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## IMPROVEMENTS IN TRANSIENT PERFORMANCE UNDER LOCOMOTIVE DIESEL-GENERATOR MODE CHANGING CONDITIONS

### POLEPSZENIE JAKOŚCI PRZEBIEGU PROCESU PRZEJŚCIA PRZY ZMIANIE WARUNKÓW PRACY ZESPOŁU SILNIK-PRĄDNICA LOKOMOTYWY SPALINOWEJ

#### Abstract

The algorithm of transient process control in electrohydraulic united regulator of locomotive diesel generator and in microprocessor system of adjusting diesel crankshaft rotation frequency and power of traction generator ERChM30T is observed. The new definition of speed restrictive performance of transient process is given as well as methods of its determination and representation in microprocessor system.

*Keywords: diesel-generator of a diesel locomotive, quality, transient process, limiting characteristic, method for determination*

#### Streszczenie

Zastosowanie elektronicznego regulatora obrotów wału korbowego i mocy prądnicy trakcyjnej ERCM30T, w miejsce elektrohydraulicznego, pozwala znacznie polepszyć jakość regulacji procesu przejścia i wyeliminować nieproduktywną dawkę paliwa. Przedstawiono metodykę określenia dopuszczalnej dawki paliwa w procesie przejścia zespołu silnik-prądnica lokomotywy spalinowej

*Słowa kluczowe: silnik-prądnica lokomotywy spalinowej, jakość, proces przejścia, charakterystyka graniczna, metodyka określenia*

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## 1. Introduction

A frequent change of power equipment mode is rather typical of diesel-locomotive operation. According to statistical observations, a change of diesel-generator speed rate occurs 50 to 60 times during each working hour during shunting and 200 to 250 times during an hour of power operation on mainline diesel locomotives. Therefore, full attention is given to the improvement in diesel-generator performance during transient (speed rate changing) processes. Accuracy and performance control of these processes is of prime importance while boosting diesel-engine by mean effective pressure [1].

## 2. Hydromechanical governor 4-7RS2

Hydromechanical governor 4-7RS2 developed by the holding company JSC “Kolomensky Zavod” (under the leadership of B.P. Kolosov) proves to be one of the high-water marks as far as transient process arrangement is concerned [2]. The governor high control performance is achieved through restraining fuel injection into cylinders and limiting the generator capacity in accordance with air pressure in the diesel inlet manifold. Characteristics of the fuel injection corrector and the traction generator load control (within the governor) in function of charging pressure are represented in Fig. 1.

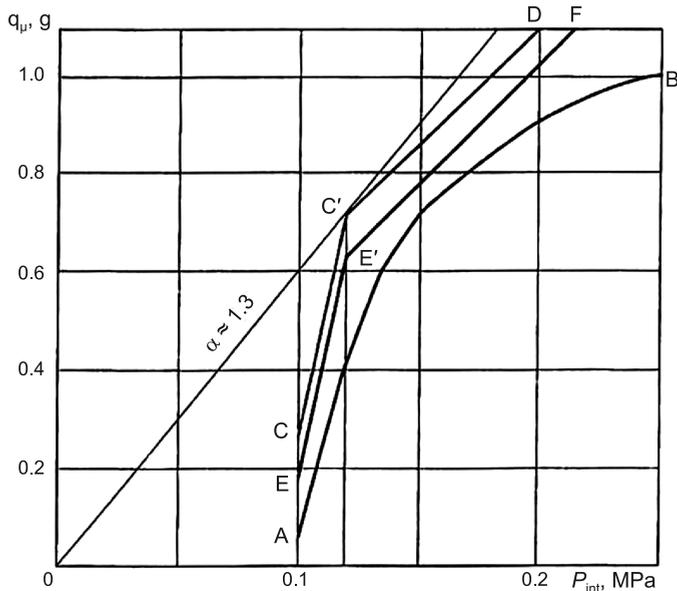


Fig. 1. Characteristics of fuel limiter and load of diesel-generator 1A-9DG installed on diesel locomotive 2TE116 (represented schematically): AB – diesel locomotive related specified speed characteristic under steady-state conditions; CCD – limiting of fuel injection in function of charging pressure; EE'F – characteristic of power governor action aimed to reduce in diesel-generator capacity

Displacement of the locomotive handle causes mismatching between specified and actual crankshaft speeds. Therewith the speed governor draws control racks so as to increase fuel injection.

The corrector blocks off fuel injection according to the CCD curve which corresponds to preset specified value of air-to-fuel ratio (excess air factor  $\alpha$ ). Limiting of fuel injection guarantees high quality of work process in diesel engine, reduces thermal overloads of the sleeve assembly components and smoking at the exhaust. However the load produced by traction generator may turn out to be intolerably high thus making too low (or even equal to zero) the crankshaft angular acceleration necessary for mode changing. Then with satisfactory work process parameters the diesel-engine crankshaft will accelerate too slow thus increasing the transient process duration. To eliminate such possibility the corrector was modified with introduction of limiting characteristic EE'F. Provided that cyclic injection gets higher than this curve, power governor moves inductive sensor in the direction of traction generator load reduction, securing specified angular acceleration of the crankshaft (i.e. necessary rapidity of transient process).

Hydromechanical governors 4-7RS2 were mounted on diesel locomotives 2TE116, TEP70, TEM7 et al. (on diesel-engines D49). Such governor main drawbacks are instability and adjustment complexity of its characteristics under operating conditions. With further boosting of diesel-engine by mean effective pressure hydromechanical governors can't provide for adequate control accuracy and stability of diesel-engine characteristic.

### **3. Microprocessor control systems ERChM30T**

Microprocessor control systems ERChM30T of crankshaft speed and traction generator capacity have been installed on diesel locomotives since 2000. Utilization of such a control system allows for the improvement of crankshaft speed maintenance accuracy and adjustment stability of diesel-engine and traction gear characteristics under operating conditions.

The ERChM30T governors have been installed on more than 2.000 diesel locomotives (types ChME3, TEM2, 2TE10MK, 2TE116, TEP70 etc.). The rpm maintenance accuracy amounts to  $\pm 1.0$  rpm within the range 300 to 1,000 rpm. There is virtually no need for correcting the specified characteristics in operation. The microprocessor system capabilities have made possible considerable improvement in control quality and accuracy of speed characteristics of steady state modes and transient processes due to major changes in their organizational pattern. First and foremost, this concerns the method of setting transient process limiting characteristic. Previously, it was believed [1] that fuel injection limiting in the course of the transient processes is governed through specifying the value of total excess air factor ( $\alpha_2$ ). As a rule, this value was selected experimentally based on observations of diesel engine smoking at the exhaust and set at a level ranging from 1.25 to 1.30 within an accuracy of  $\pm 0.1$  (not always observed). The present paper presents another approach to solving the defined problem.

#### 4. Analysis of the indicated power variation at the transient process

Let us analyse the indicated power variation at the initial phase of the transient process. We shall assume that in the course of the transient process, a new rpm setting causes fast acting speed governor to increase fuel injection. With this process under way, crankshaft and turbocompressor rotor speeds remain constant, thus making a constant diesel engine airflow. Diesel locomotive traction generator and ancillary equipment capacities of and in-diesel engine friction power also do not suffer changes.

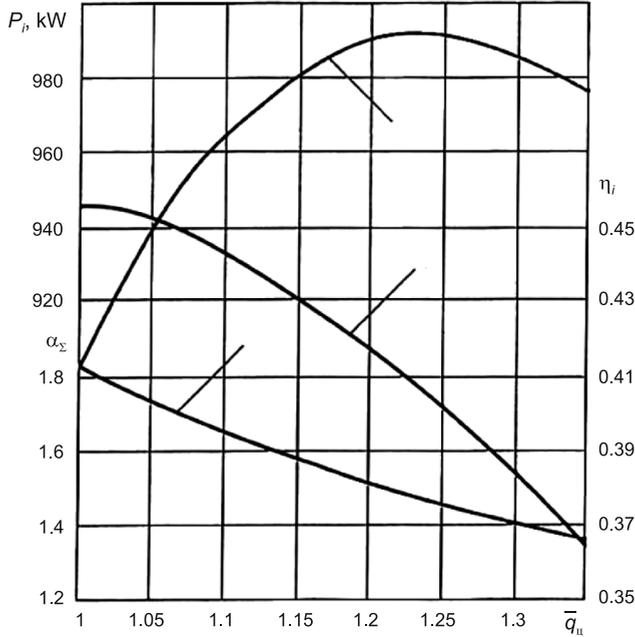


Fig. 2. On defining transient process related diesel engine speed limiting characteristic (diesel engine 12ChN26/26, crankshaft speed 64.9 rad/s (620 rpm)):  $\bar{q}_u$  – relative increment of cyclic fuel injection (0.65 g/cycle is taken as a unit);  $\alpha_\Sigma$  – total excess air factor;  $\eta_i$  – indicated efficiency;  $P_i$  – indicated power (kW)

As the cyclic fuel injection increases, the excess air factor varies in inverse proportion to it:

$$\alpha_\Sigma = \frac{G_{V_i} 2\pi\tau}{\lambda_0 q_F \omega_i Z} \quad (1)$$

where:

- $G_{V_i}$  – engine airflow (kg/s),
- $q_u$  – cyclic fuel injection (kg/cycle),
- $Z$  – number of cylinders,
- $\lambda_0$  – stoichiometric relationship,

- $\tau$  – engine taticity coefficient,  
 $\omega_i$  – crankshaft speed, rad/s.

Considering that in respect to this process  $G_{vi} = \text{const}$ ,  $\omega_i = \text{const}$ , we may write:

$$d\alpha_\Sigma = \frac{d\alpha_\Sigma}{dq_F} dq_F \quad (2)$$

where:

$$\frac{d\alpha_\Sigma}{dq_F} = - \frac{G_{vi}}{\omega_i} q_F^{-2} \frac{2\pi\tau}{\lambda_0 Z}$$

Let us define the variation in the indicated power:

$$P_i = \frac{H_8 q_F \eta_i \omega_i Z}{2\pi\tau} \quad (3)$$

where:

- $H_{vi}$  – the lowest heat value of fuel (kJ/kg),  
 $\eta_i$  – indicated efficiency (coefficient of performance).

With made assumptions we obtain:

$$dP_i = \frac{H_8 Z \omega_i}{2\pi\tau} (dq_F \eta_i + d\eta_i q_F) \quad (4)$$

with regard to (1) we have:

$$dP_i = \frac{H_8 Z \omega_i}{2\pi\tau} \left( dq_F \eta_i + q_F \frac{d\eta_i}{d\alpha_\Sigma} d\alpha_\Sigma \right) \quad (5)$$

or

$$dP_i = \frac{H_8 Z \omega_i}{2\pi\tau} \left( dq_F \eta_i + q_F \frac{d\eta_i d\alpha_\Sigma}{d\alpha_\Sigma dq_F} dq_F \right) \quad (6)$$

with regard to (2) we have

$$dP_i = \frac{H_8 Z \omega_i}{2\pi\tau} dq_F \left( \eta_i - \frac{G_{vi} 2\pi\tau}{\lambda_0 Z \omega_i} q_F^{-1} \frac{d\eta_i}{d\alpha_\Sigma} \right) \quad (7)$$

In the course of the process under consideration, indicated power  $P_i$  achieves its maximum under  $dP_i = 0$ , i.e under:

$$\eta_i = \frac{G_{vi} 2\pi\tau}{\lambda_0 Z \omega_i} \frac{1}{q_F} \frac{d\eta_i}{d\alpha_\Sigma} \quad (8)$$

or with regard to (1) we have:

$$\eta_i = \alpha_\Sigma \frac{d\eta_i}{d\alpha_\Sigma} \quad (9)$$

Indicated efficiency value  $\eta_i$ , depends on  $\alpha_\Sigma$  and crank-shaft speed [1].

Basing on experimental data for every specified crank-shaft speed value, we determine relationships to be stored in the microprocessor control system.

$$\eta_i = \eta_i(\alpha_\Sigma) \quad \text{and} \quad \frac{d\eta_i}{d\alpha_\Sigma} \quad (10)$$

As a case in point, Fig. 2 represents the dependencies of diesel-engine indicated efficiency  $\eta_i$ , total excess air factor  $\alpha_\Sigma$  and indicated power  $P_i$  under crankshaft speed  $\omega_i = 64,8$  rad/s from relative increments of fuel injection. The relationships were obtained by resultant data processing of type 2TE25 locomotive diesel-engine tests carried out by JSC “Kolomensky Zavod”.

As is clear from Fig. 2, increases in fuel injection by more than 20% do not cause any increase in indicated power, thus they are fully unjustified. Herewith the excess air factor amounts to 1.5. Previously the permissible value of excess air factor was believed [1] ranging from 1.30 to 1.35. The governor 4-7RS2 limiter was specifically adjusted for such value thus allowing for injection of 10 to 15% excess fuel into cylinders. Of course this fuel combusted through-and- through, contributing to larger heat load density of structural components and more intensive smoking at the exhaust but not to increase in the indicated power.

## 5. Rational load control algorithm

Rather strict regulation of fuel injection increments superimposed by microprocessor system is compensated with rational load control algorithm of traction generator and correct variation of permissible injection value in terms of increasing turbocompressor rotor speed and charging pressure. In Fig. 3, an oscillograph record is represented showing the transient process of diesel-generator 2A-9DG installed on a microprocessor system equipped diesel locomotive TEP70 as for the case of drawing locomotive handle from the first to the fifteenth position.

At the transient process initial phase control racks (hp) instantaneously get on the fuel injection limiting position (hp). Microprocessor system controls traction generator current ( $I_{mc}$ ) so as to provide for specified angular acceleration of the crankshaft (curve  $\omega_d$  in Fig. 3) and near-the-limiting position of control racks  $h_{p/p}$ . On reaching the specified crankshaft speed (in Fig. 3 it occurs in the course of 66s), the traction generator load is regulated so as to force control racks to draw nearer to the limiting position, but not quicker than the permissible loading rate of the traction generator in tractive mode.

The represented oscillograph record demonstrates that the transient process realized in the ERChM30T microprocessor control system meets the most severe requirements of quality and accuracy of locomotive diesel-generator control. This process may be considered optimum with regard to the definition proposed in [1]. Elimination of nonproductive fuel injection according to the relationship (9) leads to an increase in fuel efficiency by 2–5%, ensures diesel-engine overloading protection and reduces hazardous emission, this is not the whole story. Fuel efficiency enhancement highest potential lies in that achieved control quality and accuracy allow for raising the level of specified (diesel locomotive) speed characteristic, thus drawing it nearer to limiting characteristic of the steady-state regime.

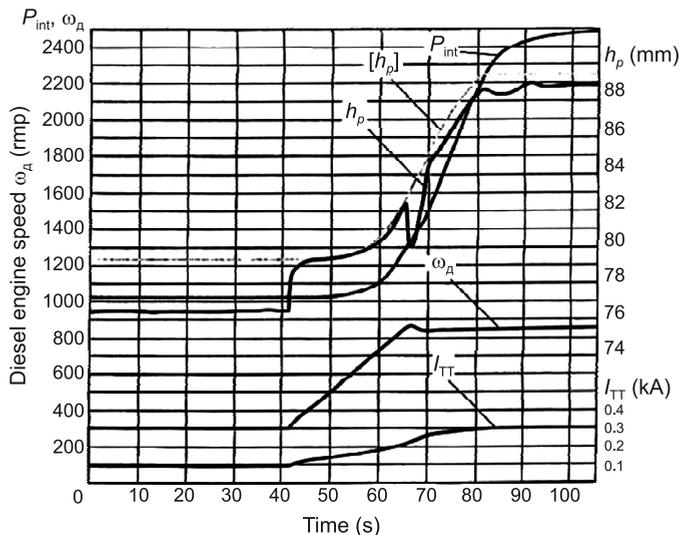


Fig. 3. Diesel engine transient process

Table 1 contains the transient process related permissible increment values of fuel injection (marked blue) depending on the indicated power level of the diesel engine 12ChN26/26 basic static characteristic at a speed of 64.9 rad/s. With high level power of the steady- state regime permissible fuel injection increment is nothing more than 10%. This implies that diesel engine crankshaft angular acceleration in the course of transient process will be low, thus contributing to an increase in the process duration. Such increment values are acceptable for mainline diesel locomotives, not affecting their productivity but contributing to an additional reduction in fuel consumption by 2–3%. Employing high-efficiency engine on shunting locomotives demands for special measures to be taken, such as the installation of a power circuit storage [3] et al.

Table 1

**On defining of limiting speed characteristic as related to transient process in diesel-engine 12ChN26/26 at a speed of 64.9 rad/s**

$\bar{\delta}_T$	$B_T$ kg/h	$\alpha_\Sigma$	$\eta_l$	$g_i$ kg/kW·h	$P_i$ kW	$\bar{\delta}_T$	$B_T$ kg/h	$\alpha_\Sigma$	$\eta_l$	$g_i$ kg/kW·h	$P_i$ kW	$B_T$ kg/h	$\alpha_\Sigma$	$\eta_l$	$g_i$ kg/kW·h	$P_i$ kW	$B_T$ kg/h	$\alpha_\Sigma$	$\eta_l$	$g_i$ kg/kW·h	$P_i$ kW
1,0	85,1	2,61	0,459	0,1838	463	1,0	167,1	1,82	1,456	0,185	903,2	215,9	1,65	0,44	0,191	1130	269,5	1,59	0,424	0,1987	1356
1,1	93,6	2,37	0,4595	0,1835	486	1,05	175,5	1,73	0,452	0,1865	941	227	1,57	0,425	0,1984	1144	283	1,514	0,412	0,2046	1383
1,2	102,1	2,17	0,4595	0,1835	556	1,1	183,8	1,65	0,443	0,1903	966	237,5	1,5	0,41	0,206	1153	296	1,445	0,403	0,2012	1415
1,3	110,6	2,01	0,457	0,1844	600	1,15	192,2	1,58	0,430	0,196	980,6	248,2	1,43	0,402	0,211	1177	310	1,38	0,38	0,222	1396
1,4	119,0	1,86	0,455	0,1851	643	1,2	200,5	1,52	0,417	0,202	992,6	259	1,375	0,375	0,2248	1152	323,4	1,32	0,357	0,236	1370
1,5	128,0	1,74	0,4525	0,1863	687	1,25	208,9	1,46	0,400	0,2108	991	270	1,32	0,357	0,236	1144					
1,6	136,0	1,68	0,4505	0,189	719,6	1,3	217,2	1,40	0,383	0,2203	986										
1,65	144,6	1,53	0,405	0,208	695	1,35	225	1,34	0,365	0,231	976,7										
1,7	153,0	1,45	0,365	0,2303	662																
1,75	161,7	1,37	0,34	0,248	652																

Note:  $B_T$  – fuel injection (kg/h);  $\bar{\delta}_T$  – relative variation of fuel injection;  $g_i$  – indicated specific fuel consumption (kg/kW·h)

## 6. Conclusions

1. Application of microprocessor governor of crankshaft speed/traction generator capacity contributes to significant improvement of transient process control performance and eliminates nonproductive fuel injections.
2. The represented method for determination of affordable fuel injection in the course of locomotive diesel generator transient process may be used for the purpose of transient process analysis of any other dedication diesels.
3. Microprocessor control application to power equipment renders possible fuel saving at diesel locomotives of about 3–6%.

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