# CONTROL STRATEGY OF INJECTION RAIL PRESSURE OF DIESEL ENGINE BASED ON T-S MODEL AND ADAPTIVE NEURAL FUZZY INFERENCE SYSTEM

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*The control of rail pressure in the injection system of diesel engine determines the combustion effect and emission performance. In this paper, on the basis of research for conventional proportion-integration-differentiation (PID) controller, using a large number of input/output data monitored in engineering application, combined with the Takagi-Sugeno (T-S) model and the adaptive neuro fuzzy inference system (ANFIS), the membership functions and fuzzy control rules are optimized and adjusted, and the closed-loop PID control algorithm based on the adaptive neuro fuzzy inference system are designed. The algorithm can adjust the control parameters of rail pressure in real time on line according to the target rail pressure and the measured rail pressure. The closed-loop control algorithm improves the accuracy and stability of rail pressure control. The control algorithm is embedded into the whole model of diesel engine, and the dynamic simulation is carried out to verify the correctness of the control strategies such as fuel injection quantity, common rail pressure and fuel injection timing under different working conditions. Finally, a complete and reliable control strategy model of high-pressure common rail electronic control injection system is put forward, and the control strategy bench tests of diesel engine starting and idling conditions, transient conditions and steady-state conditions are carried out. The test results show that the time when the fuel injection quantity, speed and rail pressure reach the predetermined values during engine starting is reduced, the maximum fluctuation of the transient rail pressure is small, and the transition time is short; the rail pressure response follows well in the transient condition; the increase of the rail pressure reduces the fuel injection advance angle and the fuel injection pulse width in the steady condition, so as to ensure the good fuel injection and combustion conditions.*

**Keywords**: Adaptive neuro fuzzy inference system (ANFIS), T-S model, PID control, Diesel engine, Fuel injection system, High pressure common rail.

## 1. Introduction

A lot of research on rail pressure control of diesel fuel injection system has been carried out abroad. A dual controller is designed to control common rail pressure, which can ensure that the current value of fuel metering unit (FMU) and

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pressure control valve (PCV) can be stabilized near the expected value when the voltage and coil impedance change [1]. A model reference adaptive control (MRAC) method is proposed [2]. When the parameters of diesel engine change and the rail pressure fluctuation is caused by non-periodic disturbance, the parameters can be identified in time, but the control process is somewhat complicated.

There are many studies on rail pressure control strategy and control algorithm in China. Li Honghuai of Jiangnan University studied the control strategy of rail pressure at different stages, based on the BOSCH-CR system matching with the GW2.8TC (4JB1) diesel engine, according to the rail pressure demand under different working conditions [3]. Jinjiangshan of Shanghai711 institute has studied the pressure control strategy of high-pressure common rail [4]. The PID control algorithm is applied to the closed-loop control of rail pressure. A test platform is built to verify the step response performance of the algorithm. Xu Jinsong of Kunming University of Science and Technologyhas made a thorough study on the characteristics of delay, rail pressure disturbance and non-linearity in the control process, and proposed a method of series connected control using two regulators, the main regulator and the secondary regulator [5]. At this time, the secondary loop is equivalent to a servo system. Ren Weijun of Chang'an University completed the common rail pressure control, and studied the control strategy of starting, idling, transient and special conditions [6]. On the basis of the GD-1 high-pressure common rail system, Xiao Wenyong of Shanghai Jiaotong University proposed the fuzzy PID compound control method and the PID parameter fuzzy self-tuning control method [7]. Wang Yong of Dalian University of Technology put forward the idea of combining artificial neural network with rail pressure control [8]. According to back propagation (BP) neural network, the PID parameters were adjusted. First, the neural network function was compiled, and the simulation model was built. The robustness and dynamic performance of the control algorithm were verified by simulation. Finally, the further verification was completed on the oil pump test platform. Yu Tengfei of Hunan University proposed an adaptive PID control algorithm based on radial basis function (RBF) neural network, which simplified the PCV mathematical model into a third-order transfer function [9]. The numbers of input nodes, hidden nodes of Gauss function and output nodes of the neural network were set to 6, 8 and 3 respectively to ensure that the PID parameters could be adjusted and the response speed could be improved when the diesel engine working conditions change. Even if the negative step signal input will have a sharp jump, it will quickly restore stability.

It can be seen from the above that the main work of the research on common rail pressure control strategy is to study and improve the algorithm of its closed control loop. Most of them are based on conventional PID control, combined with intelligent control methods such as pre-control, parameter identification, fuzzy control, neural network and genetic algorithm to design a new rail pressure controller, which improves the steady-state and dynamic characteristics of the control system to a certain extent [10]. The diesel engine itself is complex and the engineering application environment is changeable. The influence of these complex factors cannot be solved by a single intelligent control method. Therefore, it is necessary to design more prominent control algorithm combining the advantages of multiple intelligent control methods to further improve the anti-interference and follow-up of rail pressure control.

## 2. Injection rail pressure control system

The greatest advantage of high-pressure common rail system is that it does not depend on the speed and load, and avoids the compressibility and pressure fluctuation of the fuel itself. That also avoids the residual in the high-pressure fuel pipe to change after each injection cycle, so resulting in that the final injection state is not consistent with the established law of plunger motion fuel supply [11], and unstable injection phenomena occurs. Therefore, to highlight the advantages of the fuel injection system and improve the control accuracy of common rail pressure is the basis for optimizing other control variables.

In the high-pressure common rail electronic control fuel injection system, there are three common ways to regulate the common rail pressure:

(1) Variable displacement method: The common rail pressure is controlled by changing the fuel quantity into the high-pressure oil pump according to the change of the speed and load of the diesel engine. This method is adopted by the EDU-U2 electronic control fuel injection system of the Japanese DESON company.

(2) Oil intake throttle control technology: A proportional throttle valve is usually installed at the inlet of high-pressure oil pump. Pulse width modulation (PWM) signal is used to control the current of electromagnet coil at different duty ratios to change its attraction, so as to change the flow area of valve port to control the oil intake quantity in the process of oil suction, and finally to complete the adjustment of common rail pressure. This method is efficient and has no overflow losses.

(3) Cylinder shutdown technology: The numbers of plunger chambers of high-pressure oil pump are changed when it is in normal operation. When the common rail pressure needs to be reduced, it is necessary to reduce the oil supply to it. By supplying power to the solenoid valve, its core can hold the suction valve all the time, so that the intake valve in the cylinder keeps open, and the high-pressure circuit and the low-pressure circuit are connected. The plunger cannot compress the internal oil in the chamber during the oil supply journey, while the

fuel flows back to the low-pressure passage from the normally opened intake valve during the oil pressure journey. His chamber plunger supplies still normally fuel, so that the fuel pressure in the common rail tube can be adjusted and controlled, which can reduce power loss in the process of adjustment.

In this paper, the regulation technology of proportional throttle valve is combined with the cylinder shutdown technology. When the diesel engine operating conditions are different, the common rail pressure control mode is different. When idling and no-load, the combination of proportional throttle valve and cylinder shutdown technology can be used. The proportional throttle valve can be adjusted in the other conditions. In addition, when over-pressure occurs, the proportional throttle valve is closed and the pressure control valve at one end of the common rail pipe is opened for rapid pressure relief.

How to adjust the proportional throttle valve timely and accurately is the key to realize the precise control of rail pressure. When starting, low speed and signal detection may cause time delay, so open-loop control must be used to quickly establish a certain common rail pressure, that is, to quickly establish common rail pressure by setting the opening degree of a proportional throttle valve as large as possible through a fixed frequency. When the rail pressure rises to the desired value, the control of the proportional throttle valve starts to switch to the closed-loop mode. Fig. 1 shows that the target rail pressure can be obtained by looking up the target rail pressure chart according to the speed of diesel engine and the current fuel injection quantity, and then the target value can be corrected by combining the state information of diesel engine, and the final target rail pressure can be obtained by limiting the change rate of the target rail pressure. In order to prevent rail pressure fluctuation and maintain the stability of common rail pressure under different working conditions, the actual value of rail pressure monitored by sensors is compared with the final target value, and the real-time closed-loop control of common rail pressure is completed by using adaptive neuro-fuzzy PID control algorithm. The simulation model of common rail pressure control is built, as shown in Fig. 2.

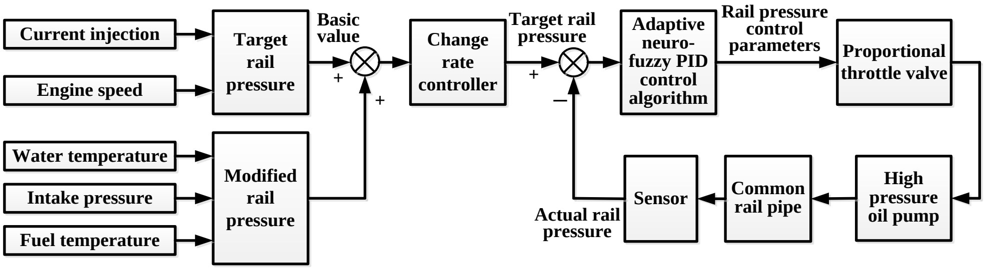


Fig. 1. Block diagram of common rail pressure control

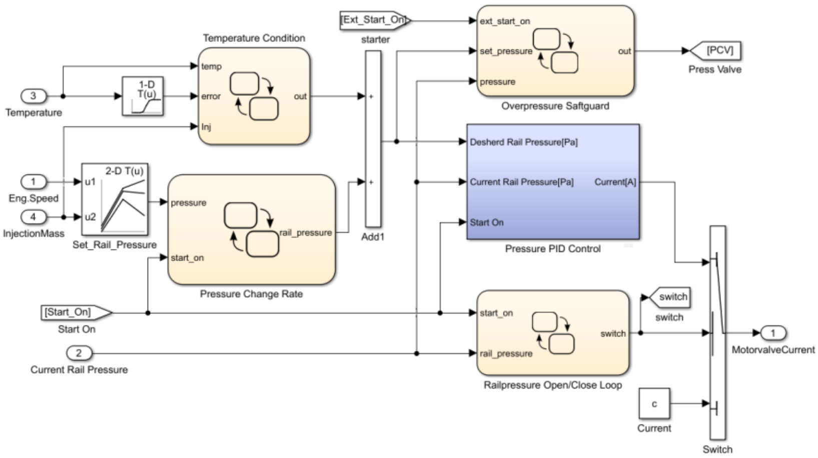


Fig. 2. Simulation model of common rail pressure control strategy

This paper studies the self-developed and improved fuel injection system, and the main relevant parameters used in diesel engine modeling and test are shown in Table1.

*Table 1*

**Main relevant parameters of diesel engine**

| Type | 4 cylinders |
|---|---|
| Diameter×stroke | 85mm×83mm |
| Displacement | 19L |
| Compression ratio | 18.5:1 |
| Common rail pipe | Volume:10mm$^3$, Maximum rail pressure:180MPa |
| High pressure oil pump plunger | Lift:5mm, Area:32.1mm$^2$, Number:3 |
| Low pressure pipe volume | 125cm$^2$ |
| Rated speed | 3200r/min |
| Maximum torque | 285Nm |
| Speed ratio of oil pump to diesel engine | 1:2 |

## 3. Common rail pressure control strategy

Diesel engine itself belongs to a nonlinear time-varying strong-coupling system. At the same time, working conditions are changeable. The control of common rail pressure requires good steady-state and dynamic performance under various working conditions. It can produce a good rapidly changing strategy for system changes, so the control of rail pressure in practical application is quite complex. In this paper, based on the research of conventional controllers, using a large number of input and output data samples monitored in engineering applications, combined with the model-based (T-S) adaptive neuro-fuzzy inference system (ANFIS) to adjust the membership functions and fuzzy control rules, an adaptive neuro-fuzzy closed-loop control algorithm is designed to improve the stability of rail pressure, which can real-time adjust the parameters of rail pressure control on-line according to the target rail pressure and the measured rail pressure.

### 3.1 Fuzzy PID control based on T-S model

The working condition of high-pressure common rail system of diesel engine is complex and changeable, which makes the closed-loop control system of common rail pressure highly time-varying and non-linear. There is no clear mathematical model and law to follow, and conventional PID control cannot meet the effect of system requirements. Therefore, the calculation based on T-S type fuzzy inference is convenient, and is advantageous to mathematical reasoning and analysis, and the coordination with PID control and other optimization methods is easier [12]. A new fuzzy PID controller is composed of PID regulators, which can adjust the control parameters adaptively by monitoring the rail pressure fluctuation to improve the stability of the system.

T-S fuzzy controller module consists of three parts: a) fuzzification (D/F); b) fuzzy rule base (if-then rule); c) reasoning decision mechanism (T-S reasoning). As shown in Figure 3, the target rail pressure is used as input and the measured rail pressure is used as output in the whole rail pressure control structure. The fuzzy controller in the figure uses 2×3 T-S type fuzzy inference system (FIS). The deviation *e* and the deviation change rate *ec* between the target value of rail pressure and the measured value are input. After fuzzification, three adjustments of $\Delta K_p$, $\Delta K_i$ and $\Delta K_d$ calculated by the fuzzy rules in T-S type fuzzy inference system, which are used as the input of the PID regulator to adjust the three control parameters of $\Delta K_p$, $\Delta K_i$ and $\Delta K_d$.

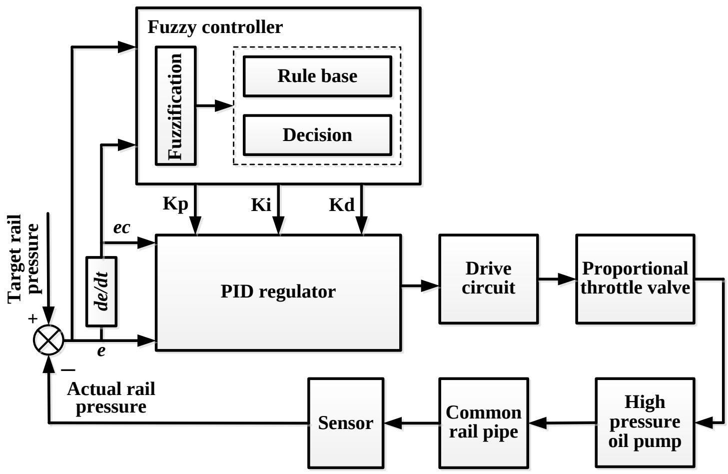

Fig. 3. Structure of fuzzy PID controller for rail pressure

### 3.2 Adaptive Neuro-Fuzzy-PID Control of Rail Pressure

T-S type fuzzy controller is mainly based on a large number of input-output data for structure identification and parameter identification [13]. Only after the parameter identification is completed, the structure identification can be carried out and the optimal output can be determined. Parameter identification is mainly divided into two categories: the former and the latter. Because of the huge amount of measured data, neural network is used to process [14]. In order to avoid the large error and poor performance caused by adjusting membership functions according to human thinking in the design of fuzzy controller, an adaptive neuro-fuzzy inference system (ANFIS) is established. After determining the neural network structure of ANFIS, only the parameters of the former and the latter must be updated. Through forward learning, the parameters of the former are guaranteed to remain unchanged, and the parameters of the latter are calculated by the least square method. While the parameters of the former are guaranteed to remain unchanged, the parameters of the former and the shape of the membership function are adjusted by the reverse back propagation (BP) approximation error until the error satisfies the precision of the training. Finally, ANFIS calculates the deviation *e* and deviation rate *ec* according to the target rail pressure and the measured rail pressure at each time, adjusts the PID control parameters of $\Delta K_p$, $\Delta K_i$ and $\Delta K_d$, and completes the design of adaptive neuro-fuzzy PID.

The input of T-S type fuzzy rail pressure controller is the deviation *e* and deviation rate *ec* between the target rail pressure and the measured value. The output is the adjustment of three PID parameters. The control principle of three parameters of PID regulator based on ANFIS fuzzy controller is the same. The simplified structure of ANFIS system with two inputs and one output can be established. As shown in Fig. 4, the total consists of five layers:

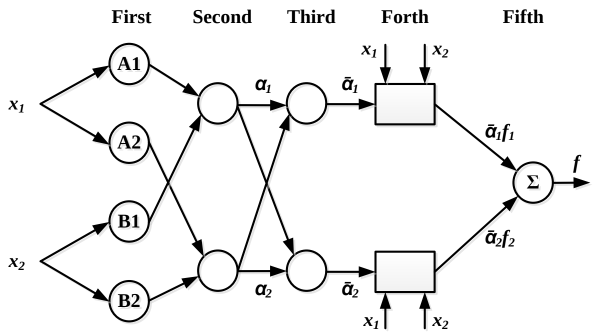


Fig. 4. Simplified structure of ANFIS neural network

The first level: the membership degree of each input in the corresponding domain is calculated by the selected membership function. Each node represents a linguistic variable (e.g. “small” or “big”), and the function shown in formula (1) is used to realize the adaptive function.

$$L_i^1 = \mu_{A_{j1}}\left(x_1 = e\right) \qquad j1 = 1, \cdots, 4 \qquad L_i^1 = \mu_{B_{j2}}\left(x_2 = ec\right) \qquad j2 = 1, \cdots, 4 \quad (1)$$

In the formula: $L_i^1$ is the membership degree of the fuzzy subset $A_{j1}$ or $B_{j2}$ . The default choice is “gbellmf” (bell-shaped function): $\mu(x) = \frac{1}{1+\left|\left(x-c_j\right)/a_j\right|^{2b_j}}$ , where the former parameters $a_j, b_j, c_j$ determine the shape of the membership function.

The second level: Each node *i* actually represents a fuzzy rule and the total rules are $m = 4\times 4 = 16$. From this, the fitness of each rule can be obtained. The calculation is shown in equation (2):

$$L_i^2 = \alpha_j = min\left\{\mu_{A_j}\left(e\right), \ \mu_{B_j}\left(ec\right)\right\} \quad j = 1, 2, \ldots m \tag{2}$$

The third level: Fixed node *i* determines the proportion of the rule *j* fitness to all rule fitness, and expresses the normalized rule fitness, such as formula (3):

$$L_i^3 = \bar{\alpha}_j = \frac{\alpha_j}{\sum_{j=1}^{m}\alpha_j} \tag{3}$$

The forth level: This layer mainly calculates the latter output of the *j* rule, as shown in Formula (4).

$$L_i^4 = \bar{\alpha}_j f_j = \bar{\alpha}_j\left(p_j e + q_j ec + r_j\right) \tag{4}$$

Formula: $p_j, q_j, r_j$ are the latter parameters.

The fifth level: the total output of the system is calculated. The formula (5) is derived from the formula (3) and (4).

$$L^5 = \sum_{j=1}^{m}\bar{\alpha}_j f_j = \sum_{j=1}^{m}\left(\bar{\alpha}_j ep_j + \bar{\alpha}_j ecq_j + \bar{\alpha}_j r_j\right) \tag{5}$$

The greatest characteristic of the adaptive neuro-fuzzy inference system is the self-learning ability of the neural network, which can adjust the structure and parameters of the control system according to the existing sample data to get the best value. After the structure of the neural network is completed, only the coefficients of membership function and output function need to be adjusted. Considering the computational difficulty and speed, a hybrid learning algorithm of gradient descent method and least square method (LSE) is chosen to adjust the system. In this paper, the ANFIS system with double input and single output is used to illustrate that the mixed learning rule of forward and backward learning is used [15], as shown in Table2. From forward learning to the fourth layer of

ANFIS neural network, the latter parameters ( $p_j, q_j, r_j$ ) are calculated by least square method (LSE). When the latter parameters remain unchanged, the direction of the former parameters from reverse learning to error reduction determines self-selection of the most appropriate input layer or middle layer parameters, and the former parameters are optimized by the error rate of feedback. Until the error reaches the accuracy, the training is stopped and the final membership function is obtained.

*Table 2*

**Learning rule**

| Parameter | Forward learning | Backward learning |
|---|---|---|
| former parameters | Fixed | Gradient descent method identification |
| latter parameters | Least square method (LSE) identification | Fixed |

## 4. Simulation analysis and experimental verification

According to the adaptive neuro-fuzzy inference system (guiya.fis) for the common rail pressure and the PID controller, the simulation model of common rail pressure control algorithm is built in Matlab/Simulink. When the initial condition is 0, the control mathematical model of the controlled object is obtained by Laplace transformation [16], as shown in formula (6).

$$G(s) = \frac{0.7}{0.000512s^3 + 0.04s^2 + 0.24s + 1} \quad (6)$$

On this basis, an adaptive neuro-fuzzy PID control simulation model is established to verify the correctness of common rail pressure control algorithm. The above model is compared with the conventional PID control simulation model, as shown in Fig. 5. The models take the deviation *e* and deviation rate *ec* between the target value of common rail pressure and the measured value as the input of the controller. After the controller acts on the controlled object of the system, the response curves of the two algorithms can be obtained, as shown in Fig. 6 and Fig. 7. The stability, dynamic performance and anti-jamming ability of the system with their respective control are compared through preliminary simulation analysis under different input signals.

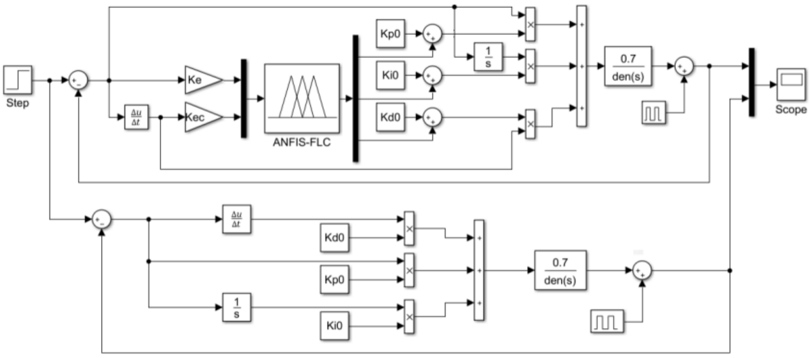


Fig. 5. Adaptive neural fuzzy PID and conventional PID control simulation mode

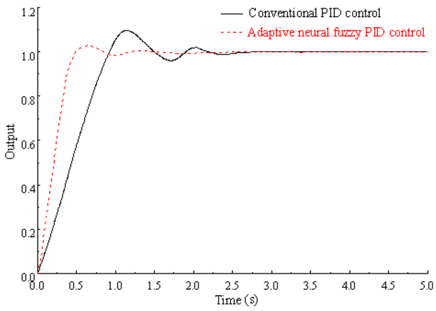


Fig. 6. Step response curve

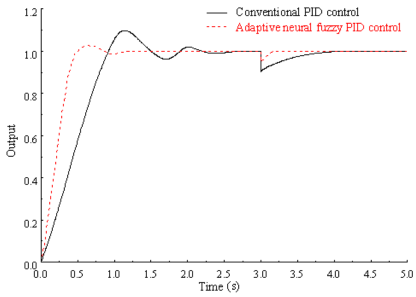


Fig. 7. Impulse response curve

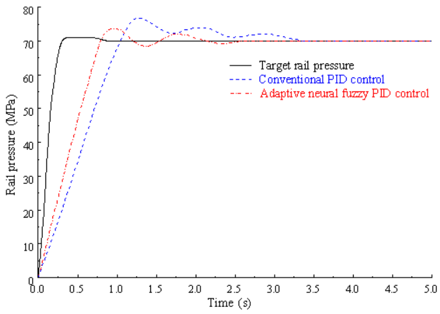


Fig. 8. Simulation results of rail pressure under starting and idling conditions

Fig. 6 shows that when the output of the system model changes by step, the rise time of the conventional PID control is about 0.7s, the peak time is 1.1s, the overshoot is 10%, the adjusting time is 1.6s, and it tends to be steady after 2.5s.While the rise time of the adaptive neuro-fuzzy PID control is about 0.3s, the overshoot is about 3%, and it is completely stable after 1.2s.

After applying a pulse disturbance with an amplitude of 0.9 to the system at 3s, it can be clearly observed from Fig. 7 that the fluctuation of the adaptive neuro-fuzzy PID control is smaller than that of the conventional PID control, and it can quickly recover to the equilibrium state within 0.2 seconds.

As shown in Fig. 8, the simulation results of rail pressure under starting and idling conditions are given. It can be seen from the figure that 0-2s is the initial stage of start-up. In order to establish the oil pressure in a short time, the throttle valve has the largest driving current, the valve is all opened, and the three plungers of the high-pressure oil pump supply oil at the same time. At this time, the pressure rises rapidly, and the whole process belongs to open-loop control. The simulation results are slower than the expected rail pressure response. After 2 seconds, the closed-loop mode is chosen, and the common rail pressure begins to fall back. The deviation between the actual value and the expected value of the two control algorithms is reduced and maintained at about 50 MPa. However, the maximum fluctuation of the conventional PID control is greater than 5 MPa, and the time to fall back to stability is longer. So the control strategy under the adaptive neuro-fuzzy PID control basically meets the stability requirements of the rail pressure at idle speed.

The control accuracy of fuel injection timing determines the performance of combustion, and also greatly affects the fuel economy, power performance and emission of diesel engines [17].When the speed is low, there is a large demand for fuel, while when the speed is increased, the amount of oil injected slowly decreases to the amount injected at idle speed [18]. Electronic control unit (ECU) can distinguish the cooling engine state or the heat engine state according to the temperature of cooling water. The cooling engine state needs to increase the oil amount to accelerate the evaporation and atomization of fuel so as to improve the starting performance. When the engine is hot, the amount of oil injection is moderately reduced to avoid black smoke phenomenon as far as possible. Therefore, the flexible control of fuel injection can be realized and the optimal starting effect can be obtained.

In different working conditions, besides maintaining the common rail pressure stability, the diesel engine should also ensure the best follow-up and response ability of the common rail pressure in transient working conditions, so as to achieve a smooth transition between the working conditions of the diesel engine. When suddenly changing speed, the common rail pressure of diesel engine will fluctuate abruptly, which will affects the performance of diesel engine. As shown in Fig. 9, when the system accelerates after 15 seconds, the actual rail pressure value is slightly smaller than the target value due to the lag of the control system. At the same time, there will be a small fluctuation, and the stable rail pressure will be maintained at 100 MPa. At 50s, the system slows down suddenly, and the system basically keeps in line with the target rail pressure, and finally falls back to the stable value. Under transient conditions, the fluctuation of conventional PID control is larger than that of adaptive neuro-fuzzy PID control, and it takes longer to reach the stable value. Therefore, the feasibility of the adaptive neuro-fuzzy PID control algorithm is further validated. The simulation results show that the designed control strategy has achieved the desired effect on the rail pressure control.

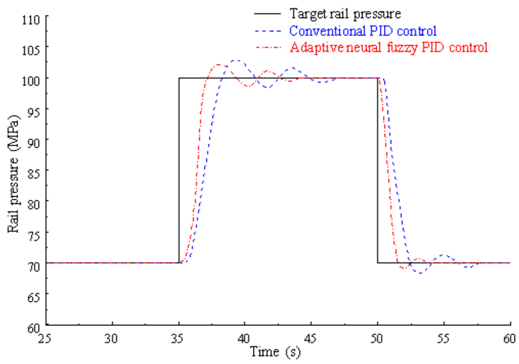


Fig. 9. Simulation results of rail pressure under transient condition

The diesel engine test bed and test equipment are shown in Fig.10. The equipment used in the test process is shown in Table3.

*Table 3*

**Test equipment**

| Name | Type | Function |
|---|---|---|
| Control and measuring cabinet | EST2008 | Measuring and controlling diesel engines |
| Hydraulic dynamometer | W series | Loading the diesel engine and absorbing its power |
| Fuel consumption meter | STYH-125 | Measuring fuel consumption of diesel engines |
| Exhaust analyzer | DiGas4000Light | Measuring the diesel exhaust emissions of $CO$, $CO_2$, $O_2$, HC, and $NO_x$ |
| Electronic control unit (ECU) | Self-developed ECU | Writing program, making calibration experiment and controlling the diesel engine |
| Debugging tool | DAP MinWiggle | Communicating, debugging and downloading the program between ECU and calibration software |
| Calibration software | INCA | Monitoring the software parameters in ECU and modifying the parameters online to realize the calibration of diesel engine |


Fig. 10. Diesel engine test bed and test equipment

Steady state test of diesel engine mainly verifies the change rule and rationality of other injection parameters in the process of rail pressure change. During the test, the cooling water temperature is 75 ℃, and the speed and torque of the diesel engine are controlled to respectively be 1800r/min and 60Nm by the dynamometer. At this time, the rail pressure is adjusted from 70MPa to 115MPa with 5MPa interval. The changes of the fuel injection parameters under the corresponding control strategy are as shown in Fig. 11.

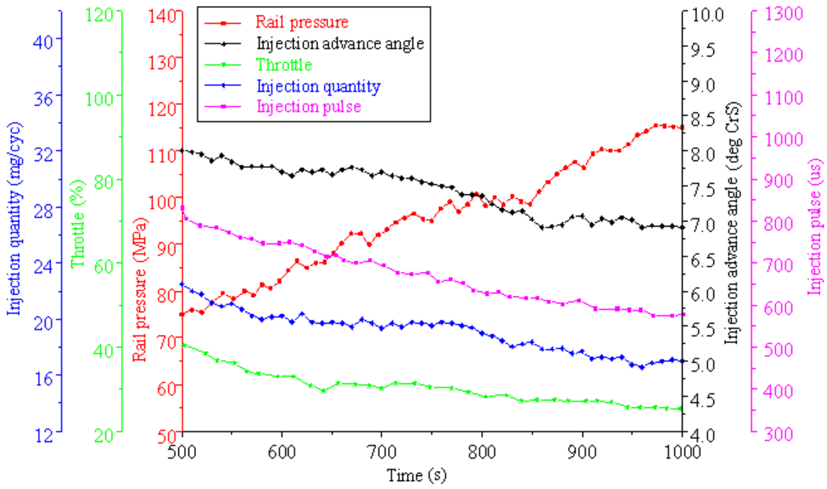


Fig. 11. Influence of common rail pressure on injection parameters in steady state

As can be seen from the figure, when the rail pressure increases from 70MPa to 115MPa, the throttle changes from 40% to 25%, the injection volume decreases from 22.5mg/cyc to 17mg/cyc, the injection advance angle decreases from 8.0deg to 6.9deg, and the injection pulse width changes from 800us to 584us, so all the injection parameters decrease. This is because the output power of the diesel engine is almost unchanged in the steady state. When the fuel injection rate is fixed and the rail pressure is not high enough, the fuel atomization effect is not ideal, which makes the oil-gas mixing degree low, leads to insufficient combustion of the diesel engine, the output power cannot reach the expected value, and causes the phenomenon that the speed and torque decrease. Therefore, it is necessary to increase the throttle opening and fuel injection in time to meet the current power needs. When the speed is unchanged and the rail pressure is not high enough, the injection volume is large, and the injection advance angle can be increased appropriately, so as to ensure that the injection is finished before the top dead point of the compression of the diesel engine, so that the fuel can be fully burned near the top dead point. In order to keep the torque and speed of diesel engine unchanged, the throttle pedal should be controlled to reduce the fuel injection volume, and the injection pulse width and injection advance angle should also be reduced accordingly, so that the fuel injection can be completed near the top dead point of the compression. Therefore, when the common rail pressure increases, the injection advance angle and injection pulse width decrease, which can ensure that the final injection process and combustion process can achieve the desired results.

## 6. Conclusions

Based on the research of conventional PID controller, this paper uses a large number of input and output data samples monitored in engineering application, and combines the adaptive neural fuzzy inference system (ANFIS) based on T-S model to adjust the membership function and fuzzy control rules, and designs an closed loop control algorithm of adaptive neural fuzzy PID model which can adjust the rail pressure control parameters online and in real time according to the target rail pressure and the measured rail pressure. The control algorithm can improve the stability of rail pressure. Combined with conventional PID control and T-S fuzzy control, T-S fuzzy PID controller is analyzed. According to the principle of adaptive neural network control and a large number of rail pressure test data, a common rail pressure control algorithm based on the combination of T-S adaptive neural fuzzy inference system (ANFIS) and PID controller is proposed.

The simulation models of two algorithms of common rail pressure are established, which verify the correctness of the adaptive neural fuzzy PID control algorithm and the superiority over the conventional PID control. The control algorithm is embedded in the whole model of diesel engine, and the dynamic simulation of diesel engine is carried out, which verifies the rationality of the control strategies such as fuel injection quantity, common rail pressure and fuel injection timing under different working conditions. Finally, a complete and reliable control strategy model of high-pressure common rail electronic control injection system is formed, and the program code is generated by Real-Time Workshop, which completes the bench test verification of the rationality of the control strategy under the starting and idling conditions, transient conditions, and steady-state conditions of the diesel engine. The test results are as follows.

(1) The time for the fuel injection quantity, speed, and rail pressure to reach the predetermined value is short during the starting process of the diesel engine, and the open and close loop control switch of rail pressure is timely after reaching the starting pressure. The maximum fluctuation during the idle speed is only 5MPa, and the time to reach the stability is only 1.25s.

(2) Under the transient condition, the rail pressure has a good response to the change of speed and fuel injection quantity, and the control strategy of the system adapts to the sudden change of the working condition of the diesel engine. It results in the good follow-up of the actual system control.

(3) In the steady state working condition, the rail pressure has a great influence on the injection parameters. In the process of increasing the rail pressure, the injection advance angle and the injection pulse width decrease nonlinearly, and the change trend of each parameter is normal, thus ensuring the good injection and combustion conditions.

**Acknowledgement**

This research was financially supported by the National Science Foundation (NO. 51675148).

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