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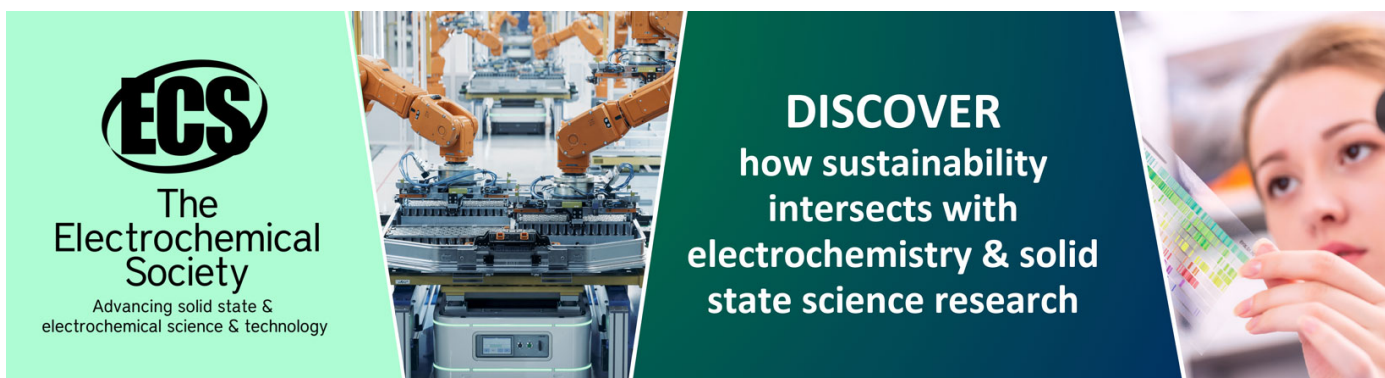
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Improvement of automatic control system for high-speed current collectors

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Abstract. The article considers the ways of regulation of pantographs to provide quality and reliability of current collection at high speeds. To assess impact of regulation was proposed integral criterion of the quality of current collection, taking into account efficiency and reliability of operation of the pantograph. The study was carried out using mathematical model of interaction of pantograph and catenary system, allowing to assess contact force and intensity of arcing at the contact zone at different movement speeds. The simulation results allowed us to estimate the efficiency of different methods of regulation of pantographs and determine the best option.

1. Introduction

One of the major problems at higher speeds on the electrified Railways is provision of reliable current collection in the context of significant electrical current, mechanical and aerodynamic loads. To improve the quality of the current collection at high speeds we can use automatic control systems that allows to regulate contact force between pantograph and contact wire with respect to conditions of the interaction process.

2. Statement of the problem

To achieve high quality current collection it is necessary to provide continuous contact of pantograph strips with contact wires, the pressing force of strips on contact wire should be in the narrow range of acceptable values.

Reducing the contact force leads to sparking and arcing in the contact that causes excessive wear of the current collecting strips and overheating of the pantograph. The increase of force leads to increased mechanical wear due to friction forces and heating of the pantograph.

With the increase of speed of electric rolling stock dispersion of contact force is increased due to raise of aerodynamic effects and vibration of vehicle. [1].

The study was conducted to assess the effectiveness of the various automatic control systems in the design of modern high-speed pantographs that operates on railroads of Russia.

3. Theory

When designing a system of automatic control of the pantograph we need to define quality criterion of regulation, which will allow us to select the optimal implementation of control system. The main criterion are the efficiency of the current collection associated with the service life of the contact materials and reliability, that depends on probability of failure of pantograph or catenary.



The current collection efficiency can be estimated by the wear rate of the contact strips of the pantograph, which at nominal current depends on the contact force. With increasing contact force increases the intensity of wear, reduction of force leads to arcing and electrical erosion of materials. Dependence of wear rate from contact force $\gamma(P_{cf})$ is a U-shaped curve, the shape of the curve is determined by the contact materials, current density in the contact and other factors. For each pair of materials in contact, the U-shaped curve is determined by the results of experimental studies [2].

The reliability of current collection is influenced by a big number of random factors, such as the technical condition of overhead lines and pantograph, the impact of weather events and many others. It is not possible to take into account impact of all factors in assessing the quality of regulation, therefore, as the main criterion of reliability of current collection we used requirements for safe operation of power equipment, among which was selected main criterion – maximum allowable value of the contact force $P_{cf \max}$. Exceeding this value can lead to failures of elements of the catenary network. To account for the excess of the contact force over the allowable value in quality criterion of current collection used penalty coefficient k_c . The final quality criterion of current collection can be expressed by the following relationship:

$$k_c(P_{cf}) = \begin{cases} \gamma(P_{cf}), & P_{cf} \leq P_{cf \max} \\ k_{c\max}, & P_{cf} > P_{cf \max} \end{cases} \quad (1)$$

Evaluation of quality of automatic regulation should be performed by measuring the integral quality criterion I_{kc} obtained by integrating criterion $k_c(P_{cf})$ by the time of experiment:

$$I_{kc} = \int_0^t k_c(P_{cf}(t)) dt \quad (2)$$

For optimal regulation of contact force it is necessary to minimize the value of the integral quality criterion of current collection.

One of design feature of most modern pantographs is rubber-cord pneumatic lifting mechanism. This mechanism allows to change the contact force of the pantograph by adjusting the pressure in the pneumatic system. To implement the automatic regulation system of pantograph pneumatic mechanism can be equipped with additional electro-pneumatic valves, that will allow to change pressure in the rubber-cord of the pantograph. Depending on the operating conditions, the controller may switch one of the valves, raising or lowering the lifting force of a pantograph. Figure 1 shows a diagram of the pneumatic control with two pressure steps [3].

The disadvantage of such a system is a significant duration of the transition process when valve is switched caused by inertia of the pantograph lifting mechanism.

The most effective input signal for automatic control system is contact force, since it directly affects the quality criterion of current collection. Difficulty of measurement of contact force caused by a number of factors such as high cost of equipment, the necessity to modify the design of a pantograph for mounting the sensors and the requirements for electrical safety. In this regard other input signals was considered in development of automatic control system. As such signals is considered the speed of the electric rolling stock and the ratio of arcing in sliding contact.

The ratio of arcing is defined as the ratio of arcing duration to the total duration of the movement, it indicates loss of contact and low quality of current collection. Measurement of arcing can be executed with optical or electromagnetic sensors. Sensors can be placed on the roof of electric rolling stock and don't require modification of the pantograph [4].

To evaluate process of automatic control of contact force we developed a mathematical model of the pantograph in mathematical environment MATLAB/Simulink. The scheme of the pantograph is an uniaxial two-mass model with two degrees of freedom. The model consists of a point-mass system of pantograph parts, the frequency and amplitude of pantograph base vibrations have a dependency on the speed of the electric rolling stock.

The static uplift force of the pantograph is set by the model of rubber-cord lifting mechanism, its input connected to the signal of pressure in the pneumatic system. Lifting and lowering mechanism is

modeled with a transfer function which is determined experimentally for the chosen design of the pantograph [5].

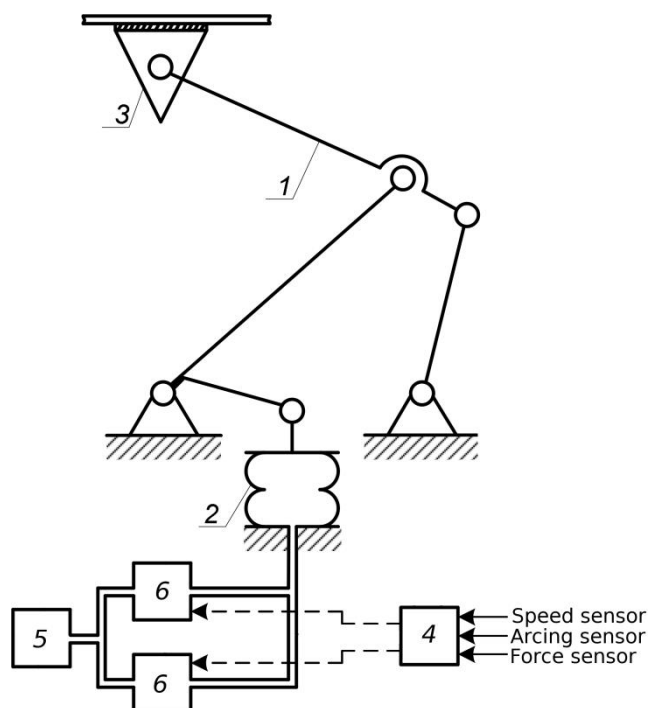


Figure 1. System pneumatic control of the pressing of current collector: 1 – system of movable frames of the pantograph; 2 – rubber-cord; 3 – contact strips; 4 – control unit; 5 – source of compressed air; 6 – electro-pneumatic dispenser.

Arcing at the contact is modeled with a uniform random function. The value of the function is set to zero when contact force exceed minimum threshold values $P_{cf \min}$.

Figure 2 shows scheme of a mathematical model of automatic control system of a pantograph constructed in Simulink.

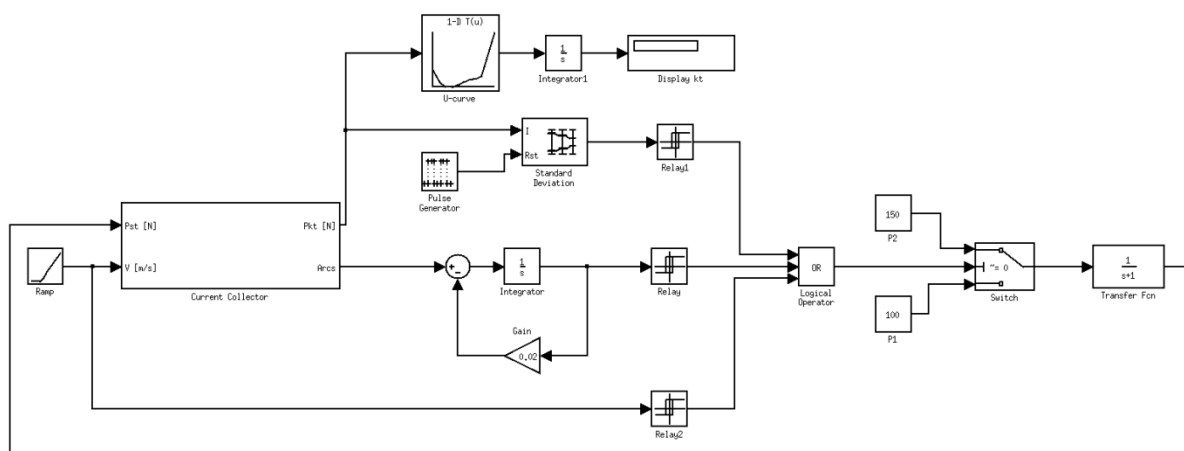


Figure 2. Scheme of mathematical model of automatic control of a pantograph in the Simulink environment.

The movement speed control subsystem uses Relay element, which produces the control signal for switching to the high pressure when the threshold speed value v_t is reached.

Since the lifting and lowering mechanism is characterized by long transient process, we can't use rapidly changing contact force signal directly in control system, so the contact force automatic control subsystem performs calculation of the standard deviation of contact force σP_{cf} at a fixed time window. System switches pressure when standard deviation of contact force reaches threshold limit $\sigma P_{cf t}$.

Arcing control subsystem performs integration of the arcing intensity $i(t)$. When integrated signal reaches threshold value $I_{\Sigma t}$, the valve is switched to high pressure. After the cessation of sparking, the system switches pressure to previous level, providing a return of depression to the pre-set level.

The control signals of all the controllers are combined by using Boolean function "OR", which allows parallel work of each subsystem.

4. The results of the experiments

The aim of the study was to determine the optimal control scheme of pantograph and suitable threshold values for each control subsystem. This was accomplished through a series of experiments in which we simulated the process of current collection during acceleration of electric rolling stock up to the maximum speed. Figure 3 shows results of the simulation of current collection with automatic control system. Changes of static contact force P_{st} corresponds to the switching instants of the pressure valves caused by signal the automatic control system. Graph of intensity of arcing $i(t)$ shows the relative intensity of arcing at the points of the low contact force. Quality criterion of current collection k_c have U-shaped form that resembles the shape of the intensity of wear of the contact material; the minimum value of the criterion $k_{c \min}$ corresponds to the optimal value of the contact force $P_{cf \text{ opt}}$, the maximum value of the criterion corresponds to the zero value of contact force (loss of contact) or exceeding maximal allowable value for safe operation $P_{cf \text{ max}}$.

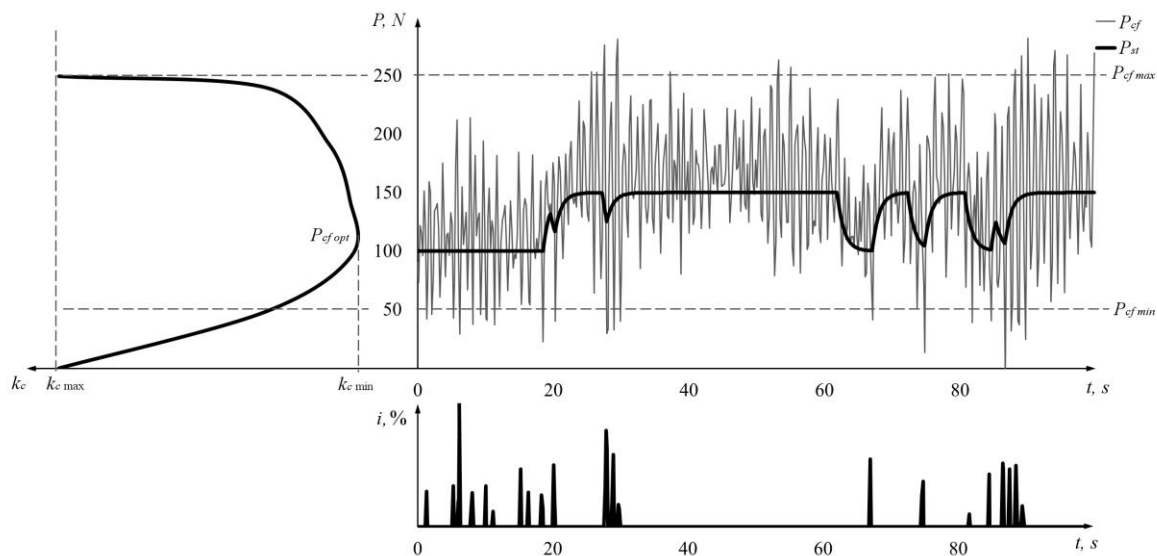


Figure 3. The results of simulation of automatic control system of pantograph: k_c – quality criterion of current collection, P_{cf} – contact force, P_{st} – static contact force, $i(t)$ – intensity of the arcing.

Table 1 shows the resulting values of integral quality criterion of current collection while using each control subsystem individually. For easy comparison of the effectiveness of each controller subsystem table shows relative values of a gain of integral quality criterion $\Delta I_{kc} = I_{kc b} - I_{ct}$ relative to the base value of the criterion $I_{kc b}$, obtained by simulation of the process without automatic control system.

The simulation results show that the most effective regulation of pantograph can be achieved by using input signal of contact force and arcing. Controlling by movement speed signal have lower

efficiency due to the lack of feedback loop. Figure 4 shows relative increment of integral quality criterion of current collection with different threshold parameters of the regulators.

For evaluation of simultaneous work of control subsystems we conducted a series of experiments with different combinations of threshold values of contact force deviation and arcing rate. The results of the experiments are shown in table 2.

The results of the experiments showed a slight increase in the quality of current collection when combined control scheme is used. The maximum quality increase above separated control subsystem amounted to 0.3 %.

Table 1. Quality criterion of current collection with different regulation schemes.

Control by contact force			Control by arcing			Control by movement speed		
$\sigma P_{cfb}, N$	I_{kc}	$\Delta I_{kc}/I_{kc b}$	I_{Σ}	I_{kc}	$\Delta I_{kc}/I_{kc b}$	$v_b, m/c$	I_{kc}	$\Delta I_{kc}/I_{kc b}$
10	31.5	0.6 %	5	31.0	2.2 %	25	31.5	0.6 %
20	31.2	1.6 %	10	30.2	4.7 %	30	31.3	1.3 %
30	31.1	1.9 %	15	30.1	5.0 %	35	30.7	3.2 %
40	30.2	4.7 %	20	29.6	6.6 %	40	30.2	4.7 %
50	29.2	7.9 %	25	29.5	6.9 %	45	30.1	5.0 %
60	29.7	6.3 %	30	29.1	8.2 %	50	30.4	4.1 %
70	30.9	2.5 %	35	29.4	7.3 %	55	30.5	3.8 %
80	31.6	0.3 %	40	29.6	6.6 %	60	31.6	0.3 %

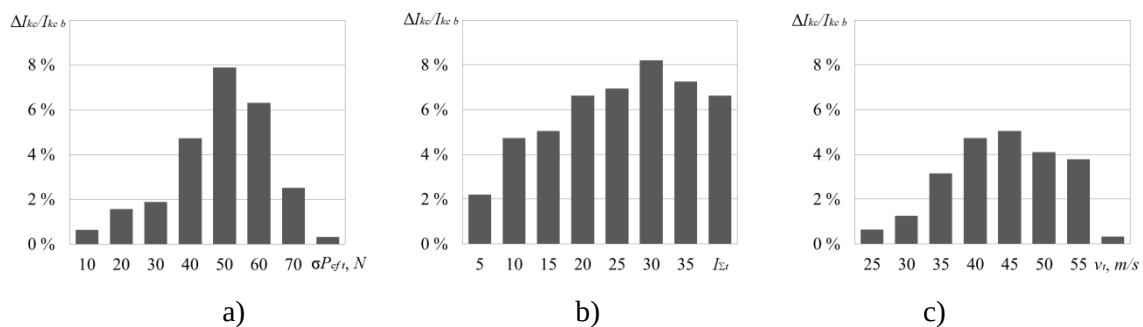


Figure 4. The relative increment of the integral quality criterion of current collection, when using control system with following input signals: contact force (a), arcing rate (b) and movement speed (c).

Table 2. Increase of integral quality criterion of current collection $\delta I_{kc} / I_{kc b}$ (%) with combined control subsystems.

$\sigma P_{cfb}, N$	I_{Σ}							
	5	10	15	20	25	30	35	40
10	0.6	0.6	0.9	1.6	1.3	1.3	0.9	0.9
20	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6
30	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9
40	1.9	1.9	1.9	4.4	4.7	4.7	4.7	4.4
50	2.2	4.7	6.9	7.9	7.6	7.6	7.3	6.6
60	2.2	3.8	4.4	6.6	7.6	8.5	7.9	7.3
70	2.2	3.5	4.7	5.4	6.3	8.2	7.3	6.3
80	2.2	4.7	5.0	6.3	6.6	8.2	7.3	6.6

5. Discussion of results

The experimental results show that the use automatic control system in design of pantographs can improve the quality and reliability of the current collection at high speeds. Using movement speed as input signal for control system is less effective compared to other options, since the control signal is not linked with contact force directly and lacks feedback loop. Use of arcing rate as input signal for automatic control system can be almost as effective as using direct contact force measurement.

6. Conclusion

Considered automatic control system with stepping change of pressure in pneumatic lifting mechanism of pantograph showed the possibility of effective application for improve the quality of current

collection at high speeds. Use arcing rate as input signal for control system appears to be most promising judging by high effectiveness and low implementation costs

To further improve automatic control systems of pantographs it is possible to consider increasing the number of steps of pressure regulation and optimization of control algorithms. To achieve a substantial improvement of the current collection it is necessary to solve the problem of long duration of transients with a step-like pressure control, this can be achieved by means of special control mechanisms embedded in the design of the pantograph.

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