

Article

Position Control Study on Pump-Controlled Servomotor for Steam Control Valve

Guishan Yan ^{1,2,*}, Zhenlin Jin ^{1,2,*}, Tiangui Zhang ² and Penghui Zhao ²

¹ School of Mechanical Engineering, Yanshan University, Qinhuangdao 066004, China; yanguishanasd@163.com

² Heavy-Duty Intelligent Manufacturing Equipment Innovation Center of Hebei Province, Qinhuangdao 066004, China; TianguiZhangSU@163.com (T.Z.); PenghuiZhaoPZ@163.com (P.Z.)

* Correspondence: zljjin@ysu.edu.cn; Tel.: +86-0335-8074783

Abstract: In steam turbine control and actuation, the steam control valve plays a key role in operability and reliability. The electrohydraulic regulating system for the steam control valve, usually called the servomotor, needs to be reliable and high performing under nonlinear excitation interference in actual conditions. Currently, electrohydraulic servo valve control technology is widely used in servomotors. Although this technology has good control performance, it still has some technical defects, such as poor antipollution ability, low energy efficiency, large volume size, and limited installation space. Aiming at the abovementioned technical shortcomings of electrohydraulic servo valve control technology, a servomotor-pump-hydraulic cylinder volume control scheme is proposed in this paper, forming a pump-controlled servomotor for the steam control valve. By analyzing the working principle of the pump-controlled servomotor position control in the steam control valve, the mathematical model of a pump-controlled servomotor for the steam control valve is established. The sliding mode variable structure control strategy is proposed, and the variable structure control law is solved by constructing a switching function. To verify the performance of the proposed control method, experimental research was conducted. The research results show that the proposed sliding mode variable structure control strategy has a good control effect, which lays the theoretical and technical foundation for the engineering application and promotion of pump-controlled servomotors for steam control valves and helps the technical upgrade and product optimization of steam turbines.

Keywords: steam turbine; steam control valve; pump-controlled servomotor; sliding mode variable structure; position control



Citation: Yan, G.; Jin, Z.; Zhang, T.; Zhao, P. Position Control Study on Pump-Controlled Servomotor for Steam Control Valve. *Processes* **2021**, *9*, 221. <https://doi.org/10.3390/pr9020221>

Received: 24 December 2020

Accepted: 20 January 2021

Published: 25 January 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

The steam turbine uses high-pressure steam produced by the boiler to rotate its main shaft, and the main shaft drives the generator through a hydraulic coupling to generate electricity by excitation. As the most widely used prime mover equipment in the power industry [1], the steam turbine is widely used in the metallurgical industry, chemical industry, and ship power systems [2,3]. The electrohydraulic regulating system for the steam control valve, usually called the servomotor (referred to as SM), plays a very important role in the steam turbine.

The working conditions of the steam turbine include turning, vacuuming, increasing speed and grid-connection, with load, full load, load rejection, shutdown, etc. Under different working conditions, the servomotor can adjust the actual position of the output of the execution terminal according to the needs. In the load and full load stages, the SM changes the intake of high-pressure steam by adjusting the steam control valve, thereby regulating the power of the system. This allows the steam turbine to meet the changing needs of users' electricity consumption while ensuring that the speed is within the normal range. Further, the high-performance control of the servomotor plays an important role in the quality adjustment of power and frequency for steam turbines and is also significant

for improving the working performance of steam turbines [4,5]. The SM includes spring, mechanical connecting rod and other components [6]. The structural principle of the SM is shown in Figure 1.

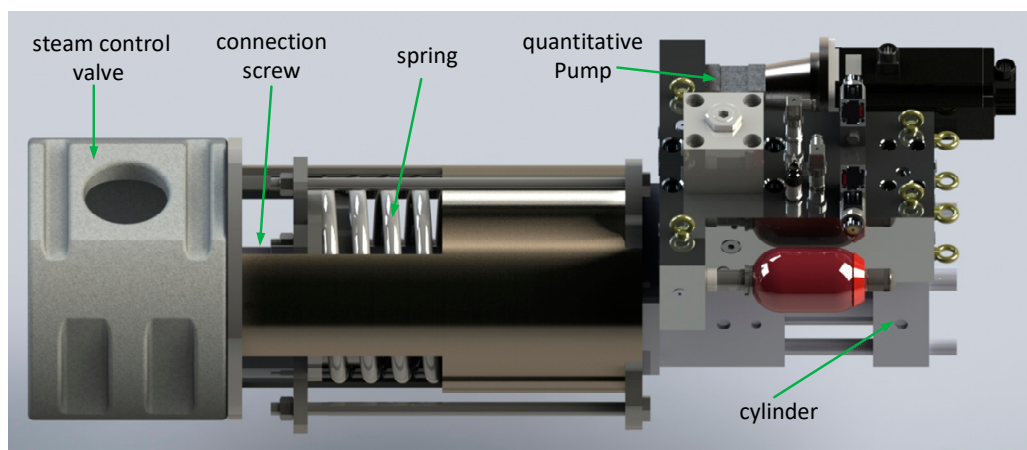


Figure 1. Working principle diagram of a SM.

The SM uses a hydraulic cylinder to drive the mechanical connecting rod to adjust the opening of the steam control valve, thereby changing the high-pressure steam intake and finally realizing the overall power control of the steam turbine. In this way, the steam turbine can meet the changing demand of electricity consumption and ensure that the speed is working within the normal range. When the system fails, the pressure in the high-pressure chamber of the hydraulic cylinder is quickly unloaded, the regulating steam valve is quickly closed under the action of the mechanical spring, and the equipment stops running to avoid major accidents. In the field of high-performance control of SM, the position control of the hydraulic cylinder is a key technical issue for the high-performance operation of steam turbines.

In recent years, experts and scholars have never stopped researching on SM, the current research is mainly focused on the overall performance control of the SM and the steam turbine. The drive and control part of the SM usually adopts electrohydraulic servo-valve-controlled technology; that is, the hydraulic station provides system oil supply pressure, and the hydraulic cylinder is controlled by the throttle characteristic of the servo valve to adjust the opening of the steam control valve. Although this technology has good control performance, it has technical defects such as poor antipollution ability, low energy efficiency, large volume size, and limited installation space [7]. The application of electrohydraulic servo pump control technology in the field of SM has mostly focused on the analysis of structural principles, and there is a lack of in-depth research on its specific control strategies. Several studies have been carried out on SM position control, and many studies have utilized simulations and experiments. Related research status is as follows.

M. Pondini et al. of the Pisa Research Institute used Simulink simulation tools to establish a dynamic model of a steam turbine governor and analyzed the governor's effect on the stability of the power system [8]. Annamaria Signorini et al. of General Electric analyzed the working principle and important role of the electrohydraulic servo-valve-controlled system of the SM. According to its working principle, a dynamic model simulation model was established, and the system performance indicators were tested experimentally [9]. Abhay Patil et al. of Texas A&M University analyzed the dynamic characteristics of the steam turbine under single-phase and air–water two-phase action and obtained the performance law of steam turbine inlet pressure and power input in the speed range [10]. Mohammad Ali Azizi studied the speed control strategy and transient performance characteristics of steam turbine and discussed the control effects of different control strategies on the variable

speed and constant speed operation of the system. Through these studies, the influence of key system parameters on its performance was obtained [11].

Yuan Xiaohui of Huazhong University of Science and Technology established a virtual power regulation system dynamic model and proposed an imperialist competitive algorithm (ICA) algorithm for its nonlinear control problem, which effectively improved the robustness of the system under load disturbance [12]. Yan Junjie et al. of Xi'an Jiaotong University established a transient simulation model of a steam turbine power generation system, analyzed the performance indicators of the SM control system, and took power control and operational flexibility as the optimization goals to obtain the best control strategy for the system [13]. Dong Yuliang et al. designed a virtual system simulation experiment platform based on the working principle of the SM for a steam turbine, which met the specific experimental requirements in terms of openness and sharing of experimental capabilities [14]. Cao Yifan used a fuzzy controller to ensure stable operation of the system, given the nonlinear chaotic vibration phenomenon of the steam turbine regulation system [15]. Jiang Jihai et al. proposed a direct-drive electrohydraulic servomotor and analyzed its principle, composition, and characteristics [16].

This paper proposes a volume control scheme to form an electrohydraulic pump-controlled servomotor technology (referred to as PCSM). In this scheme, the quantitative pump (refers to hydraulic pumps with an axial piston design and a swash plate) is directly connected with two load ports of the hydraulic cylinder driven by the servo motor. This technology replaces traditional servo-valve-controlled servomotors (referred to as SVCSM) and has the advantages of high efficiency, energy savings, high power-to-weight ratio, and environmental friendliness. More importantly, the control system is required to have high enough reliability in the field of thermal power generation. The anti-pollution ability of PCSM is far stronger than that of SVCSM, which greatly improves the reliability of the system. The PCSM is a new application in the field of steam turbines. Although few public documents have been published, electrohydraulic pump control technology has been successfully applied in other high-precision control fields such as vehicle suspension control, robot joint drive, and wind power transmission ratio control. However, the control performance of the PCSM has always been an important factor that impede its promotion. This study improves the system robustness and further improves the position control accuracy, which lays a good foundation for the promotion of the PCSM [17–19].

This paper studies the position control of the PCSM for steam turbines, analyzes the working principle of the PCSM, and establishes the mathematical model of the PCSM. On this basis, a sliding mode variable structure control strategy is proposed [20–26]. By constructing a switching function to solve the variable structure control law, the nonlinear excitation interference of the system is overcome. The system robustness is improved, and the high-precision control of the SM position is realized.

2. System Overview

The servomotor-quantitative pump-hydraulic cylinder volume control scheme is proposed in this paper. The volume control scheme, which forms the PCSM technology, is used as the servo driving link of the servomotor position control.

The PCSM includes a servomotor, a quantitative pump, hydraulic valves, an accumulator, a hydraulic cylinder, a servo drive, and a controller. Figure 2 shows the system composition.

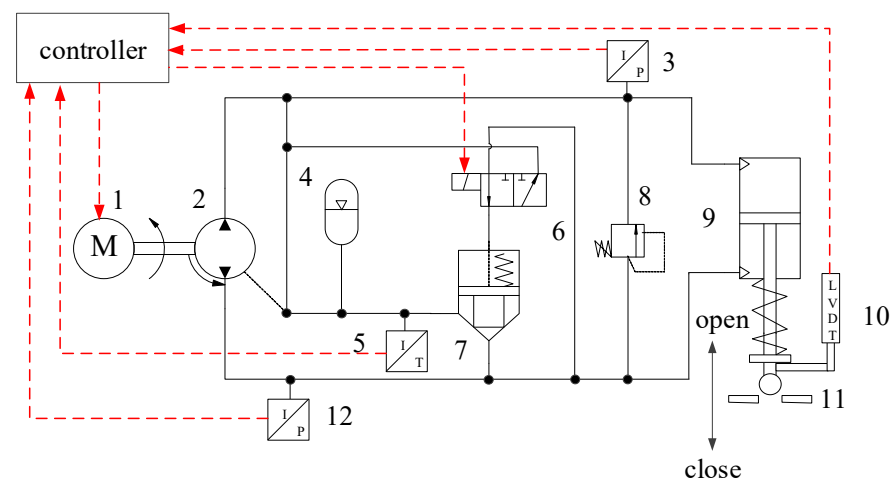


Figure 2. 1: servomotor, 2: quantitative pump, 3: low-pressure sensor, 4: accumulator, 5: temperature sensor, 6: electromagnetic directional valve, 7: two-way cartridge valve, 8: relief valve, 9: hydraulic cylinder, 10: displacement sensor, 11: steam control valve, 12: high-pressure sensor. Working system diagram of PCSM.

As shown in Figure 2, the PCSM adopts the servomotor driving quantitative pump form, and the quantitative pump suction and discharge ports are directly connected to high and low-pressure load chambers of the cylinder. The accumulator is connected to the system's low-pressure chamber, and the accumulator replenishes the hydraulic oil for the system. The relief valve performs pressure overload protection. When the system fails, the two-way cartridge valve and electromagnetic reversing valve work together, and the high-pressure chamber of the cylinder quickly unloads. Because of the action of the mechanical spring, the hydraulic cylinder rod extends and the steam control valve is quickly closed.

The controller collects status information such as system displacement, pressure, and temperature, and then controls the speed of the servomotor through the servo drive to achieve high-precision position control of the hydraulic cylinder. The hydraulic cylinder pushes the connecting rod to realize the precise adjustment of the steam control valve opening. Through the analysis of the working principle of the PCSM, it is concluded that to achieve high-precision position control, mathematical modeling of the core components in the system and analysis of its control principles are required.

3. Mathematical Modeling of the PCSM

The following is the mathematical modeling analysis for the core components of the PCSM, including the servomotor, the quantitative pump, and the cylinder, and the analysis of the load characteristics of the PCSM. Based on this analysis, the position control system of the PCSM is studied.

3.1. Mathematical Model of the Servomotor

In the process of position control of the PCSM, the servomotor is used as the execution terminal of the control algorithm, in position control. The mathematical model for the core components of the servomotor is as follows:

The servomotor stator flux linkage equation can be expressed as follows:

$$\begin{cases} \psi_d = L_d i_d + \psi_f \\ \psi_q = L_q i_q \end{cases} \quad (1)$$

The servomotor stator voltage equation can be expressed as follows:

$$\begin{cases} U_d = R_s i_d + \frac{d}{dt} \psi_d - \omega_e \psi_q \\ U_q = R_s i_q + \frac{d}{dt} \psi_q + \omega_e \psi_d \end{cases} \quad (2)$$

The servomotor electromagnetic torque equation can be written as follows:

$$T_e = \frac{3}{2} p_n [\psi_f i_q + (L_d - L_q) i_d i_q] \quad (3)$$

The servomotor motion equation can be written as follows:

$$T_e - T_L = J_L \frac{d\omega_m}{dt} + D\omega_m \quad (4)$$

where Ψ_d, Ψ_q are the d-q axis components of the stator flux linkage, L_d, L_q are the equivalent inductance of the stator inductance of the d-q axis, i_d, i_q are the stator d-q axis components of the current, Ψ_f is the permanent magnet flux linkage, U_d, U_q are the d-q axis components of the stator voltage, R_s is the stator resistance, ω_e is the angular velocity of the motor rotor, T_e is the electromagnetic torque of the motor, p_n is the number of pole pairs of the servomotor, T_L is the servomotor load torque, J_L is the rotation equivalent converted moment of inertia of the subaxis, ω_m is the mechanical angular velocity of the servomotor, and D is the damping coefficient of the servomotor.

3.2. Mathematical Model of the Quantitative Pump

The quantitative pump is the power element of the PCSM, which provides hydraulic power input for the movement of the cylinder. The flow output of the pump is related to the displacement and speed, and the leakage will affect its flow rate. The quantitative pump mathematical model is as follows:

The flow output equation of the quantitative pump is

$$Q_p = D_p \omega_p - C_p P_L \quad (5)$$

where ω_p is the angular velocity of the quantitative pump, D_p is the rated displacement of the quantitative pump, Q_p is the output flow of the quantitative pump, C_p is the leakage coefficient of the quantitative pump coefficient, and P_L is the load pressure.

3.3. Mathematical Model of the Cylinder

The cylinder is the executive element of the steam control valve, which is the executive terminal of the PCSM and the load. The position control of the cylinder determines the opening of the steam control valve. The mathematical model of the cylinder is as follows:

The flow continuity equation of the cylinder is

$$Q_L = A_p s X_p + C_t P_L + \frac{V_t}{4\beta_e} s P_L \quad (6)$$

Hydraulic cylinder as the internal dynamic characteristics of the system is poor executive components. Its response speed constrains the dynamic characteristics of the whole system. Here we analyze the load characteristics of the cylinder, so as to study its performance under external load interference.

The force balance equation between the cylinder and load is

$$A_p P_L = m_t s^2 X_p + B_p s X_p + K X_p + F_L \quad (7)$$

where A_p is the effective area of the cylinder, Q_L is the cylinder load flow, C_t is the total leakage of the cylinder, V_t is the system total compression volume, β_e is the effective bulk elastic modulus of oil, m_t is the total mass of the piston and load converted to the piston,

B_p is the viscous damping coefficient of the piston and the load, K is the spring stiffness of the load, X_p is the output displacement of the cylinder, and F_L is the external load force acting on the piston.

3.4. Load Mathematical Model

The cylinder of the PCSM is subjected to hydraulic pressure, spring force, mechanical friction force, and valve steam force during the movement. Based on the mass–spring system model, the load force of the cylinder was analyzed, as shown in Figure 3.

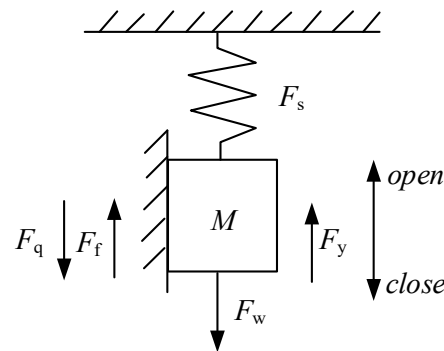


Figure 3. Load force analysis of the PCSM.

All moving masses and external load forces are converted into the equivalent force on the centerline of the piston in the cylinder according to the lever ratio. According to Newton's second law of motion, the force equation of the system can be obtained as

$$F_s + F_w - F_f + F_q - F_y = m_t a \quad (8)$$

where

$$\begin{cases} F_L = F_w - F_f + F_q \\ F_q = A_u \times \Delta P \end{cases} \quad (9)$$

where Stribeck friction model can better describe the relationship between friction force and velocity of mechanical system [27]. The Stribeck friction model is

$$F_s = \begin{cases} F(v) & v \neq 0 \\ F_e \operatorname{sgn}(F_e) & v = 0 \mid |F_e| < F_j \\ F_j \operatorname{sgn}(F_e) & v = 0 \mid |F_e| \geq F_j \end{cases} \quad (10)$$

$$F(v) = \operatorname{sgn}(v) \left[F_k + (F_j - F_k) \exp \left(- \left| \frac{v}{v_s} \right|^\tau \right) \right] + Bv \quad (11)$$

where F_L is the external load force acting on the piston, F_s is the equivalent spring force, F_w is the equivalent gravity of the system, F_f is the equivalent friction of the system, F_q is the equivalent steam force of the steam control valve, A_u is unbalanced area of steam control valve, ΔP is the pressure difference before and after steam control valve, and K_{ce} is the hydraulic driving force of the cylinder, F_e is external load of system, F_j is the maximum static friction force, F_k is coulomb friction, v_s is Stribeck velocity, B is coefficient of viscous friction, τ is experience factor.

3.5. Model Analysis of the Position Control System

A block diagram of the position control for the PCSM can be established by Formulas (5)–(7), as shown in Figure 4.

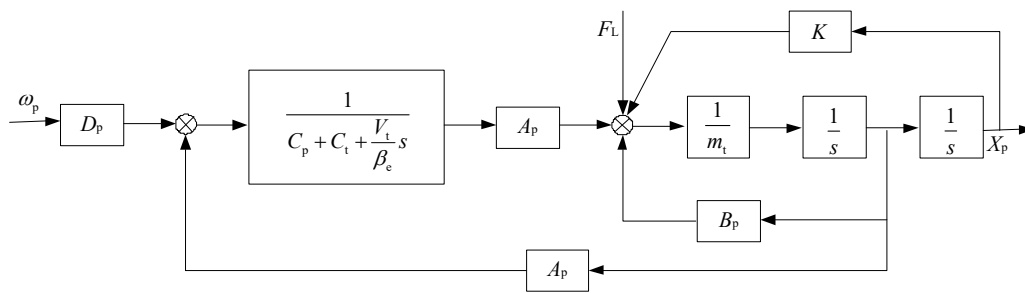


Figure 4. Block diagram of position control for the PCSM.

From Figure 4, the position servo open-loop transfer function of the PCSM can be derived as

$$X_p = \frac{\frac{D_p \omega_p}{A_p} - \frac{K_{ce}}{A_p^2} \left(1 + \frac{V_t}{4\beta_e K_{ce}} s\right) F_L}{\frac{m_t V_t}{4\beta_e A_p^2} s^3 + \left(\frac{m_t K_{ce}}{A_p^2} + \frac{B_p V_t}{4\beta_e A_p^2}\right) s^2 + \left(1 + \frac{B_p K_{ce}}{A_p^2} + \frac{K V_t}{4\beta_e A_p^2}\right) s + \frac{K_{ce} K}{A_p^2}} \quad (12)$$

where K_{ce} is the total flow–pressure coefficient.

Considering that PCSM has a large elastic load ($K \neq 0$), the transfer function of hydraulic cylinder output displacement to servo motor speed can be obtained from Equation (12):

$$\frac{X_p}{\omega_p} = \frac{\frac{K_{ps} A_p}{K}}{\left(\frac{s}{\omega_r} + 1\right) \left(\frac{s^2}{\omega_0^2} + \frac{2\zeta_0}{\omega_0} s + 1\right)} \quad (13)$$

where $K_{ps} = \frac{D_p}{K_{ce}}$ is the total pressure gain of the system.

$\omega_r = \frac{K_{ce}}{A_p^2 \left(\frac{1}{K} + \frac{1}{K_h}\right)}$ is the inertial link turning frequency.

$\omega_0 = \omega_h \sqrt{1 + \frac{K}{K_h}} = \sqrt{\frac{4\beta_e A_p^2}{V_t m_t} \left(1 + \frac{K}{K_h}\right)}$ is the combined natural frequency.

$\zeta_0 = \frac{1}{2\omega_0} \left[\frac{4\beta_e K_{ce}}{V_t \left(1 + \frac{K}{K_h}\right)} + \frac{B_p}{m_t}\right]$ is the combined damping ratio.

$K_h = \frac{4\beta_e A_p^2}{V_t}$ is the hydraulic spring stiffness.

The main performance parameters of servo motor speed affecting the output displacement of hydraulic cylinder are $\frac{K_{ps} A_p}{K}$, ω_r , ω_0 and ζ_0 . The proportional system $\frac{K_{ps} A_p}{K}$ is called the position amplification factor, which represents the sensitivity of servo motor speed to hydraulic cylinder displacement control. The position amplification system changes with the change of working point and is related to the load stiffness.

The integrated natural frequency ω_0 is the ratio of the stiffness of the hydraulic spring in parallel with the load spring to the load mass. The load stiffness increases the natural frequency of the second-order oscillation link, and the load stiffness reduces the damping ratio of the second-order oscillation link. The natural frequency ω_0 has an important effect on the response speed of the system.

The inertial link turning frequency is the ratio between the stiffness and damping of the hydraulic spring and the load spring in series. The ω_r varies with the load stiffness. If the load stiffness is very small, the ω_r is very small, and the inertia link can be approximately regarded as an integral link.

4. Control Scheme

The PCSM has nonlinearity and parameter perturbation. It is difficult to meet the robustness requirements of the system with simple proportion integration differentiation (PID) control. This paper proposes a sliding mode variable structure control algorithm. The dynamic invariance of the sliding mode variable structure control algorithm will effectively

overcome the disturbance of nonlinear factors to the control in the SM. The open-loop transfer function of the position servo in the PCSM is simplified into the transfer function of the following form:

$$x_p''' + a_2 x_p'' + a_1 x_p' + a_0 x_p = b_0 u(t) + d \quad (14)$$

where $u(t)$ is the system control input command, and d is the external compound interference of the system.

Selecting the output displacement of the cylinder as the state variable of the system, we can get

$$\begin{cases} x_1 = x_p \\ x_2 = x_p' \\ x_3 = x_p'' \\ y = x_1 \end{cases} \quad (15)$$

Further, the state equation of the position control system of the PCSM is

$$\begin{cases} x_1' = x_2 \\ x_2' = x_3 \\ x_3' = -a_0 x_1 - a_1 x_2 - a_2 x_3 + b_0 u(t) + d \end{cases} \quad (16)$$

Let r be the system input signal, and the system deviation $e = r - y$, we can make

$$\begin{cases} e_1 = e = r - y \\ e_2 = e' = r' - y' \\ e_3 = e'' = r'' - y'' \end{cases} \quad (17)$$

The above formula can be further written as

$$\begin{cases} e_1' = e_2 \\ e_2' = e_3 \\ e_3' = -a_0 e_1 - a_1 e_2 - a_2 e_3 - b_0 u(t) + F(t) \end{cases} \quad (18)$$

The error vectors of the sliding mode surface and the sliding mode surface of the position control system in the selected PCSM are

$$\begin{cases} C = \begin{bmatrix} c_1 & c_2 & 1 \end{bmatrix} \\ E = \begin{bmatrix} e & e' & e'' \end{bmatrix} \end{cases} \quad (19)$$

The sliding mode variable structure control switching function can be obtained as

$$s = CE = c_1(r - x_1) + c_2(r' - x_2) + (r'' - x_3) \quad (20)$$

Using exponential reaching law $rlaw = -\varepsilon \operatorname{sgn}(s) - ks$, then

$$s' = c_1(r' - x_2) + c_2(r'' - x_3) + (r''' - x_3') = rlaw \quad (21)$$

After finishing, the output of the system controller is

$$u = \frac{1}{b_0} \begin{bmatrix} r''' + c_1 e_2 + c_2 e_3 + a_0(r - e_1) \\ + a_1(r' - e_2) + a_2(r'' - e_3) + d - rlaw \end{bmatrix} \quad (22)$$

5. Experimental Research

In this study, we relied on the PCSM test platform to test the proposed sliding mode variable structure control strategy. The whole test platform is shown in Figure 5. A servomotor, a quantitative pump, hydraulic valves, and an accumulator were integrated into the cylinder. The cylinder was connected with the mechanical spring through the

control seat. The electric control cabinet integrated the axis controller, the servo drive, and the isolation module.

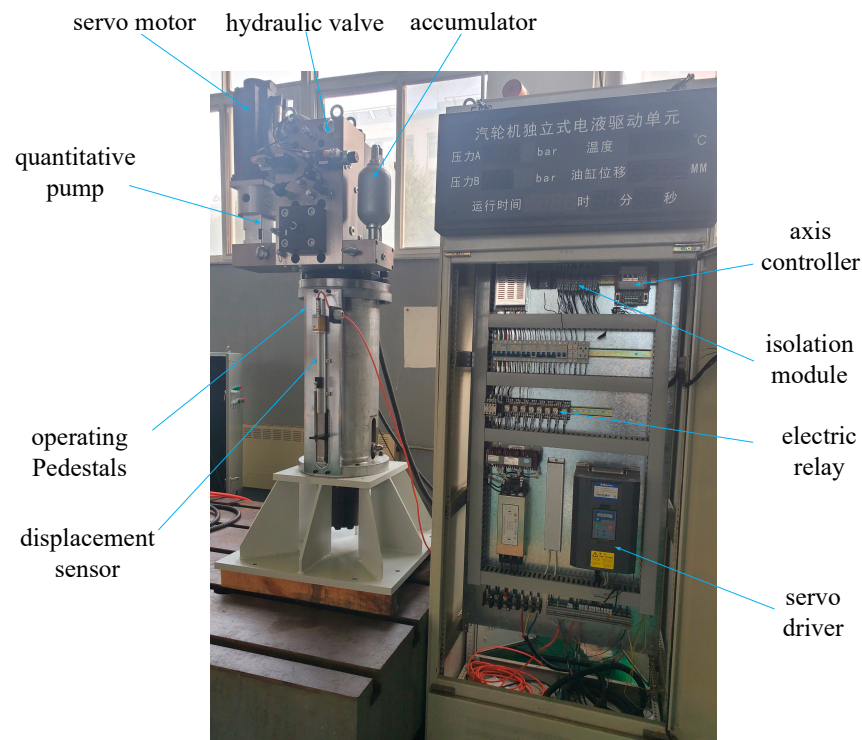


Figure 5. Test platform of PCSM.

The axis controller MACS software (here refers to Moog Axis Control Software) was used to compile the monitoring and data acquisition interface of the PCSM experiment platform based on codesys (here refers to Controlled Development System), as shown in Figure 6.

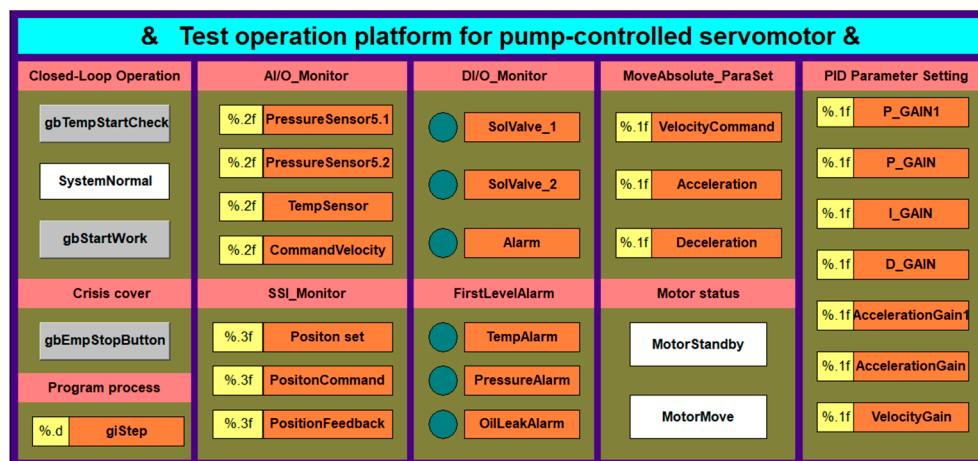


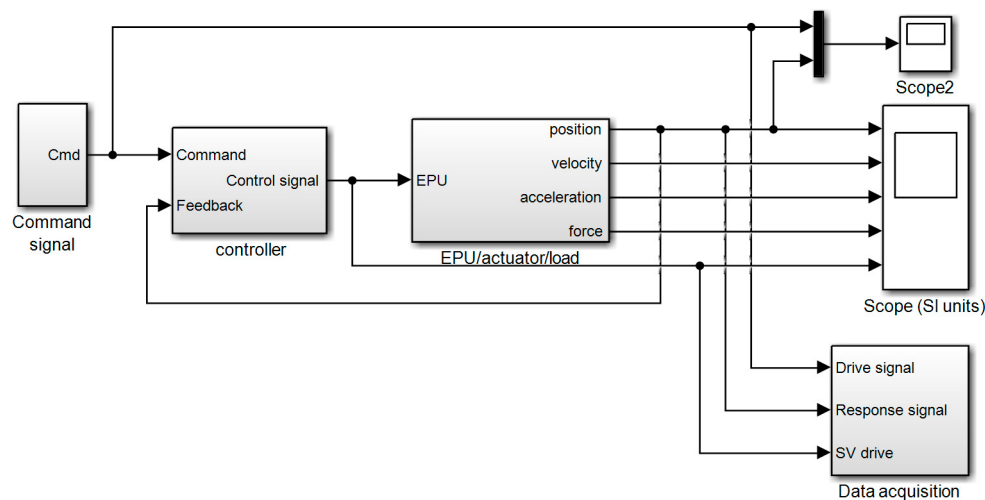
Figure 6. The test operation platform for the PCSM.

The working parameters of the PCSM test platform are shown in Table 1.

Table 1. Test platform parameter table.

Order Number	Name	Parameter	Unit
1	Servomotor rated torque	23.5	Nm
2	Servomotor rated speed	2000	r/min
3	Servomotor rated power	4.9	kW
4	Pump displacement	6.3	mL/r
5	Maximum speed of pump	3000	r/min
6	Maximum work pressure	21	MPa
7	Cylinder specifications	Φ135/Φ63–65	mm

Based on the PCSM test platform, according to the proposed sliding mode variable structure control algorithm, a system simulation platform was built using MATLAB/Simulink, including the servomotor module, quantitative pump module, cylinder module, and controller module. The simulation platform is shown in Figure 7.

**Figure 7.** Simulation platform of the PCSM.

The off-line semi-physical test of the SM and the steam turbine is carried out. Simulink is used to establish simulation models of the equivalent friction force of the system and the equivalent steam force of the steam control valve according to the mathematical models of Equations (8) and (9). Download to the system axis controller. In the actual test process, the simulation force is superimposed with the actual spring force of the spring seat and the hydraulic driving force of the hydraulic cylinder in the actual working process of the test bench to obtain the PCSM test platform environment. During the test, the valve regulating system of the steam turbine was simulated. When the steam control valve was closed, the cylinder of the PCSM received the position command to move from 0 to 10 mm. The test data are shown in Figure 8.

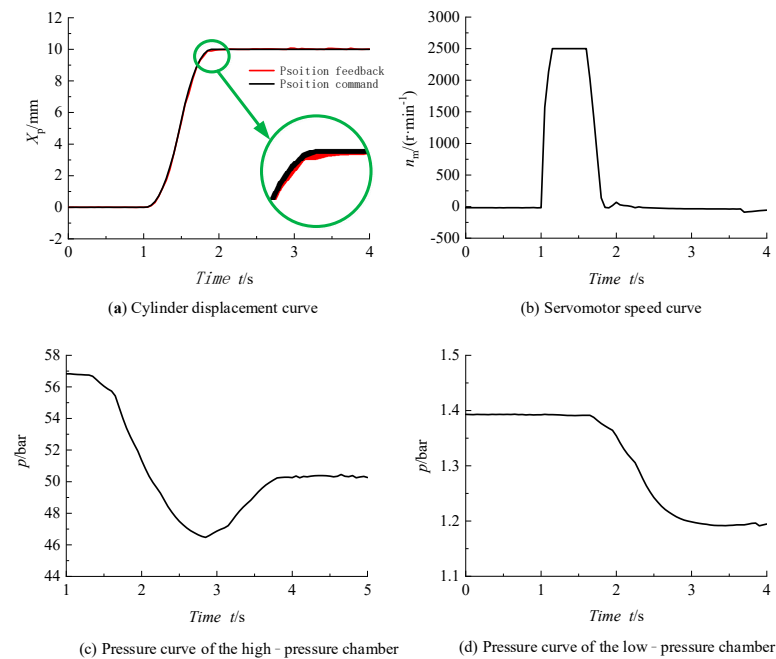


Figure 8. The response curve of valve closing test.

Figure 8 shows that using the sliding mode control strategy, the cylinder displaced from 0 to 10 mm, and the servomotor speed and system pressure responded quickly. At this time, the pressure in the high-pressure chamber was reduced, the lowest pressure in the high-pressure chamber was 46 bar, and the pressure in the low-pressure chamber was reduced by about 0.2 bar. The peak speed of the servomotor could reach 2500 r/min, and the position of the cylinder reached the steady-state position within 2 s. The steady-state accuracy of the cylinder position was ± 0.01 mm.

When the steam control valve was opened, the cylinder of the PCSM received the position command to move from 10 to 5 mm. The test data are shown in Figure 9.

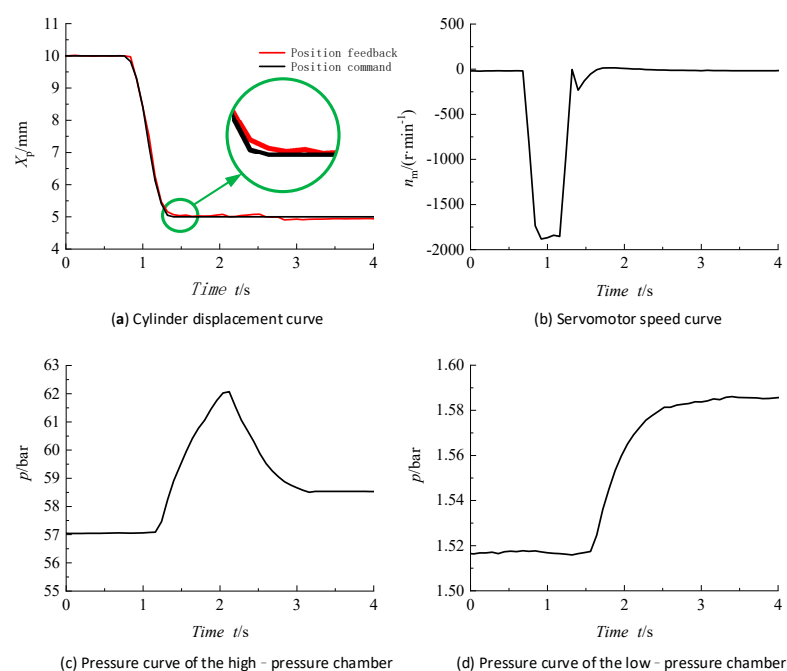


Figure 9. The response curve of valve opening test.

Figure 9 shows that using the sliding mode control strategy, the cylinder displaced from 10 to 5 mm, and the servomotor speed and system pressure responded quickly. At this time, the peak pressure of the high-pressure chamber was 62 bar, and the pressure in the low-pressure chamber increased by about 0.2 bar. The peak speed of the servomotor could reach -1800 r/min, and the position of the cylinder reached the steady-state position within 1.5 s. The steady-state accuracy of the cylinder position was ± 0.01 mm.

In order to confirm the superiority of the control strategy adopted in this study, a simple PID controller is set up in this paper for comparison with the sliding mode variable structure control, as shown in the Figure 10.

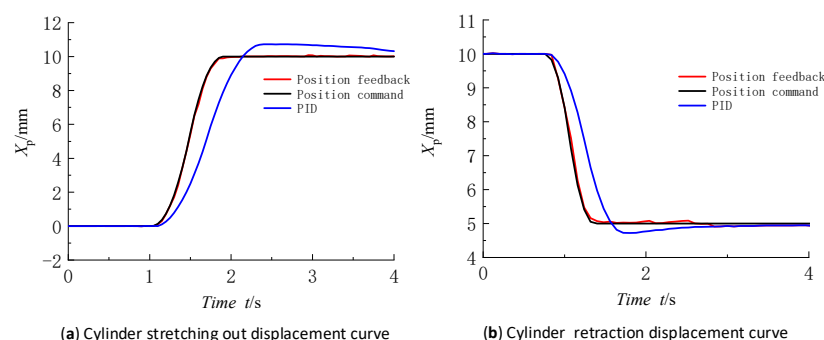


Figure 10. Control strategy performance comparison.

As shown in Figure 10, in the stretching and retraction stage of the hydraulic cylinder, compared with the displacement feedback obtained by simple PID adjustment, the following effect and control precision of the sliding mode variable structure control strategy are greatly improved. It fully shows that the sliding mode variable structure control strategy has a good control performance when applied to the PCSM system.

6. Conclusions

Based on extensive research on the steam turbine valve control system, this paper proposed a sliding mode variable structure control strategy for the position control of a PCSM. Aiming at the PCSM system, a mathematical model of the important components of the PCSM was established. Through mathematical modeling and simulation test analysis, we sought to solve the variable structure control law by constructing a switching function to overcome the system's nonlinear excitation interference, improve the system robustness, and realize the high-precision control of the PCSM position. Experimental analysis shows that the proposed control method has a good control effect, which lays the theoretical and technical foundation for the engineering application and promotion of SM technology. Therefore, high-precision position control of PCSM is suitable for adopting the sliding mode variable structure control strategy.

Author Contributions: Investigation, G.Y., Z.J., and T.Z.; Methodology, G.Y., Z.J., and P.Z.; Software, G.Y. and Z.J.; Simulation and Analysis, G.Y.; Experiment and Analysis, G.Y. and T.Z.; Writing and Editing, P.Z. and T.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the Key R&D Projects in Hebei Province (No. 20314402D) and the Key Project of Science and Technology Research in Hebei Province (No. ZD2020166).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Cao, L.; Jia, Y.; Li, P.; Hu, P.F.; Li, Y. Numerical analysis on leakage flow of blade tip stepped seal in steam turbine. *J. Zhejiang Univ.* **2016**, *50*, 1545–1550.
2. Chen, K.; Tang, R.; Li, C. Fractional order PI lambda controller synthesis for steam turbine speed governing systems. *Isa Trans.* **2018**, *77*, 49–57. [\[CrossRef\]](#)
3. Wang, P.; Ma, H.; Bryan, Q.; Santavicca, D.A.; Liu, Y. Computational fluid dynamics of steam flow in a turbine control valve with a bell-shaped spindle. *Appl. Therm. Eng. Des. Process. Equip. Econ.* **2018**, *129*, 1333–1347. [\[CrossRef\]](#)
4. Qi, J.; Jin, G.; Yang, T. Effect of turbine deh proportional differential feedforward control on stability of the power system. *J. Chin. Soc. Power Eng.* **2019**, *39*, 280–285.
5. Wang, X.; Li, X.; Li, F. Analysis on oscillation in electro-hydraulic regulating system of steam turbine and fault diagnosis based on PSOBP. *J. Expert Systems with Applications.* **2010**, *37*, 3887–3892.
6. Pondini, M.; Signorini, A.; Colla, V. Steam Turbine Control Valve and Actuation System Modeling for Dynamics Analysis. *J. Energy Procedia.* **2017**, *105*, 1651–1656. [\[CrossRef\]](#)
7. Xue, L.; Wu, S.; Xu, Y.; Ma, D. A Simulation-based multi-objective optimization design method for pump-driven electro-hydrostatic actuators. *Processes* **2019**, *7*, 274. [\[CrossRef\]](#)
8. Pondini, M.; Signorini, A.; Colla, V.; Barsali, S. Analysis of a simplified steam turbine governor model for power system stability studies. *Energy Procedia* **2018**, *158*, 2928–2933. [\[CrossRef\]](#)
9. Pondini, M.; Colla, V.; Signorini, A. Models of control valve and actuation system for dynamics analysis of steam turbines. *Appl. Energy* **2017**, *207*, 208–217. [\[CrossRef\]](#)
10. Abhay, P.; Shyam, S.; Wang, Y.; Solom, M.; Kirkland, K.V. Characterization of steam impulse turbine for two-phase flow. *Int. J. Heat Fluid Flow* **2019**, *79*, 1–11.
11. Azizi, M.A.; Brouwer, J. Progress in solid oxide fuel cell-gas turbine hybrid power systems: System design and analysis, transient operation, controls and optimization. *Appl. Energy* **2018**, *215*, 237–289. [\[CrossRef\]](#)
12. Chen, Z.; Yuan, X.; Yuan, Y.; Lei, X.; Zhang, B. Parameter estimation of fuzzy sliding mode controller for hydraulic turbine regulating system based on HICA algorithm. *Renew. Energy* **2019**, *131*, 551–565. [\[CrossRef\]](#)
13. Yong, Z.; Ming, L.; Chaoyang, W.; Li, X.; Chong, D.; Yan, J. Increasing operational flexibility of supercritical coal-fired power plants by regulating thermal system configuration during transient processes. *Appl. Energy* **2018**, *228*, 2375–2386.
14. Dong, Y.; Yang, Z.; He, C.; Wu, A. *Design of Virtual Simulation Experiment Project for Steam Turbine DEH System Oriented to Engineering Education, Proceedings of the 2019 International Conference on Advanced Education Research and Modern Teaching (AERMT 2019)*; Atlantis Press: Paris, France, 2019.
15. Cao, Y.; Wu, F. Nonlinear dynamic analysis and fuzzy control of turbine regulating system. *Turbine Technol.* **2015**, *57*, 203–206, 209.
16. Chen, J.; Wang, B.; Chang, H.; Ma, C.J.; Jiang, J.H.; Liu, Q.H. Research on direct drive volume control electro-hydraulic servo cylinder of feed water pump turbine. *Turbine Technol.* **2010**, *38*, 96–100.
17. Kou, F.; Du, J.; Wang, Z.; Li, D.; Xu, J. Nonlinear modeling and coordinate optimization of a semi-active energy regenerative suspension with an electro-hydraulic actuator. *Algorithms* **2018**, *11*, 12. [\[CrossRef\]](#)
18. Buchun, S.; Lee, D.; Sang, Y.P. Design and performance of nonlinear control for an electro-hydraulic actuator considering a wearable robot. *Processes* **2019**, *7*, 1–6.
19. Minh, T.N.; Tri, D.D.; Kyoung, K.A. Application of electro-hydraulic actuator system to control continuously variable transmission in wind energy converter. *Energies* **2019**, *12*, 1–19.
20. Wei, G.; Miao, W.; Tao, L.I. Fractional Order PID Sliding Mode Variable Structure Control based Inverter Circuits. *Control Eng. China* **2019**, *26*, 1397–1404.
21. Bin, W.; Kun, Z.; Xiaoyan, S. Direct Torque Control of Permanent Magnet Synchronous Motor Based on Sliding Mode Variable Structure. *Open Access Libr. J.* **2019**, *6*, 1–10.
22. Zhao, Z.; Li, M.; Wang, C.; Jiang, L.; Wang, M. Dynamic Modeling of Brake in Power-Split DHT and Pressure Tracking Control with Sliding Mode Variable Structure Method. *Int. J. Automot. Technol.* **2019**, *20*, 521–530. [\[CrossRef\]](#)
23. Bu, W.; Zhang, X.; He, F. Sliding mode variable structure control strategy of bearingless induction motor based on inverse system decoupling: SMVS control of blim based on inverse decoupling. *IEEE Trans. Electr. Electron. Eng.* **2018**, *13*, 1052–1059. [\[CrossRef\]](#)
24. Yong, H.; Lei, W. Integral Sliding Mode Variable Structure Control for Five-DOF Active Magnetic Bearing. *Bearing* **2017**, *4*, 16–20.
25. Huali, G.U.; Kairu, Z.; Dongzhao, D.I. The PWM Rectifier Based on Fuzzy Adaptive Sliding Mode Variable Structure. *Power Syst. Clean Energy* **2016**, *32*, 40–45, 50.
26. Zheng, B.-C.; Fei, S.; Liu, X. Event-Triggered and Memory-Based Sliding Mode Variable Structure Control for Memristive Systems. *Electronics* **2018**, *7*, 253. [\[CrossRef\]](#)
27. Brian, A.-H.; Dupont, P.; Carlos, C.D.W. A survey of models, analysis tools and compensation methods for the control of machines with friction-ScienceDirect. *Automatica* **1994**, *30*, 1083–1138.