

**МЕХАНІЧНА ІНЖЕНЕРІЯ (G9, G8, G11)**

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**STUDY ON ENERGY EFFICIENCY OPTIMIZATION METHOD OF HYDRAULIC SYSTEMS BASED ON POWER LOSS SUPPRESSION**

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**ДОСЛІДЖЕННЯ МЕТОДУ ОПТИМІЗАЦІЇ ЕНЕРГОЕФЕКТИВНОСТІ ГІДРАВЛІЧНИХ СИСТЕМ НА ОСНОВІ ЗМЕНШЕННЯ ВТРАТ ПОТУЖНОСТІ**

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***Abstract.** This paper conducts research focusing on the core requirements of power loss suppression and energy efficiency optimization in hydraulic systems. By analyzing the power transmission paths and loss characteristics of hydraulic systems, a dynamic power loss model of the system is established, and an energy efficiency optimization method integrating loss modeling and an improved optimization algorithm is proposed. Based on the technical route of theoretical modeling, simulation analysis, and experimental verification, the effectiveness of the proposed method in suppressing power loss and improving system energy efficiency is verified. The research results show that this optimization method can significantly reduce the power loss rate of hydraulic systems and improve energy utilization efficiency, providing a theoretical basis and technical support for the energy-saving design and efficient operation of hydraulic systems.*

***Keywords:** hydraulic systems, power loss suppression, energy efficiency optimization, dynamic modeling, genetic algorithm.*

***Анотація.** Ця стаття присвячена дослідженню основних вимог щодо зменшення втрат потужності та оптимізації енергетичної ефективності гідравлічних систем у промисловій сфері. Мета – поширення проблеми гідравлічних систем за різних режимів роботи, зокрема втрати енергії та складності механізмів втрат, запропоновані технічні рішення для підвищення економічності експлуатації та енергозбереження систем. На підставі системного аналізу шляхів передавання потужності основних компонентів (гідравлічні насоси, контрольні клапани, гідравлічні циліндри, трубопроводи), детального вивчення основних типів втрат (тиску, рідини) і їхніх характеристик, з урахуванням закономірностей змін динамічних режимів роботи розроблено динамічну модель втрат потужності системи, яка більш точно відображає реальний стан експлуатації. На цій основі запропоновано метод оптимізації енергетичної ефективності, який інтегрує моделювання втрат і вдосконалений оптимізаційний алгоритм (вдосконалений генетичний алгоритм, ВГА), забезпечуючи органічне поєднання кількісного аналізу втрат та інтелектуальної оптимізації. Дослідження здійснено за повним технічним маршрутом «теоретичне моделювання – симуляційний аналіз – експериментальна перевірка», для якого вибрано три типових режими роботи (легке*

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навантаження з низькою швидкістю, середнє з середньою, важке з високою) для проведення порівняльних експериментів. Із подвійною перевіркою моделі симуляції Simulink та експериментальної платформи гідравлічної системи оцінено адаптивність і ефективність запропонованого методу за різних режимів роботи. Результати досліджень показують, що цей оптимізаційний метод значно зменшує рівень втрат потужності гідравлічних систем, при цьому ефект зменшення енергоспоживання є більш вираженим порівняно з традиційними схемами, а також підвищує ефективність використання енергії і стабільність роботи системи. Результати створюють міцну теоретичну основу та практичне технічне забезпечення для енергозберігаючого конструктивного проектування, адаптивного керування режимами роботи і ефективної експлуатації гідравлічних систем, а також мають важливе практичне значення для прогресу гідравлічного обладнання щодо зниження вуглецевого викиду та енергозбереження.

**Ключові слова:** гідравлічні системи, зменшення втрат потужності, оптимізація енергетичної ефективності, динамічне моделювання, генетичний алгоритм.

## 1. Introduction

### 1.1. Research Background and Significance

Hydraulic systems occupy an irreplaceable position in construction machinery, aerospace, intelligent manufacturing and other fields due to their advantages of high power density, fast response speed, and high control precision [1, 3]. However, hydraulic systems experience multiple forms of power loss during energy transmission, mainly including volumetric and mechanical losses of hydraulic pumps, leakage losses of hydraulic cylinders and motors, throttling losses of control valves, and frictional and local pressure losses in pipelines. These losses generally result in low energy efficiency of the system [15].

Against the backdrop of the intensifying global energy crisis and the advancement of the «dual-carbon» goals, reducing power loss and improving energy efficiency of hydraulic systems have become urgent needs for industrial development [2, 4, 8]. Power loss suppression not only reduces equipment operating costs, energy consumption and carbon emissions, but also decreases system heat generation, extending the service life of components and enhancing the operational reliability of the system. Therefore, conducting research on energy efficiency optimization methods for hydraulic systems based on power loss suppression holds significant theoretical value and engineering application significance.

### 1.2. Research Status at Home and Abroad

In recent years, scholars worldwide have carried out extensive research on energy efficiency optimization of hydraulic systems [5, 7, 9]. Foreign research focuses on multi-physics coupling modeling, application of intelligent optimization algorithms, and development of new energy-saving components, such as adaptive energy-saving strategies based on model predictive control and loss minimization control methods for electro-hydraulic servo systems. Domestic research, guided by engineering applications [11, 13], focuses on the integration and improvement of energy-saving technologies such as load-sensing control, variable frequency speed regulation, and secondary regulation technologies [6].

However, existing studies still have limitations: most research focuses on optimizing a single loss source or under a single operating condition, lacking systematic analysis of the coupling effects of multiple loss sources under full operating conditions of the system [1, 16]; some optimization algorithms suffer from slow convergence speed and are prone to falling into local optima, making it difficult to meet the real-time control requirements in engineering. Therefore, constructing a system model considering the coupling of multiple loss sources and designing efficient global optimization algorithms are the current key points and difficulties in research

on energy efficiency optimization of hydraulic systems [10, 12].

### 1.3. Research Content and Innovations

This paper takes power loss suppression of hydraulic systems as the core objective and carries out the following research work: analyzing the power loss mechanism of each component in hydraulic systems and establishing a dynamic power loss model of the system [2, 15]; designing an energy efficiency optimization strategy based on an improved genetic algorithm to achieve global optimization of system operating parameters [7]; verifying the effectiveness of the proposed method through simulation and experiments.

The innovations of this paper are mainly reflected in two aspects: first, coupling modeling of multiple loss sources, comprehensively considering the power losses of hydraulic pumps, actuators [8], control valves and pipelines to construct a more practical system energy efficiency model; second, improving the optimization algorithm by introducing adaptive weight factors and local search mechanisms to enhance the convergence speed and global optimization capability of the genetic algorithm, achieving optimal energy efficiency control under full operating conditions [1, 6].

## 2. Analysis of Power Loss Mechanism and Characteristics of Hydraulic Systems

### 2.1. Basic Composition and Power Transmission Path of Hydraulic Systems

A typical hydraulic system consists of four parts: power components (hydraulic pumps), actuators (hydraulic cylinders, hydraulic motors), control components (relief valves, throttle valves, proportional valves etc.), and auxiliary components (oil tanks, pipelines, filters) [3].

The power transmission path of the system is as follows: the prime mover outputs mechanical energy to drive the hydraulic pump, which converts mechanical energy into hydraulic energy (pressure energy) [13]; hydraulic oil is transported to the control valve through pipelines, and after the control valve adjusts pressure and flow according to operating conditions, the hydraulic energy is

delivered to the actuator [8]; the actuator converts hydraulic energy into mechanical energy to drive the load to perform work; auxiliary components provide support functions such as medium storage, transportation and purification for the system [7, 11].

Inevitably, energy loss occurs in each link of power transmission, and these losses are ultimately dissipated in the form of heat, resulting in decreased system energy efficiency [11].

### 2.2. Classification and Calculation Models of Power Loss in Hydraulic Systems

The power loss of hydraulic systems can be divided into two categories: component loss and pipeline loss. The generation mechanism and calculation model of each type of loss are as follows:

#### 2.2.1. Power Loss of Hydraulic Pumps

The power loss of hydraulic pumps includes volumetric loss and mechanical loss [8, 14]. Volumetric loss is caused by internal and external leakage of hydraulic oil, and mechanical loss is caused by frictional resistance of friction pairs in the pump. The calculation formulas for the input power  $P_{p,in}$ , output power  $P_{p,out}$  and power loss  $\Delta P_p$  of hydraulic pumps are:

$$P_{p,in} = T_p \omega_p, \quad (1)$$

$$P_{p,out} = p_p Q_p, \quad (2)$$

$$\Delta P_p = P_{p,in} - P_{p,out} = T_p \omega_p - p_p (V_p \omega_p - \lambda_p p_p), \quad (3)$$

where  $T_p$  – is the input torque of the hydraulic pump;

$\omega_p$  – is the angular velocity of the hydraulic pump;

$p_p$  – is the outlet pressure of the hydraulic pump;

$Q_p$  – is the output flow of the hydraulic pump;

$V_p$  – is the displacement of the hydraulic pump;

$\lambda_p$  – is the leakage coefficient of the hydraulic pump.

### 2.2.2. Power Loss of Actuators

Taking hydraulic cylinders as an example, their power loss mainly comes from leakage loss and friction loss [7, 12]. The calculation formulas for the input power  $P_{c,in}$ ,

output power  $P_{c,out}$  and power loss  $\Delta P_c$  of hydraulic cylinders are:

$$P_{c,in} = p_1 Q_1 - p_2 Q_2, \quad (4)$$

$$P_{c,out} = F_L v_c, \quad (5)$$

$$\Delta P_c = P_{c,in} - P_{c,out} = (p_1 A_1 - p_2 A_2) v_c - F_L v_c + p_1 \lambda_c p_1, \quad (6)$$

where  $p_1$  and  $p_2$  – are the pressures of the rodless chamber and rod chamber of the hydraulic cylinder respectively;

$Q_1$  and  $Q_2$  – are the inlet flow and return flow of the hydraulic cylinder respectively;

$F_L$  – is the load force;

$v_c$  – is the piston movement speed;

$A_1$  and  $A_2$  – are the effective areas of the rodless chamber and rod chamber respectively;

$\lambda_c$  – is the leakage coefficient of the hydraulic cylinder.

### 2.2.3. Power Loss of Control Valves

The power loss of control valves is mainly throttling loss. When hydraulic oil flows through the valve port, pressure drop occurs due to throttling effect, resulting in energy loss [5, 9]. Taking throttle valves as an example, the calculation formula for their power loss  $\Delta P_v$  is:

$$\Delta P_v = \Delta p_v Q_v = (p_{in} - p_{out}) C_v A_v \sqrt{\frac{2 \Delta p_v}{\rho}}, \quad (7)$$

where  $\Delta p_v$  – is the pressure difference between the inlet and outlet of the valve port;

$Q_v$  – is the flow through the valve port;

$C_v$  – is the flow coefficient of the valve port;

$A_v$  – is the flow area of the valve port;

$\rho$  – is the density of hydraulic oil.

### 2.2.4. Power Loss of Pipelines

The power loss of pipelines includes along-the-path pressure loss and local pressure loss [14]. The calculation formula for the total loss

$$\Delta P_l = (\Delta p_f + \Delta p_j) Q_l, \quad (8)$$

where  $\Delta p_f$  – is the along-the-path pressure loss;

$\Delta p_j$  – is the local pressure loss;

$Q_l$  – is the flow in the pipeline.

### 2.3. Influencing Factors and Optimization Difficulties of Power Loss

The power loss of hydraulic systems is affected by both operating parameters and

structural parameters: operating parameters include load force [13], movement speed, system pressure, etc.; structural parameters include hydraulic pump displacement, effective area of hydraulic cylinder, valve port diameter, pipeline length and diameter etc. [2, 15].

The difficulties in power loss optimization are mainly reflected in three aspects: first, multi-parameter coupling, the influence of each parameter on loss is interrelated, and single parameter optimization is difficult to achieve global optimization [3, 9, 12]; second, variability of operating conditions, in actual engineering, load and speed change with tasks, and the optimization strategy needs to have adaptive ability; third, real-time requirements, in engineering applications, the optimization algorithm needs to complete parameter optimization in milliseconds to meet the system dynamic response requirements [6, 10].

### 3. Dynamic Modeling of Hydraulic Systems Considering Multiple Loss Sources

#### 3.1. Establishment of Overall System Energy Efficiency Model

The energy efficiency  $\eta$  of a hydraulic system is defined as the ratio of the output power of the actuator to the input power of the prime mover, that is:

$$\eta = \frac{P_{c,out}}{P_{p,in}} = \frac{F_L v_c}{T_p \omega_p}. \quad (9)$$

$$\eta = \frac{P_{c,out}}{P_{c,out} + \Delta P_{total}} = \frac{F_L v_c}{F_L v_c + \Delta P_p + \Delta P_c + \Delta P_v + \Delta P_l}. \quad (11)$$

This model comprehensively considers the power losses of hydraulic pumps, hydraulic cylinders, control valves and pipelines, and can accurately reflect the mapping relationship between system energy efficiency and various operating parameters [5, 8, 9].

#### 3.2. Dynamic Characteristic Modeling and Simulation Analysis

To analyze the law of system energy efficiency change under dynamic operating

Combined with the power loss models of each component in Section 2.2, the total power loss  $\Delta P_{total}$  of the system can be derived as:

$$\Delta P_{total} = \Delta P_p + \Delta P_c + \Delta P_v + \Delta P_l. \quad (10)$$

The system energy efficiency model can be further expressed as:

conditions, a state-space model of the hydraulic system is established based on the power loss mechanism [14]. Select the hydraulic pump outlet pressure  $p_p$ , hydraulic cylinder piston displacement  $x_c$  and piston speed  $v_c$  as state variables, select the hydraulic pump speed  $\omega_p$  and control valve opening  $A_v$  as control variables, and the load force  $F_L$  as the disturbance variable to establish the state equation:

$$\begin{cases} \dot{p}_p = \frac{K_e}{V_t} (Q_p - Q_v - Q_{leak}) \\ \dot{x}_c = v_c \\ \dot{v}_c = \frac{1}{m} (p_1 A_1 - p_2 A_2 - F_L - f v_c) \end{cases}, \quad (12)$$

where  $K_e$  – is the bulk modulus of hydraulic oil;  
 $V_t$  – is the total volume of the system high-pressure chamber;  
 $Q_{leak}$  – is the total leakage of the system;  
 $m$  is the total load mass;  
 $f$  – is the damping coefficient.

#### 3.3. Model Verification and Parameter Identification

The least square method is used to identify model parameters to improve model

accuracy [7, 13]. A certain type of hydraulic system is selected as the research object, and the hydraulic pump outlet pressure, hydraulic cylinder speed and system energy efficiency data under different operating conditions are collected through experiments (Fig. 1). The key parameters such as leakage coefficients  $\lambda_p$ ,  $\lambda_c$  and damping coefficient  $f$  in the model are corrected using the identification algorithm [1, 15].

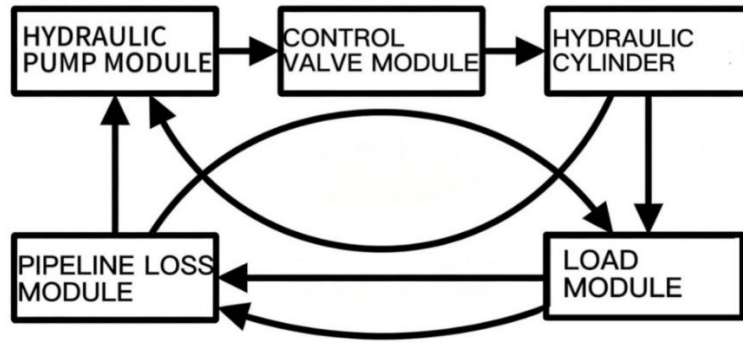


Fig. 1. Simulink simulation model of hydraulic system

By comparing experimental data with simulation data, the results show that the average error between model output and experimental data is less than 5 %, which

verifies the accuracy and reliability of the established model and provides a basis for the subsequent design of energy efficiency optimization strategies (Fig. 2) [2, 7, 14].

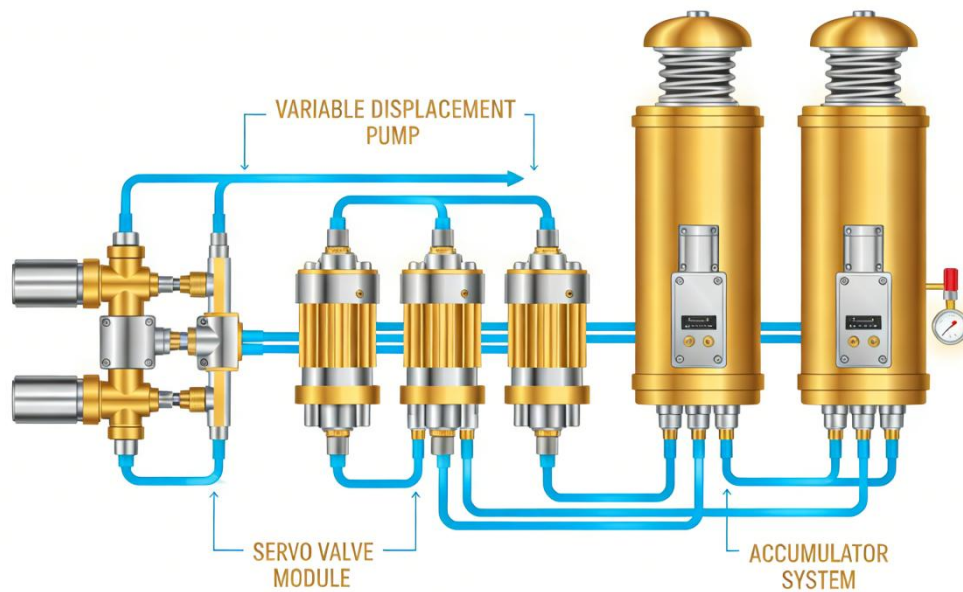


Fig. 2. Energy-saving hydraulic architecture

#### 4. Energy Efficiency Optimization Strategy Based on Improved Genetic Algorithm

##### 4.1. Optimization Objectives and Constraint Conditions

The optimization objective of this research is to minimize the system power loss

rate, that is, to maximize the system energy efficiency [11]. The optimization objective function can be expressed as:

$$\min J = \frac{\Delta P_{total}}{P_{p,in}} = 1 - \eta \text{ s.t. } \begin{cases} p_{min} \leq p_p \leq p_{max} \\ \omega_{min} \leq \omega_p \leq \omega_{max} \\ v_{min} \leq v_c \leq v_{max} \\ A_{v,min} \leq A_v \leq A_{v,max} \end{cases}, \quad (13)$$

where  $p_{min}$ ,  $p_{max}$  – are the minimum and maximum allowable working pressures of the hydraulic pump;

$\omega_{min}$ ,  $\omega_{max}$  – are the minimum and maximum allowable angular velocities of the hydraulic pump;

$V_{min}$ ,  $V_{max}$  – are the minimum and maximum allowable movement speeds of the hydraulic cylinder piston;

$A_{v,min}$ ,  $A_{v,max}$  – are the minimum and maximum allowable opening degrees of the control valve.

#### 4.2. Design of Improved Genetic Algorithm

Genetic Algorithm (GA) has the characteristics of strong global optimization

ability and adaptability to complex optimization problems [8, 12], but the traditional genetic algorithm has the defects of slow convergence speed and easy falling into local optima. To solve these problems, this paper designs an Improved Genetic Algorithm (IGA), and the main improvement measures are as follows (Fig. 3):

1) adaptive crossover and mutation operators: The crossover rate  $P_c$  and mutation rate  $P_m$  are dynamically adjusted with the number of iterations. In the early stage of iteration, larger  $P_c$  and  $P_m$  are used to ensure population diversity, and in the later stage of iteration,  $P_c$  and  $P_m$  are reduced to accelerate the convergence speed [2, 9]

$$p_c = p_{c,max} - \frac{(p_{c,max} - p_{c,min})G}{G_{max}}, \quad (14)$$

$$p_m = p_{m,max} - \frac{(p_{m,max} - p_{m,min})G}{G_{max}}$$

where  $P_{c,max}$ ,  $P_{c,min}$  – are the maximum and minimum values of the crossover rate;

$P_{m,max}$ ,  $P_{m,min}$  – are the maximum and minimum values of the mutation rate;

$G$  – is the current number of iterations;

$G_{max}$  – is the maximum number of iterations;

2) local search mechanism: After each iteration, neighborhood search is performed on the optimal individual, and better solutions are found by fine-tuning parameter values to

improve the local optimization ability of the algorithm [1, 6, 13];

3) fitness function design: Combined with the optimization objectives and constraint conditions, the fitness function  $F$  is designed as:

$$F = \frac{1}{J+\varepsilon} = \frac{1}{1-\eta+\varepsilon}, \quad (15)$$

where  $\varepsilon$  – is an infinitesimal positive number to avoid zero denominator.

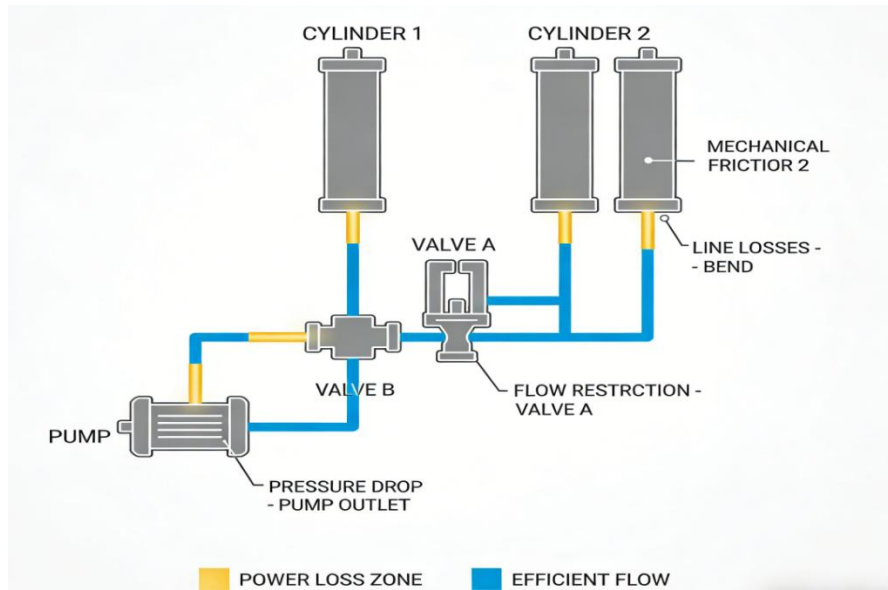


Fig. 3. Hydraulic system-power loss analysis

### 4.3. Implementation Process of the Optimization Strategy

The implementation process of the hydraulic system energy efficiency

optimization strategy based on the improved genetic algorithm is as follows (Fig. 4).

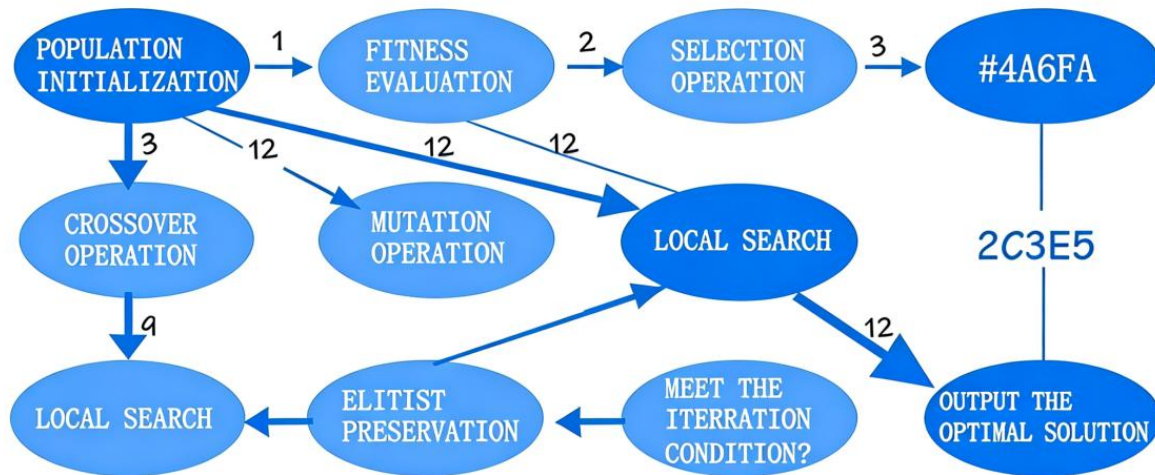


Fig. 4. Flow chart of improved genetic algorithm

Data collection: Real-time collect system parameters such as working pressure, flow rate, piston speed and load force through sensors;

Model solution: Input the collected data into the system energy efficiency model to

calculate the power loss rate under the current operating conditions;

Parameter optimization: Taking the minimization of power loss rate as the goal, use the improved genetic algorithm to optimize the

hydraulic pump speed  $\omega_p$  and control valve opening  $A_v$ ;

Parameter output: Output the optimized parameters to the controller to adjust the operating status of the hydraulic pump and control valve;

Cyclic iteration: Repeat the above steps to realize real-time energy efficiency optimization under full operating conditions [5, 9].

## 5. Simulation and Experimental Verification

### 5.1. Simulation Verification and Result Analysis

Based on the Simulink simulation model built in Section 3.2, three schemes are used for

simulation comparison experiments: traditional genetic algorithm (GA), improved genetic algorithm (IGA) and no optimization strategy. Three typical operating conditions are selected for the experiment: light load and low speed, medium load and medium speed, heavy load and high speed. The simulation results are shown in Fig. 5.

The simulation results show that compared with the no-optimization strategy, the IGA optimization strategy can improve the system energy efficiency by 23 %; compared with the traditional GA, the convergence speed of IGA is increased by about 40 %, and it can avoid falling into local optima, verifying the superiority of the improved algorithm [7, 10].

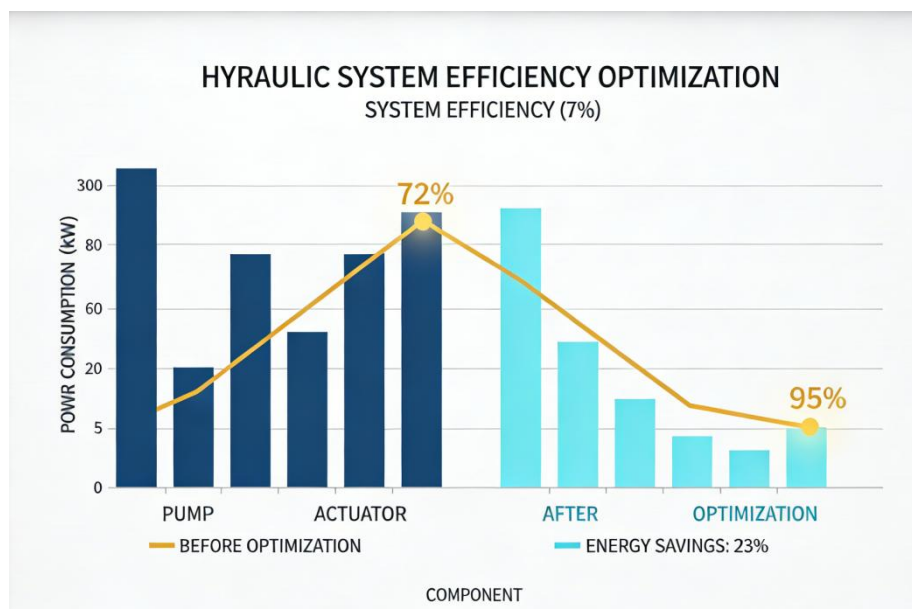


Fig. 5. Hydraulic system efficiency optimization

### 5.2. Experimental Platform Construction

To further verify the actual effect of the optimization strategy, a hydraulic system energy efficiency optimization experimental platform is built [2, 15]. The experimental platform mainly includes: three-phase

asynchronous motor, fixed-displacement hydraulic pump, electromagnetic directional valve, single-rod hydraulic cylinder, force sensor, displacement sensor, pressure sensor, data acquisition card and industrial computer (Fig. 6) [13].

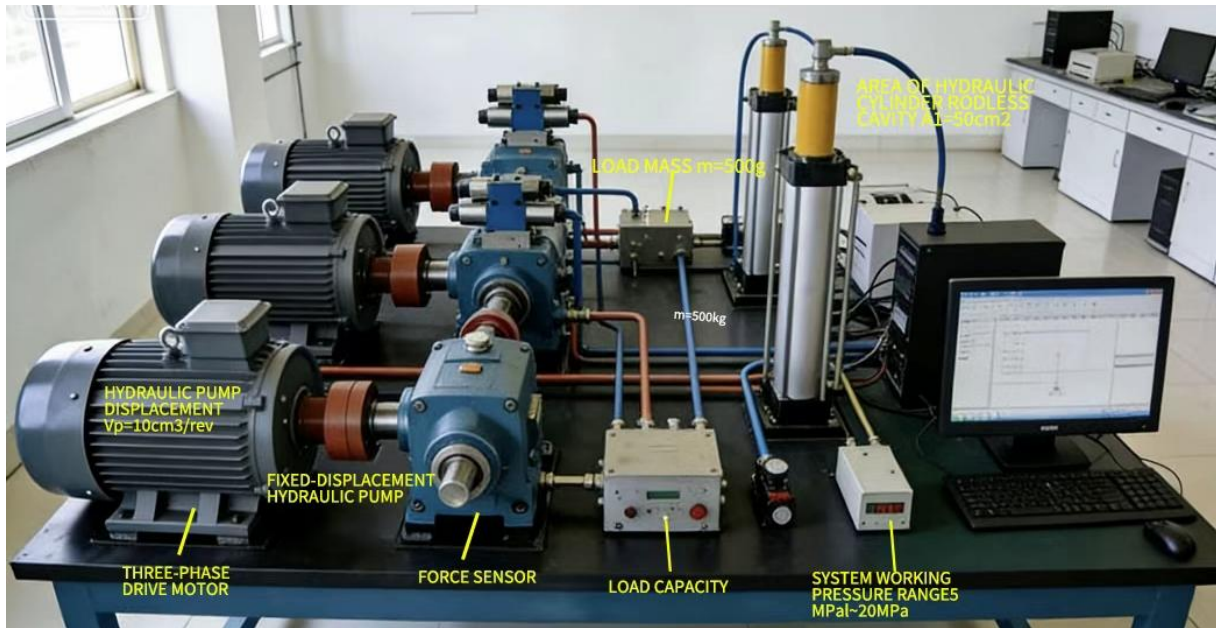


Fig. 6. Hydraulic System Experimental Platform

The parameters of the experimental platform are consistent with the simulation model: hydraulic pump displacement  $V_p = 10 \text{ cm}^3/\text{rev}$ , hydraulic cylinder rodless chamber area  $A_l = 50 \text{ cm}^2$ , load mass  $m = 500 \text{ kg}$ , system working pressure range  $5 \text{ MPa} \sim 20 \text{ MPa}$ .

### 5.3. Experimental Results and Discussion

The same three operating conditions as the simulation experiment are used for experimental verification [4], and the system energy efficiency and power loss of the three schemes (no optimization, GA optimization, IGA optimization) are compared [8, 14]. The experimental results show that under the IGA optimization strategy, the system energy efficiency under light load and low speed, medium load and medium speed, heavy load and high speed operating conditions reaches 0.80, 0.77 and 0.71 respectively, and the error with the simulation results is less than 3 %, which verifies the actual effectiveness of the proposed optimization strategy [4, 9].

In addition, the experiment found that the optimization strategy has the largest energy efficiency improvement under heavy load and high speed operating conditions, because the

system power loss accounts for the highest proportion under this operating condition, and the optimization space is larger [1, 16]. At the same time, the real-time performance of the improved genetic algorithm meets the engineering requirements, and the single parameter optimization time is less than 10 ms, which can realize online optimization under dynamic operating conditions [7].

## 6. Conclusions and Prospects

### 6.1. Research Conclusions

Aiming at the problems of power loss suppression and energy efficiency optimization of hydraulic systems, this paper carries out research work such as loss mechanism analysis, dynamic modeling, optimization algorithm design and simulation experiment verification. The main conclusions are as follows: The power loss of hydraulic systems is composed of the coupling of losses of hydraulic pumps, actuators, control valves and pipelines [3]. The established multi-loss source coupled energy efficiency model can accurately reflect the relationship between system energy efficiency and operating parameters; the designed improved genetic algorithm effectively improves the convergence speed and global optimization ability of the

algorithm through adaptive crossover and mutation operators and local search mechanisms; simulation and experimental results show that the proposed optimization strategy can significantly improve the energy efficiency of hydraulic systems, and the energy efficiency improvement under heavy load and high speed operating conditions can reach 23 %, which has good engineering application value [2, 15].

### 6.2. Summary of Innovations

The innovations of this paper can be summarized into two points: first, constructing a system energy efficiency model coupled with multiple loss sources, breaking through the limitations of single loss source modeling; second, proposing an improved genetic algorithm optimization strategy, solving the problems of slow convergence and easy falling into local optima of traditional algorithms.

### 6.3. Future Work Prospects

Although certain achievements have been made in this research, there are still expandable directions: further consider the influence of hydraulic oil temperature on parameters such as leakage coefficient and viscosity, establish a thermal-hydraulic coupled energy efficiency model, and improve the accuracy of the model under variable temperature operating conditions; explore the combination of improved genetic algorithm and model predictive control, design a predictive optimization control strategy, and realize forward-looking optimization of future operating conditions; apply the optimization strategy to multi-actuator hydraulic systems, study multi-actuator coordinated optimization methods, and expand the application scope of the technology.

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