RESEARCH ON THE PRINCIPLE OF THE ELECTRONIC CLOSED-LOOP SYSTEM OF PROPORTIONALLY ENLARGED VALVES BASED ON PID CONTROL WITH GENETIC ALGORITHM

by

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Existing proportional throttle valves, which utilize a proportional control pilot stage and cartridge valve, suffer from poor dynamic performance and high steady-state errors. This paper takes the Valvistor valve as the research object and proposes an electronic closed-loop feedback control method. This method applies proportional-integral-derivative control based on the genetic algorithm to monitor the valve operation in real-time, aiming to enhance its performance. Additionally, MEMS technology is integrated, and sensitive and miniaturized sensors are used to achieve real-time parameter monitoring. A SimulationX model is built for analysis. The results show that the closed-loop - controlled valve has a response time 20 ms faster than the original valve and exhibits no overshoot. After optimizing the proportional-integral-derivative parameters and adding a feed - forward controller, the valve demonstrates excellent dynamic performance, meeting all requirements. This research provides an effective solution for improving the performance of proportional throttle valves and holds great significance for the development of hydraulic control systems.

Key words: *valvistor valve, electronically closed-loop control, genetic algorithm, proportional-integral-derivative control, MEMS technology, proportional throttle valve*

Introduction

In the intricate and vital hydraulic system, the throttle valve [1, 2] plays a pivotal role. The system efficacy is attributable to its capacity for precise load speed regulation, achieved through throttle opening adjustment and system flow regulation. This versatility has led to its extensive utilization across a range of applications. The electro-hydraulic proportional control throttle valve [3, 4] has emerged as the prevailing standard due to its simplicity, high frequency response, and noteworthy precision control characteristics. This transition can be attributed to the continuous evolution of electrical components and the mounting demand for enhanced precision in hydraulic systems.

During the 1980's, the development of electro-hydraulic proportional throttle valves underwent a significant transformation with the rapid advancement of cartridge valve technology. Cartridge valves garnered increased attention due to their capacity to meet the de-

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mands of high pressure and substantial flow volumes [5, 6]. Consequently, numerous principles and products incorporating cartridge valves emerged.

The hydraulic feedback proportional throttle valve [7, 8] has garnered significant attention in practical applications due to its flow-amplifying capability. It was designated the hydraulic triode, analogous to the triode in the electronic field. Following the introduction of the Valvistor valve [9, 10], numerous scholars have undertaken research endeavors focusing on this subject. For instance, Luomaranta *et al.* [11] employed the Valvistor valve to regulate a single-rod hydraulic cylinder and developed a comprehensive mathematical model of the system. Through the implementation of simulation and experimental methodologies, the validity of the proposed scheme was substantiated. Hao *et al.* [12] conducted a study of an electro-hydraulic proportional flow valve, exploring the valve performance when controlled by a pilot pump. A series of experiments and analyses were conducted, yielding results that offer insights into the optimization of these valves within hydraulic systems.

However, extant proportional throttle valves continue to confront challenges, including suboptimal flow control accuracy and deficient dynamic response [13, 14]. The present study focuses on the Valvistor valve. In order to rectify the aforementioned issues, a proposal is put forth for a proportional-integral-derivative (PID) self-tuning control algorithm that is based on the genetic algorithm. Furthermore, an electric closed-loop control system is to be integrated into the Valvistor valve. This apparatus facilitates precise measurement and real-time feedback of the valve operating state, thereby markedly enhancing the valve response characteristics.

Furthermore, the present study investigates the implementation of micro-electro-mechanical systems (MEMS) technology [15-17]. The MEMS-based sensors, characterized by their high sensitivity and miniaturized form factor, can be integrated into the valve system. This integration enables the precise and instantaneous monitoring of parameters such as pressure, flow rate, and temperature. This integration does not result in a substantial alteration of the valve dimensions or functionality.

The Valvistor valve system is characterized by its stringent requirements for high-precision flow control, rapid and accurate dynamic response, and long-term operation stability. The proposed PID self-tuning control algorithm, based on the genetic algorithm, continuously optimizes the control parameters with the objective of improving flow control accuracy [18, 19]. The incorporation of electric closed-loop control facilitates real-time observation and assessment of the valve condition, thereby augmenting its dynamic responsiveness. The integration of MEMS technology with highly sensitive sensors enables precise parameter measurement, thereby enhancing the overall performance and stability of the Valvistor valve system.

The objective of this research is to develop an advanced control system for the Valvistor valve. The implementation of a genetic algorithm-based PID control strategy, in conjunction with the integration of MEMS technology, is intended to enhance the valve dynamic response and ensure enhanced accuracy. It is hypothesized that this approach can effectively reduce the valve response time, eliminate overshoot, and enhance its adaptability to varying pressure differences. The effectiveness of the proposed method will be verified through comprehensive simulations and analyses.

Conventional PID control frequently encounters challenges in accurately calibrating parameters for intricate systems, leading to suboptimal control outcomes. The genetic algorithm, an optimization algorithm with the characteristic of global search, can find the best-fit PID parameter combinations in a complex parameter space. This improvement in control performance of the system is significant. In analogous industrial automation domains, the genetic algorithm has been successfully implemented to optimize various control strategies, yielding commendable outcomes. To address the limitations of conventional PID control, we have incorporated the genetic algorithm into the PID control framework. This integration aims to enhance the precision and efficiency of control systems.

Working principle of electronically controlled proportional amplifying valve

The electrically controlled proportional amplifier valve, designated as the Valvistor valve, is a state-of-the-art hydraulic component. The system is composed of several key elements that work in harmony to achieve precise control and regulation.

Firstly, the pilot valve fulfills a pivotal function in the initiation and regulation of fluid flow. It serves as the initial point of departure for the operation, thereby establishing the foundation for the subsequent components to function effectively.

The main valve is the central component that regulates the overall flow and pressure within the system. The primary function of this apparatus is to ensure the precise direction and control of the fluid, in accordance with the particular demands of the specific application.

A proportional electromagnet plays a critical role in this system by providing the requisite force to regulate the movement of valve components. This configuration enables precise calibration and expedites responsiveness.

The incorporation of a displacement sensor facilitates precise measurement of the displacement of the valve elements. This innovation enables precise control by providing real-time feedback on the position of the valve, allowing for adjustments to be made as needed.

The inclusion of an amplifier serves to enhance the electrical signals, thereby ensuring optimal control of the electromagnet. This ensures that the electromagnet receives the correct signals to operate effectively.

The feedback slot is engineered to facilitate feedback regarding the operation of the valve, thereby ensuring precise control and stability. The implementation of continuous monitoring of valve performance facilitates the expeditious identification and rectification of any deviations.

Additionally, a PID controller has been integrated to ensure precise calibration of the valve performance [20]. The PID controller is designed to ensure that the valve operates at optimal efficiency and accuracy by continuously monitoring and adjusting the control parameters.

Additionally, the implementation of MEMS technology has the potential to augment the functionality of the Valvistor valve [21, 22]. The integration of MEMS-based sensors into the valve system facilitates the acquisition of precise and real-time data on various parameters, including pressure, flow rate, and temperature. These sensors offer high sensitivity and miniaturized form factors, allowing them to be seamlessly incorporated within the valve structure without significantly affecting its overall size and functionality. The integration of conventional components with MEMS technology has the potential to enhance the performance and reliability of the Valvistor valve.

The schematic diagram of the Valvistor valve, as depicted in fig. 1, offers a visual depiction of the intricate interconnection and operation of these components [23].

The proportional electromagnet is responsible for generating the force that enables the precise control of the pilot valve movement. Subsequently, the pilot valve exerts influence on the pressure within the upper cavity of the main valve, thereby affecting the position of the main valve poppet and its interaction with the valve sleeve. The feedback position sensor is responsible for measuring the displacement of the valve elements for the purpose of control.

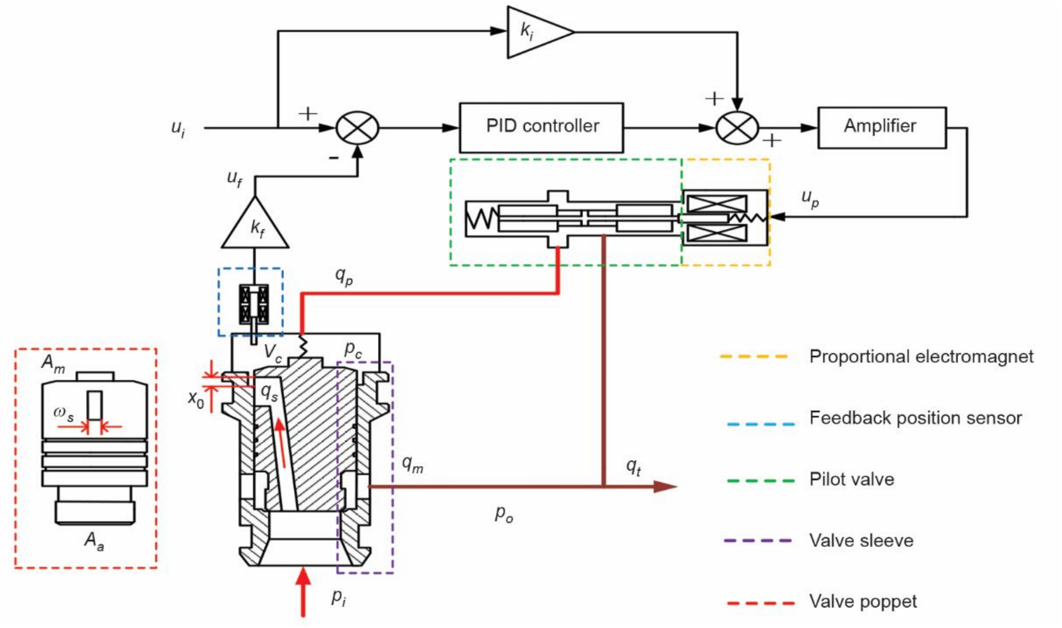

Figure 1. Schematic diagram of the Valvistor valve

Valvistor valve working principle of the original valve

When the proportional electromagnet is de-energized, the pilot valve remains in its original state due to the action of spring force. At this juncture, hydraulic oil at the oil inlet of the main valve enters the spring chamber through the feedback narrow port x_0 of the flow valve. Consequently, the pressures in the spring chamber and the oil inlet chamber are equal. The large ratio of the upper and lower areas of the main valve core (A_m:A_a) results in the main valve being closed under the combined action of the upper and lower chamber pressures and spring force.

The input of a control signal to the proportional electromagnet results in the electromagnet becoming energized and generating an electromagnetic force. This force exerts a pressure on the pilot valve core, causing the pilot valve to undergo a corresponding displacement. The upper cavity of the main valve is then connected to the load through the pilot valve, leading to a drop in pressure in the upper cavity. The pressure differential between the upper and lower chambers exerts a force on the main valve, causing it to move upward. This movement is opposed by the spring force. Consequently, the valve port of the main valve is opened, allowing hydraulic oil to flow to the load through the main valve port. As the primary valve core ascends a specific distance, the influx of hydraulic oil into the upper cavity of the main valve is augmented. The phenomenon of an augmented feedback throat has been observed to be concomitant with an increase in pressure within the upper cavity. When the pressures in the upper and lower cavities of the main valve are balanced, the main valve ceases to move.

Upon deactivation of the proportional electromagnet, the pilot valve core will revert to its original position due to the action of spring force. Consequently, the primary valve will revert to its original position due to the combined effects of the return spring and the pressure within the upper chamber. Presently, the primary valve port will be closed.

Working principle of Valvistor electric closed-loop system

Firstly, the proportional electromagnet is equipped with an input signal UI. The input signal, which is the focus of this study, exerts control over the proportional electromagnet, thereby inducing the production of a displacement signal. The primary valve is equipped with a displacement sensor. The functionality of the sensor encompasses the acquisition of the actual displacement signal of the main valve core and its subsequent conversion into a voltage signal U_f. Subsequently, the two signals, u_i and u_f, are subtracted by a subtractor to generate a deviation signal, u_e. The adjustment of this deviation signal U_e is facilitated by a PID controller. The final stage of the signal evolution is its output to the proportional electromagnet, facilitated by an amplifier. The output signal is responsible for actuating the pilot valve core, thereby regulating the displacement of the main valve. The control schematic diagram is illustrated in fig. 2.

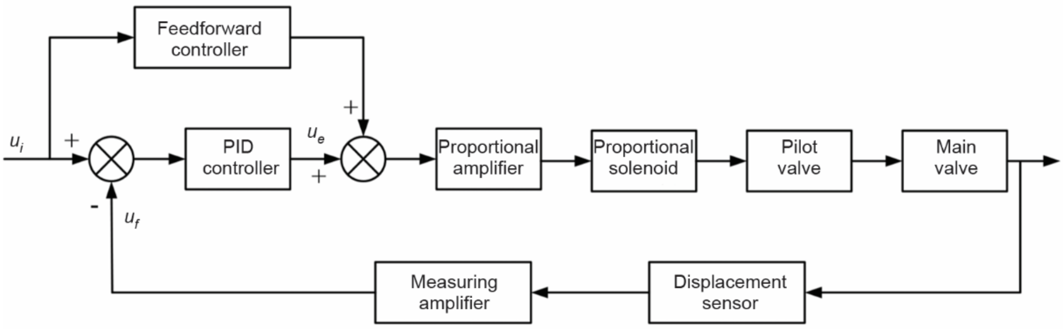

Figure 2. Schematic diagram of electric closed-loop control of Valvistor valve

In the context of an electric closed-loop control system, the incorporation of a feed -forward controller is paramount for ensuring the uninterrupted and stable operation of the system. In the event of a failure in the displacement sensor or measuring amplifier, the feedforward controller is designed to provide a reliable backup. It is important to note that the system is capable of generating control signals to ensure the uninterrupted regulation of the displacement of the main valve. This is of great significance, as it helps avoid out-of-control failures that could otherwise lead to disastrous consequences. The feedforward controller has been demonstrated to enhance the safety of the flow valve by ensuring the proper functioning of the main valve even in the face of sensor or amplifier failures.

Mathematical model of Valvistor valve

The Valvistor valve is composed of two distinct parts: the pilot valve and the main valve. Consequently, in order to establish a mathematical model for the valve, it is necessary to create two separate system mathematical models. In this section, the motion equations of the main valve and the pilot valve are established, respectively, in accordance with Newton's second law. Subsequent to this, flow equations for both components are also established. The complete mathematical model of the system can be obtained by establishing a connection between the flow equations according to the upper cavity of the main valve spool. The transfer function of the flow valve can be derived through the application of Laplace transformation and proper arrangement. This comprehensive approach facilitates a detailed understanding and analysis of the Valvistor valve behavior and performance.

In order to simplify the mathematical model, the following assumptions are made. The first point to consider is the spring of the main valve, which functions as a return spring. Its stiffness can be disregarded in this context. Secondly, the influence of temperature on the viscosity of hydraulic oil in the valve should be ignored. Finally, the influence of the dynamic characteristics of the pilot valve should also be disregarded.

The formula of flow change caused by pilot spool movement is:

$$q_p = C_{dp}\omega_p x_p \sqrt{\frac{2}{\rho}(p_c - p_o)} \tag{1}$$

The motion formula of the main valve is:

$$\frac{1}{2}A_m p_i + \frac{1}{2}A_m p_o - A_m p_c - F_{sf} = m\frac{\mathrm{d}^2 x_m}{\mathrm{d}t^2} + B_m\frac{\mathrm{d}x_m}{\mathrm{d}t} + k_m x_m \tag{2}$$

For the terms $1/2A_m p_i$ and $1/2A_m p_o$, they are derived from a detailed force analysis considering the pressure distribution and area relationships within the valve. This formulation provides a more accurate description of the forces acting on the valve components compared to alternative simpler expressions.

The force, F_{sf} is the force exerted by the feedback slot, which is an essential part of the valve feedback mechanism.

Regarding the term $k_m x_m$, although the spring of the main valve is ignored in some subsequent analyses, it was initially included in the equation as part of the general force balance equation. To avoid confusion, it should be noted that its presence does not imply that the spring force is considered in all aspects of the analysis. In the current context, its value is zero under the assumption of ignoring the spring stiffness, but it remains in the equation for the sake of maintaining the integrity of the original force balance equation structure.

In this section, we will first introduce the general theory of flow forces in poppet valves and how they are generated. Then, we will derive the expressions for calculating these forces based on the valve geometry and operating conditions. After that, we will incorporate these flow force terms into the motion equation, eq. (2), and analyze the impact on the dynamics of the proposed controller. We will use simulations and, if possible, theoretical analyses to demonstrate how the inclusion of flow forces changes the behavior of the valve system.

The flow equation of the main valve is:

$$q_m = C_{dm}\omega_m x_m \sqrt{\frac{2}{\rho}(p_i - p_o)} \tag{3}$$

The flow equation of the feedback throat of the main valve is:

$$q_s = C_{ds}\omega_s (x_0 + x_m)\sqrt{\frac{2}{\rho}(p_i - p_c)} \tag{4}$$

Because the flow rate of the $A_m[(\mathrm{d}x_m)/\mathrm{d}t]$ is much smaller relative to the pilot valve and the feedback slit, so it can be ignored, thus this equation can be concluded:

$$\frac{V_c}{\beta}\frac{\mathrm{d}p_c}{\mathrm{d}t} = q_p - q_s \tag{5}$$

Thus, the pressure dynamics, modeled by the continuity equation, can be applied to the upper chamber, resulting in eq. (5). This shows how the continuity of fluid flow leads to the specific pressure variation within the upper chamber of the valve, which is crucial for understanding the valve behavior.

Under the condition of ignoring the steady-state hydraulic force and the main valve spring, the above formula can be obtained by small incremental transformation and linear treatment:

$$ms^2 X_m + B_m s X_m = P_i A_a + P_0 (A_m - A_a) - P_c A_m \tag{6}$$

$$Q_m = K_{Qm} X_m \tag{7}$$

$$Q_p = K_{Qp} U_p + K_{Pp} P_c \tag{8}$$

$$Q_s = K_{Qs} X_m - K_{Sp} P_c \tag{9}$$

$$sP_c = \frac{\beta_e}{V_c} (Q_s + A_m s X_m - Q_p) \tag{10}$$

where

$$K_{Qm} = C_d \omega_m \sqrt{\frac{2}{\rho}(p_{i0} - p_{o0})}, \quad K_{Qp} = C_d \omega_p k_p \sqrt{\frac{2}{\rho}(p_{c0} - p_{o0})}, \quad K_{Pp} = \frac{C_d \omega_p k_p u_{p0}}{\sqrt{2\rho(p_{c0} - p_{o0})}}$$

$$K_{Qs} = C_d \omega_s \sqrt{\frac{2}{\rho}(p_{i0} - p_{c0})}, \quad K_{Sp} = \frac{C_d \omega_s (x_m + x_0)}{\sqrt{2\rho(p_{i0} - p_{c0})}}$$

Although $A_m x_m$ was ignored in the time domain analysis for simplification purposes, it remains in the Laplace-transformed equation because the Laplace transform operates on the entire equation structure. Its presence in the transformed equation does not imply that it has a significant impact on the final results, but rather it is a consequence of the mathematical transformation process.

Because the gap between the valve core and the valve sleeve is full of oil, according to the Assumption 2, the damping coefficient B_m of the main valve can be ignored, so the transfer function can be obtained:

$$X_m = \frac{A_m K_{Qp}}{As^3 + Bs^2 + Cs + D} U_p \tag{11}$$

where $A = (V_c / \beta_e) m, B = K_{Sp} m + K_{Pp} m, C = A_m^2$, and $D = A_m K_{Qs}$.

The gains K_{Qm}, K_{Qp}, K_{Pp}, K_{Qs}, and K_{Sp} are obtained through linearization at the operating point 0. The subscript 0 refers to the nominal operating conditions of the valve, which are determined based on the typical application scenarios. Specifically, K_{Qm} represents the gain for the flow rate change with respect to the main valve displacement around the operating point 0. The K_{Qp} is the gain for the flow rate change with respect to the pressure difference across the valve at the operating point 0. Similarly, K_{Pp} relates the pressure change in the pilot valve to the pressure difference across the main valve at the operating point 0. The K_{Qs} is the gain for the flow rate change through the feedback slot with respect to the pressure difference across the feedback slot at the operating point 0. Finally, K_{Sp} involves the state variable x_m and represents the gain for the pressure change in the upper chamber of the main valve with respect to the main valve displacement around the operating point 0.

The PID control based on genetic algorithm

The process of genetic algorithm consists of four main steps: parameter range determination, initial population selection, function determination, and genetic algorithm operation. The main contents are as follows.

Determine the parameter range

When applying genetic algorithm to PID value tuning, although it does not require experience and complicated rules, it is necessary to determine the approximate range of parameters. This range is usually provided by the user and then coded according to the required accuracy. The main form of coding is binary coding. Each parameter is represented by a binary string, and then operations can be performed on its string.

Selecting an initial population

The main iterative operation process of genetic algorithm is realized through a population, which can determine the complexity of the calculation. In this paper, the initial population is randomly generated by a computer.

Determine the function

The optimization of PID aims to select a set of optimal values that meet specific conditions within the parameter range. The evaluation indexes of a control system mainly include accuracy, stability, and rapidity. However, these three indexes interact with each other. For example, if the rising time of the control system is too fast, it will easily lead to instability. To achieve good control effects, the control quantity, rising time, and error are determined as the constraints of the control system. The adaptive function is related to the objective function of optimization.

For the optimization of PID parameters, we employed the MATLAB Control System Toolbox. We modeled the system dynamics using eq. (11) and combined it with the transfer function of the PID controller to create a closed-loop system model.

It should be noted that the feedforward controller was not part of the initial optimization process within MATLAB. After obtaining the optimized PID parameters, we further analyzed the performance of the system with the feedforward controller in the SIMULATIONX model [24]. This allowed us to assess the combined effect of the PID and feedforward controllers on the valve performance and make necessary adjustments to the feedforward controller parameters.

Operating genetic algorithm

The operating genetic algorithm is predicated on the copying of strings based on adaptation values and probabilities [25, 26]. Subsequently, a crossover event occurs with a specified probability. Finally, mutation occurs with a low probability. This process is repeated iteratively until a new population that meets the requirements is obtained. This method is iterative in nature and is employed for the purpose of optimization.

First, perform copying. The adaptation value is calculated by the aforementioned adaptation function, and then the corresponding copy probability is calculated for each string. Multiplying the number of strings in each generation by the copy probability will serve as the copy number for the next generation. Those with a small copy probability will be eliminated. Then, perform crossover. The probability of crossover is set to P_c. The copied strings are randomly matched with the probability of P_c, and the crossover-matching position is also random. Finally, perform mutation through the probability of P_m. The probability of mutation is relatively low, mainly by transforming the string bits into 0 and 1. After copying, crossover, and mutation, the initial random population will obtain a new population. Then, substitute it into the adaptation function to check if it meets the requirements. If it does not meet the requirements, repeat the operation until it meets the requirements.

Based on the transfer function, this paper uses MATLAB to optimize the PID parameters for the controlled object. To obtain good dynamic characteristics, the time integration performance of the absolute value of error is used as the evaluation index of the system and as the objective optimization function. At the same time, to prevent the system from having excessive capacity impact, the input square term is added to the objective optimization function.

The formula of its optimal index is:

$$J = \int_{0}^{\infty} [\omega_1 |e(t)| + \omega_2 u^2(t)]\,\mathrm{d}t + \omega_3 t_u \tag{12}$$

where $e(t)$ is the error of control system, $U(t)$ – the output of the controller, t_u – the rising time, and ω_1, ω_2, and ω_3 – the weights.

In order to avoid overshoot of the control system, a penalty function is adopted, and its expression is:

$$f\ e(t) < 0 \qquad J = \int^{\infty} [\omega_1 |e(t)| + \omega_2 u^2(t) + \omega_4 |e(t)|]\,\mathrm{d}t + \omega_3 t_u \tag{13}$$

In this algorithm, the initial population is 50, the crossover probability $P_c = 0.9$ and the mutation probability $P_m = 0.033$. The value ranges of the three parameters of PID are [0, 2], [0, 10], and [0, 1] respectively, and $\omega_1 = 0.999$, $\omega_2 = 0.001$, $\omega_3 = 2$, and $\omega_4 = 100$. The optimization process of the optimal objective function J can be obtained through 250 iterations by using real number coding, as shown in fig. 3. The optimal tuning results of PID are $kp = 1.8520$, $k_i = 7.2413$, and $k_d = 0.0098$.

When applying the genetic algorithm, a probability-based approach is used to drive the evolutionary process. The selection probability of each individual in the population is calculated based on its fitness value. This fitness value is related to how well the corresponding set of PID parameters performs in terms of achieving good control effects such as minimizing the error between the desired and actual valve behavior.

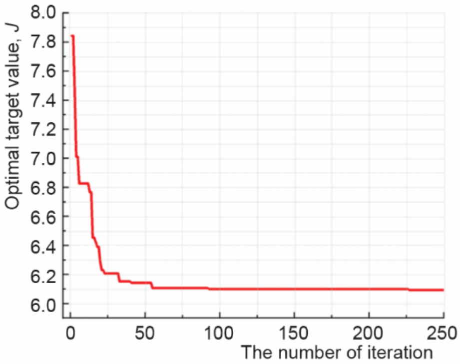

Figure 3. Iterative process of optimal function

The crossover probability, P_c, determines the chance of two selected individuals undergoing a crossover operation. During this operation, parts of their genetic material are exchanged to create new offspring with potentially improved characteristics.

The mutation probability, P_m, represents the likelihood of a random mutation occurring in an individual genetic material. This helps in maintaining genetic diversity within the population and exploring new areas of the solution space.

Discussion and conclusion

This study concentrated on the Valvistor valve to address the issues of low flow control accuracy and poor dynamic response in existing proportional throttle valves. By integrating a PID control strategy based on the genetic algorithm and MEMS technology, especially the fractal MEMS technology [27, 28], and AI technology [29, 30] significant improvements will be made to the valve performance.

The genetic algorithm effectively optimized the PID parameters. Through a series of steps, including determining the parameter range, randomly generating the initial population, defining an optimization function considering control system accuracy, stability, and rapidity, and performing genetic algorithm operations such as copying, crossover, and mutation, the optimal PID values were obtained. This approach overcame the challenges of traditional PID parameter tuning in complex systems.

An electric closed-loop control system for the Valvistor valve was constructed and analyzed. A SIMULATIONX model was developed based on the actual parameters of the valve. The simulation results indicated that under the optimized PID control, the valve response time was notably faster than that of the original valve, with almost no overshoot. For instance, in the step response of the main valve displacement, the rising response time was approximately 30 ms, 45 ms faster than the original valve, and the descending step response time was around 35 ms, 20 msfaster than the original valve. These improvements demonstrated the effectiveness of the proposed control method in enhancing the valve dynamic performance.

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