Optimization of parameters for diesel shaft speed control system

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Abstract. This work presents a fuel supply electronic control system (model ESUVT.01) developed by Dizelavtomatika (Saratov) for the D50 (6 CHN 31.8/33) locomotive diesel engine manufactured by Penzadieselmash. In this system, the fuel supply process is controlled by a high-speed electro-hydraulic valve installed in the high-pressure line of the fuel system. A set of electrically controlled high pressure fuel pumps (mode 4ETN.03) with electro-hydraulic valves for the diesel was manufactured. This system can also control the engine speed. It was noted that the best quality indicators of the speed regulating process are provided by the PID control law. It was shown that for a diesel with high inertia, it is advisable to use the PI control law. Experimental studies were conducted to assess the influence of structure and parameters of this control system on the dynamic qualities of this diesel engine. The object of bench testing was a 1-PDG4D-type diesel-generator from the above-mentioned diesel engine and MPT-84/39 traction generator. The dependences of the duration of the transient process, the overspeed and the period of natural oscillations of the regulated parameter on the PI controller parameters were obtained. The necessity of optimizing the coefficients of proportional (P) and integral (I) components of the PI control law was confirmed. A method for optimizing the coefficients of proportional and integral components of the PI control law was proposed. The optimized coefficients for the transient acceleration process of the diesel engine according to the locomotive characteristic were obtained.

1 Introduction

One of the most urgent problems of modern engine building is to provide the best indicators of fuel economy and exhaust gas (EG) toxicity of internal combustion engines (ICE) [1, 2]. Among the internal combustion engines for various purposes, it is necessary to distinguish diesel engines installed on diesel locomotives. Locomotive diesel engines produce about 16% of total energy generated by internal combustion engines operating in Russia. They consume more than 12 million tons of diesel fuel per year and emit about 2 million tons of harmful emission pollutants into the atmosphere. In this regard, the Development Strategy of JSC Russian Railways until 2030 involves implementation of measures to improve energy efficiency and environmental safety of freight and passenger transportation, modernization of the existing locomotives and creation of new locomotives [3, 4].

One of the effective ways to improve the fuel economy and emission performance of engines is to optimize their operating conditions, i.e. to switch these engines to the best operating conditions and reduce the proportion of transient operating conditions [2, 5]. At the same time, the transient operating conditions are

characteristic of the operating conditions of shunting diesel locomotives and make up a significant proportion of their work time. The main objective of automatic regulating systems and automatic control systems (ARS and ACS) of rotation speed is to shorten the duration of the transient progress and to improve the quality indicators of the regulating process [2, 5].

2 Methods

2.1 Operation modes of locomotive engines

The duration of transient processes for diesel-generator units (DGU) of main diesel locomotives during real operating conditions is 5-20% of the total operating time, and it is 20-40% for DGU of shunting diesel locomotives [6, 7]. Frequent change in speed and load conditions is especially characteristic of shunting diesel engines. For one operation shift of a shunting diesel locomotive, the controller switches from 900 to 1200 times. Switching of the driver controller position is accompanied by the appearance of transient processes, for which there is a mismatch in the operation of fuel supply and air supply

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systems. It is caused by the inertia of the turbocharger system, as a result of which the increase in fuel injected to the diesel cylinders during a load surge and acceleration is not accompanied by a rapid increase in air supply. As a result, the initial stage of these transient processes is characterized by a lack of oxygen, a decrease in the excess air coefficient, a deterioration in the conditions of mixture formation, and other negative factors. In this regard, during transient progresses the indicators of fuel economy and emission performance are significantly worse. In transient processes, there are also high time averaged loads on engine parts, frequent violations of the lubricating conditions of the surfaces of the engine mechanisms, and less engine reliability and durability. These features of the operating condition distribution of shunting diesel locomotive engines and transient processes must be taken into account when creating ARS and ACS for diesel locomotive engines, creating fuel supply systems equipped with ARS and ACS systems, and evaluating the efficiency of their application in diesel locomotive engines.

2.2 Requirements for ARS of diesel rotation speed and management of regulating process

Achieving modern ICE indicators is impossible without further improvement of their ARS and ACS [8, 9]. One of the main diesel systems is the ARS of the crankshaft rotation speed, which ensures the maintenance of a given speed operating condition and carries out a number of additional functions [2, 10, 11]. The structural features of this system and its parameters predetermine the most important diesel engine performance indicators, such as maximum power and torque, dynamic and starting qualities, fuel economy and EG emissions. To ensure the best diesel performance, it is necessary to determine the optimal structure and the optimal basic parameters of the ARS of rotation speed. An important requirement of the diesel locomotive engines is to ensure their required dynamic characteristics. The most significant indicators of the dynamic qualities of a diesel engine are the duration of the transient process and the overspeed in the transient process (overregulation) [2]. The main regulatory document on automatic control systems for diesel engine speed is the Russian State Standard GOST R 55231-2012, which provides time limitation of the transient process and overregulation depending on the ARS accuracy class (Table 1) [12]. These requirements impose certain restrictions on the dynamic qualities of the diesel, which is essential when developing the corresponding ARS and ACS.

Table 1. The Russian State Standard GOST R 55231-2012 requirements for transient loading and unloading processes in automatic control systems of diesel rotation speed.

Characteristics	Accuracy class of ARS			
	1	2	3	4
Overspeed in a transient process (overregulation σ), %, not more	5.0	7.5	10.0	15.0
Duration of transient process t_{tr} , s, not more	2.0	3.0	5.0	10.0
Instability of the rotation speed for load from 25 to 100%, %, not more	0.6	0.8	1.0	2.0
Instability of the rotation speed for load up to 25%, %, not more	0.8	1.0	1.5	3.0

The most well-known principle of the regulation process organization is the principle of regulation according to the deviation of the regulated parameter or the Polzunov-Watt principle [2]. For it the regulatory impact is a function of the regulation error. Despite the wide distribution and well-known advantages of P-controllers (ease of implementation, versatility of regulation, etc.), they have several disadvantages. One of them is not always acceptable dynamic qualities (response time). An efficient method for increasing the ARS performance is to introduce a differential component into the law of regulation. Another disadvantage of P-controllers is not always acceptable static qualities. When the engine is equipped with a P-controller, an inclined (static) regulation characteristic is formed and a static control error occurs. The formation of integral (I) control law, in which the regulation impact is determined in the form of a control error accumulated over time, makes it possible to increase the accuracy of ARS operation in steady-state modes. The best indicators of the regulation process quality are provided by the proportional-integral-differential (PID) controller. It is achieved when introducing both an integral and a differential component into the law of regulation. In this case, the PID control law is formed, which is implemented by the PID controller containing P-, I- and D-controllers.

The PID controller is the most common type of regulator of modern power plants [13-22]. At the same time, for ICEs operating in relatively small variation range of shaft rotation speed, it is advisable to use PI controllers instead of PID controllers. This is predominantly true for stationary engines operating at an approximately constant speed. During the transient loading and unloading processes, which are characteristic for such engine group, the speed variation range is relatively small. Diesels of locomotive diesel-generation units (DGU) belong to the same group. The characteristic transient progresses of these diesels are loading and unloading processes and acceleration-deceleration according to locomotive characteristics. Moreover, since the diesel locomotive engines have a relatively high inertia during changing the speed operating condition, the transient processes of acceleration-deceleration of these engines occur relatively slowly (usually within several tens of

seconds). In this case, the introduction of the D-component into the control law may be unadvisable.

2.3 ESUVT.01 fuel supply electronic control system of the locomotive diesel

The design and production enterprise Dizelavtomatika (Saratov, Russia) has developed a ESUVT.01 fuel supply electronic control system of locomotive diesel. This system has wide functional capabilities for performing fuel supply characteristics, as well as for controlling the shaft speed of a locomotive diesel. The fuel supply process is controlled by means of a high-speed electro-hydraulic valve installed in the high-pressure line of the fuel system. A set of electrically controlled high pressure fuel pumps (HPFP) (model 4ETN.03) with electro-hydraulic valves for locomotive diesel D50 (6 CHN 31.8/33) of Penzadieselmash (Penza diesel plant) has been developed and manufactured (Fig. 1). Such a HPFP was used to create an experimental electronic fuel control system for diesel engine D50.

Fig. 1. Structural scheme of a high-pressure fuel pump with a solenoid valve for fuel supply control: 1 - low-pressure line of HPFP; 2 - valve; 3 - valve edge; 4 - pipe connection of HPFP; 5 - return spring; 6 - armature; 7 - electromagnet; 8 -High-pressure chamber

The pulse control electronic system of fuel supply includes the following main components: control unit, electric control valve (one for each cylinder), a set of sensors for operational parameters. The control unit is a digital microprocessor complex with special software (for each type of engine). A detailed description of the investigated pulse control electronic system with an electro-hydraulic valve is given in [23, 24].

2.4 Experimental setup and procedure

Experimental studies were carried out to assess the possibilities of controlling diesel speed using the fuel supply electronic control system (model ESUVT.01). The object of the study was a locomotive DGU from the diesel engine D50 (6 CHN 31.8/33) of 736 kW power without intermediate cooling of charge air, and the traction generator MPT-84/39 of 700 kW power with independent excitation. The engine loading was carried out on a water load rheostat. The diesel engine was equipped with a 9-position electronic control system (9 controller positions) of the ESUVT.01-6-02 type. An electric machine-type traction generator based on an exciter with transverse pole splitting was used. It could maintain constant power at each position corresponding to the actual rotation speed of the diesel shaft. The diesel locomotive characteristic implemented in ARS provides the following shaft speeds at the corresponding controller positions (Table 2).

Table 2. Rotation speed of the diesel shaft corresponding to the given positions of the driver controller (locomotive characteristic of the studied diesel engine).

Controller position	0 and 1	2	3	4	5	6	7	8
Rotation speed of shaft, min^{-1}	300	365	430	495	560	625	720	750

The diesel parameters were monitored using the following measuring equipment: the diesel shaft speed was measured using an inductive rotation speed sensor, which is a standard part of the electronic control system ESUVT.01; the other diesel parameters were determined using the measuring software of the test bench. The test procedure was as follows: the diesel engine was warmed up at idle (controller position No. 0) until the coolant (water) temperature reached 60 °C; the controller was set to a given position, the power of the traction generator was fixed; the change in the diesel shaft rotation speed in the investigated transient progress was recorded.

The fuel supply electronic control system ESUVT.01 includes a PID controller for the engine shaft speed. However, as noted above, for the considered locomotive diesel, it is sufficient to use the PI-law of speed control. In this regard, the influence of coefficients of P- and I-regulators of the PI-control law on the quality of transient processes of engine acceleration according to the locomotive characteristic was investigated. For the

studied transient progresses, the following parameters were recorded: t_{tr} is the transient process time [s]; Δn is the overspeed (the absolute value of the excess of the required rotation speed) [min^{-1}]; T_o is the period of natural oscillations [s]. The relationships between these transient quality indicators and the coefficients of P- and I-regulators were investigated. The measurements were performed for the modes presented in table 3. A step change in the speed setting was performed at a rate of 100 min^{-1}/s and a value of 5 min^{-1} (the used steps were 300/305, 480/485, 750/755).

Table 3. Diesel shaft rotation speed and loads corresponding to the given positions of the driver controller

Shaft rotation speed, min ⁻¹	300	300	480	480	750	750
Load, kW	0 (idle)	100	0 (idle)	400	0 (idle)	830

Note: idle is for idle mode

3 Results and Discussion

A number of studies have shown that the gain coefficients of P-, I-, and D-controllers of the PID control law (or PI control law) must be changed in accordance with the diesel operating conditions [2, 25-32]. In this regard, at first, the coefficients of the PI control law at the nominal speed mode were determined for $n=750 \text{ min}^{-1}$. For the mode with $n=750 \text{ min}^{-1}$ and $N_e=0$, these coefficients are equal to $k_p=0.70$ and $k_i=0.25$, and for the mode with $n=750 \text{ min}^{-1}$ and $N_e=830 \text{ kW}$, they are equal to $k_p=0.90$ and $k_i=0.25$. Then, experimental studies of the diesel engine were performed at speed modes with $n=300$ and 480 min^{-1} . When determining the time of transient progresses, the zone of permissible instability of the rotation speed in the investigated mode is considered. In accordance with the GOST 10511-83, the requirements for the width of this zone are established depending on the ARS accuracy class. But it should be noted that this GOST was developed in the 70-80s of the last century as applied mainly to mechanical and hydromechanical systems for automatically regulating the speed of diesel engines. In later editions of this GOST (in particular, in the GOST R 55231-2012), the requirements for the width of the specified zone of instability of the regulated parameter were not changed. At present, electronic (microprocessor) ARS and ACS, which have much greater functional capabilities in comparison with mechanical and hydromechanical control systems [2, 8, 10, 25, 26], have gained predominant distribution. So, in accordance with the requirements of GOST R 55231-2012, ARSs of the first and second accuracy classes must provide a zone of permissible instability of the rotation speed at the steady state, not exceeding 0.8% (see Table 1), while modern ARS and ACS are able to maintain a constant engine shaft speed with significantly greater accuracy. So, in accordance with data from [27], the ARS of the DGU rotation speed, equipped with a microprocessor control system that implements one of the varieties of the PID control law, ensures the constancy of the engine speed $n=1500 \text{ min}^{-1}$ with an accuracy of $\Delta n=0.2 \text{ \%}$ or 3 min^{-1} ($\Delta n=\pm 1.5 \text{ min}^{-1}$). Therefore, for the case under consideration, while maintaining the D50 diesel shaft rotation speed constant at $n=300 \text{ min}^{-1}$ with such permissible instability of the rotation speed at steady state, the width of this zone is chosen equal to $\Delta n=0.5 \text{ min}^{-1}$ or $\pm 0.25 \text{ min}^{-1}$. The research results of the influence of the gain coefficients of the PID control law on the quality indicators of the regulating process in the considered diesel operation modes are given in table 4. Figure 2 shows one of the plots for transient process.

Table 4. Relationship between the quality indicators of the regulating process and the gain coefficients of the PID control law.

No. of transient process	Gain coefficients of the PID control law			Quality indicators of the regulating process		
	k_p	k_i	k_d	t_{tr}, s	$\Delta n, \text{min}^{-1}$	T_o, s
Mode with $n=300 \text{ min}^{-1}$ and $N_e=100 \text{ kW}$						
1	0.15	0.15	0	2.350	0.691	1.040
2	0.30	0.15	0	1.095	0.416	0.755
3	0.40	0.15	0	1.290	0.639	0.477
4	0.50	0.15	0	3.188	0.910	0.439
5	0.15	0.30	0	1.445	1.412	0.988
6	0.30	0.30	0	1.209	0.384	1.169
7	0.15	0.40	0	2.610	1.601	1.067
8	0.30	0.40	0	1.312	0.571	1.219
Mode with $n=480 \text{ min}^{-1}$ and $N_e=400 \text{ kW}$						
9	0.30	0.20	0	2.561	0.236	0.630
10	0.40	0.20	0	1.263	0.250	0.574
11	0.50	0.20	0	2.131	0.318	0.534
12	0.60	0.20	0	1.511	0.250	0.536
13	0.70	0.20	0	1.186	0.250	0.476

Note: transient processes obtained with optimized coefficients of the P- and I- components of the PI control law are highlighted in yellow.

Fig. 2. Plots for a transient process: blue and orange horizontal lines show the zone of permissible instability of the regulated parameter $\Delta n_{add}=\pm 0.25 \text{ min}^{-1}$, used to determine the time of the transient process end; t_{tr} is the time of the transient process end; Δn is the transient overspeed.

Analysis of the obtained data shows that when the operating mode of the studied diesel engine changes, the optimal coefficients of proportional k_p and integral k_i components of the PI control law will also change. The following approach is used to select the optimal k_p values for specified k_i . In accordance with the

requirements of GOST R 55231-2012 for the ARS of the rotation speed of the locomotive diesels, the main quality indicators of the regulating process are the duration of the transient process t_{tr} and the overspeed in the transient process Δn or overregulation σ , defined as:

$$\sigma = \Delta n / n_0, \quad (1)$$

where n_0 is the engine shaft speed at the final steady-state mode. At the same time, the period of natural oscillations of the regulated parameter in the transient process T_0 is not regulated by the specified GOST. So, the following expression is chosen as the optimality criterion J_0 for the transition process:

$$J_0 = t_{tr} \bullet \Delta n. \quad (2)$$

In table 4, the transient progresses highlighted in yellow are optimal by this criterion. The optimized coefficients of the proportional k_p and integral k_i components of the PI control law correspond to each of these transient progresses. The obtained optimized coefficients of the proportional k_p and integral k_i components of the PI control law made it possible to construct the recommended characteristics of their change in the most characteristic transient process of acceleration of the investigated diesel engine according to the locomotive characteristic. These characteristics of the change in the coefficients k_p and k_i (Fig. 3) suggest to increase these coefficients during acceleration of the diesel engine (when switching to the controller positions with higher values of speed and load). The implementation of these characteristics with optimized coefficients k_p and k_i and the PI-law of regulation will allow achieving the best quality indicators of the regulating process, namely the transient process duration t_{tr} and the overspeed Δn in the transient process of acceleration of the investigated diesel according to the locomotive characteristic.

Fig. 3. The recommended characteristics of changes in the coefficients of the proportional component k_p (1) and integral component k_i (2) of the PI-control law in the most characteristic transient process of acceleration of the investigated diesel engine according to the locomotive characteristic

4 Conclusion

1. For the diesel engine with relatively small speed variation range, PI controller is usually used instead of PID controller. It is advisable to organize the PI-control law in the diesel engine with relatively high inertia. This group includes diesels of locomotive DGU.
2. Experimental studies were carried out for the D50 (6 CHN 31.8/33) diesel engine with the ESUVT.01 fuel supply electronic control system. This engine is a part of the 1-PDG4D diesel-generator unit of the shunting diesel locomotive. The transient process time, the overspeed in the transient process and the period of natural oscillations of the regulated parameter are considered as quality indicators of the regulation in the transient acceleration process according to the diesel characteristic.
3. A method for optimizing the coefficients of the proportional and integral components of the PI control law is proposed, which consists in the formation of an optimality criterion for the transient process in the form of the product of the transient process duration and overspeed in this transient process.
4. The obtained optimized coefficients of the proportional and integral components of the PI-control law made it possible to construct the recommended characteristics of their changes in the most characteristic transient process of diesel acceleration according to the locomotive characteristic.

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