the opening of the nozzle according to control requirements, in order to effectively regulate and control the water energy entering the turbine, achieving the goal of turbine regulation. At the same time, the governor also needs to timely control the input and exit of the deflector, to solve the contradiction between the nozzle closing too fast, the pressure of the steel pipe water hammer rising too much, and the nozzle closing too slow, and the unit speed rising too high. In emergency situations, We also need to be able to safely and quickly stop all the units. Based on the above requirements, a hydraulic system for the pelton turbine governor has been designed and put into use at the Tianhu Hydropower Station in Guangxi, China, with a working head of 1074m. After years of operation, the governor hydraulic system has been stable and reliable, and its response time and dead zone are significantly better than the national standard requirements, which has been highly praised by the owner.

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