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DESIGN OF THE CURRENT LOGGER OF AUTOMATIC CONTROL SYSTEM FOR CURRENT COLLECTORS WITH ICE OR RIME FROST ON THE OVERHEAD LINE

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Key words: *automatic control system, contact strip, DC current, arcing*

Abstract. *The article considers the ways of regulation of pantographs to provide quality and reliability of current collection. 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. To monitor the contact strip it is possible to utilise the fact that arcing between the contact strip and the overhead line generates a DC component in the AC locomotive current. The paper presents a automatic control system to regulate contact force between pantograph and contact wire with respect to conditions of the interaction process. The wear of the contact strip is predicted by monitoring the running distance of the pantograph as well as the DC component of the AC locomotive current. The experimental results show that the use automatic control system in design of pantographs can improve the quality and reliability of the current collection with ice or rime frost on the overhead line. Using movement DC component of the locomotive current (I_{kc}) as input signal for control system can be almost as effective as using direct contact force measurement.*

1. INTRODUCTION

Because of the zigzag configuration of the overhead contact wire, as shown in Figure 1, v_{pant} in the lateral direction is much slower than v_{line} in the forward direction. Therefore, the arc root moves slowly along the pantograph surface and remains heated. On the other hand, the arc root moves faster along the overhead contact wire surface, is continuously changing position, and thus, is colder. Because of the sliding motion between the two electrodes, arc roots at both electrodes move along their respective surfaces at different speeds, having different electrothermal conditions [1], [2].

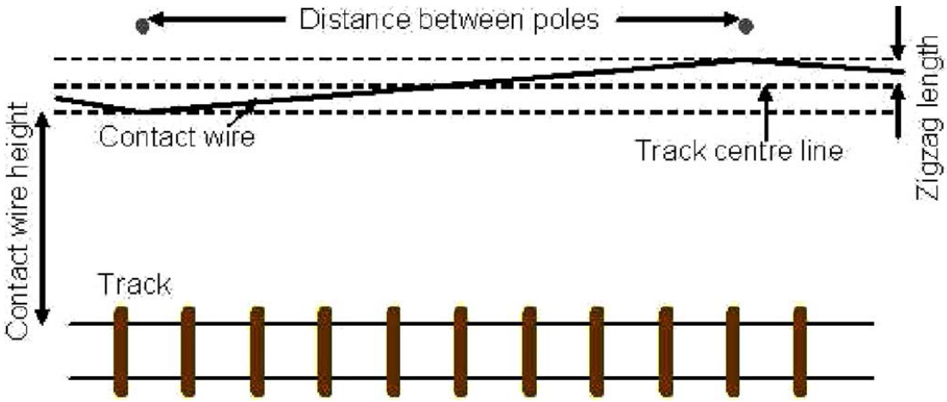

Figure 1. Layout of an overhead electrified railway showing the zigzag of the contact wire; adapted from [10].

This leads to an asymmetry between both polarities of the $U(t)$ and $I(t)$ waveforms [1-3],. Both the pantograph arcing, its polarity-dependent nature, the $U(t)$ and $I(t)$ waveforms, and arc root movements are influenced by several parameters like v_{line} , I_{rms} , U_0 , and the presence of inductive load in the circuit [1-2].

In normal weather conditions, there is a thin film of moisture between the pantograph and the overhead contact wire, which makes the sliding contact smooth [4-6] and we do not observe intense arcing. In winter, this thin layer of moisture is frozen. Apart from this, depending on the metrological conditions, there could be a thick layer of ice/snow on the overhead contact wire [7-9]. Therefore, instead of a carbon–copper sliding contact, it becomes a ice/snow-layer– carbon sliding contact as shown in Figure 2. This makes the slide between the two electrodes far from smooth and a visible bright glow of arc is noticed in almost all countries with cold weather when a train passes [2].

There are different types of ice layers that can be formed on the overhead contact wire based on the atmospheric and geographical location viz., hoarfrost, rime (soft and hard), glaze, and spray ice [7-9]. Depending on the formation and type, some of these are more sticky (hoarfrost), granular in structure (rime), harder (hard rime, glaze), and homogeneous in thickness (glaze) [7-8].When the pantograph moves through the overhead contact wire, the pantograph slides through this ice layer.

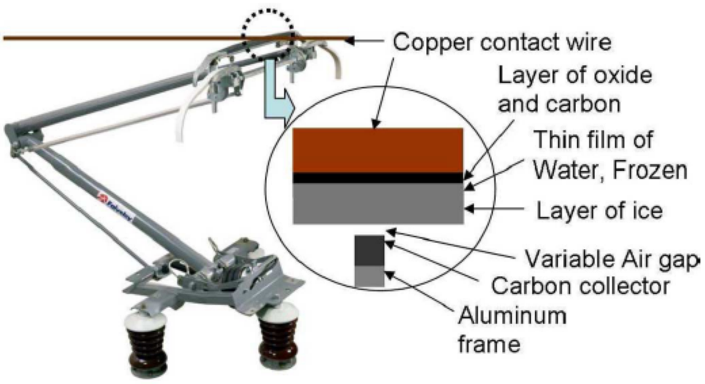

Figure 2. Details of the sliding contact between the pantograph and the overhead contact wire in winter (not to scale).

To have the power flow from the overhead contact wire to the pantograph, there has to be electrical breakdown of this dielectric layer of ice. Compared to our case with a dielectric air gap, an ice layer has a higher breakdown voltage, which increases with decreasing temperature [11-12], and hence, it requires higher voltages and longer times to be able to reignite the arc and supply the required current. This will lead to a higher level of I_{kc}

compared to our investigation in normal weather conditions, which is also experienced by different railways in many countries during winter . The I_{kc} propagates from the pantograph to the vehicle and follow the return path of the traction power system shown in Figure 3.

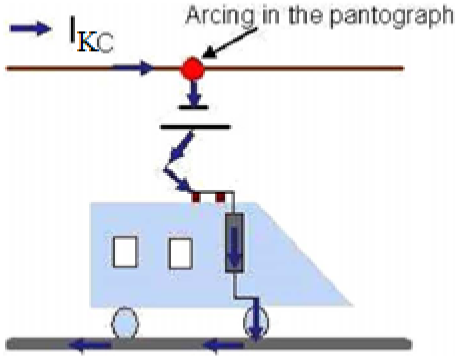

Figure 3. The I_{kc} propagates from the pantograph to the vehicle and follow the return path of the traction power system (adapted from [7]).

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..

For optimal regulation of contact force it is necessary to minimize the value of the integral quality criterion of current collection. 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 [4].

The paper described above the locomotive current I_{dc} who could be used as an indication for electric arcing. For modern vehicles this could be implemented in the train control system. Consequently, the paper described above design of the current logger in the control system based on well know theory.

2. RELATIONSHIP BETWEEN THE DC COMPONENT OF THE LOCOMOTIVE CURRENT AND THE CONTACT FORCE OF PRESSING CURRENT COLLECTOR

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 $\gamma(F_c)$ 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 [3,7,13].

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 $F_{c.max.}$ 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 $k_{c\ max}$. The final quality criterion of current collection can be expressed by the following relationship [13-15]:

$$k_c(F_c) = \begin{cases} \gamma(F_c) & F_c \le F_{c,\max} \\ k_{c,\max} & F_c > F_{c,\max} \end{cases} \quad (1)$$

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

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

Figure 4 shows a diagram of the pneumatic control with two pressure steps . 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.

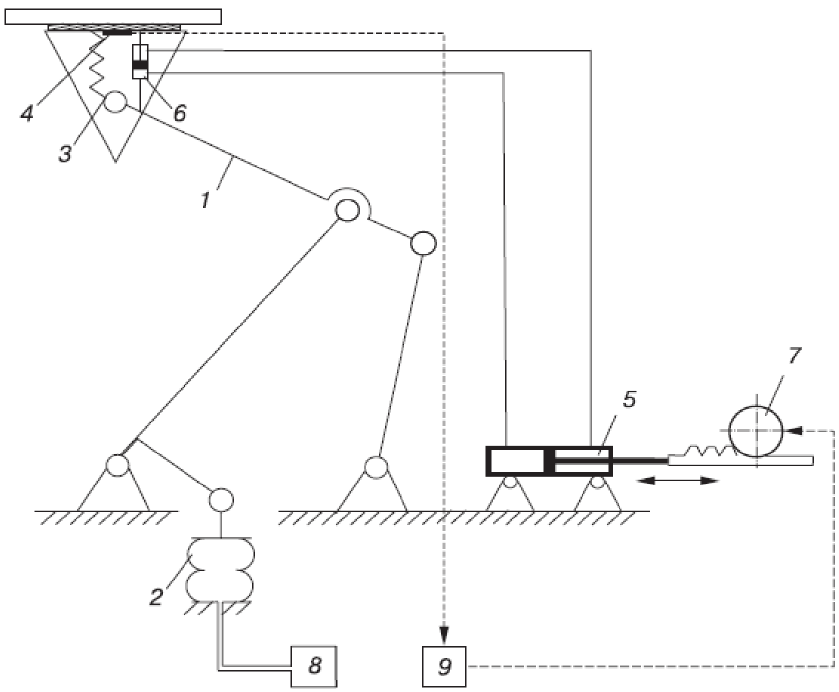

Figure 4. Scheme of rapid automatic control system of pressing current collector: *1* — system of moving frames; *2* — rubber-cord lifting element; *3* — carriage; *4* — contact pressure sensor; *5* — control pneumatic cylinder; *6* — carriage pneumatic cylinder; *7* — electric drive with proposed current logger; *8* — compressed air source; *9* — regulating device

The most effective input signal for automatic control system is the DC component of the locomotive current (I_{kc}), since it directly affects the quality criterion of current collection. Difficulty of measurement of the I_{kc} 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.

The field tests showed that there is no clear relation between the I_{kc} and the train speed. However there is a relation between the DC component, arcing intensity and the RMS value of the locomotive current. The latter indicates that the wear rate could be different at different value of the RMS current and thus the I_{kc} [2,7]. As a consequence the current logger has been prepared for logging different levels of the DC component.

As a first assumption the wear of a pantograph can be predicted as [11]:

$$W = s \cdot \omega_{mech} + \sum_{i \in I} T_{arc}^{i} \cdot \omega_{arc}^{i} \quad (3)$$

Where i is a set of DC intervals, s is the total distance, T^{i}_{arc} is the arcing time in interval i. ω_{mech} is the specific mechanical wear of the contact strip and ω^{i}_{arc} is the additional specific arc wear in interval i.

However, at least in the field tests, moderate values of the I_{kc} were the most frequent ones and it might be possible to simplify equation (3) further:

$$W = s \cdot \omega_{mech} + \omega_{arc} \cdot T_{arc} \quad (4)$$

Where ω_{arc} is the average specific additional wear during arcing and T_{arc} is the total arcing time.

The main difficulty with this approach is to find the specific mechanical wear and the additional specific wear at arcing. The ambition has not been to derive very detailed expression but to use a statistical approach to find approximate values and to calibrate these values by using long term measured values. This work is ongoing but the principle is briefly described below.

2.1 Estimation of the mechanical wear

A number of studies regarding the wear of overhead contact systems have been performed. Many of these studies have been performed on laboratory set-ups, by simulation, or during well defined operating conditions .The objective has been to describe the influence of different parameters like uplifting force, speed, and current on the wear. Although of great importance for understanding the wear, results and models are often too complex to be used for condition monitoring of the contact strip [15 - 17].

The wear limit WL is 2.5 mm. A new contact strip is 17 mm. The assumption that all contact strips are changed at the wear limit makes it possible to calculate the specific mechanical wear as [16] :

$$\omega_{mech} = \frac{N_{ch} \cdot (17 - WL)}{2 \cdot \sum s_{loco}} \text{ [mm/km]} \quad (5)$$

Where N_{ch} is the number of changed contact strips and $\Sigma\ s_{loco}$ is the total distance of the entire fleet of locomotives. The factor 2 in the denominator takes into account the fact that there are two contact strips per pantograph.

2.2. Design of the current logger

For the long time evaluation of the suggested automatic control system that allows to regulate contact force between pantograph and contact wire with respect to conditions of the interaction process has been designed to meet the following criteria [18]:

- Measure the side way movement of the contact wire
- Detect undesired peaks in contact force
- Detect contact force relief of the pantograph

- Localise the obtained results to position (+/- 1 m) on railway track record data autonomously, 24/7 operation
- Monitor thresholds and alarming of events and gives notice to operator in case a critical condition is detected immediately

As described above the locomotive current I_{kc} could be used as an indication for electric arcing. For modern vehicles this could be implemented in the train control system. The prototype current logger that was installed during the tests logged the following data [18]:

• DC component of locomotive current, sample rate 10 Hz
• Locomotive current, sample rate 1 Hz
• Line voltage, sample rate 1 Hz
• Train speed, sample rate 1 Hz

This type of data recording results in large data files indicated, the collected data, except for the I_{kc} might be of less importance for the condition measuring of the contact strip. It is therefore proposed that only the I_{kc} component should be monitored for the long time evaluation logger device [16].

The logger device designed for the long time evaluation uses the same type of current transducer and low pass filter as the prototype current logger but instead of logging the output signal, i.e. the I_{kc} , of the low pass filter the time with I_{kc} over the selected threshold current is counted. The device can count the I_{kc} in up to three adjustable levels. The logger device is described with a schematic overview shown in Figure 5.

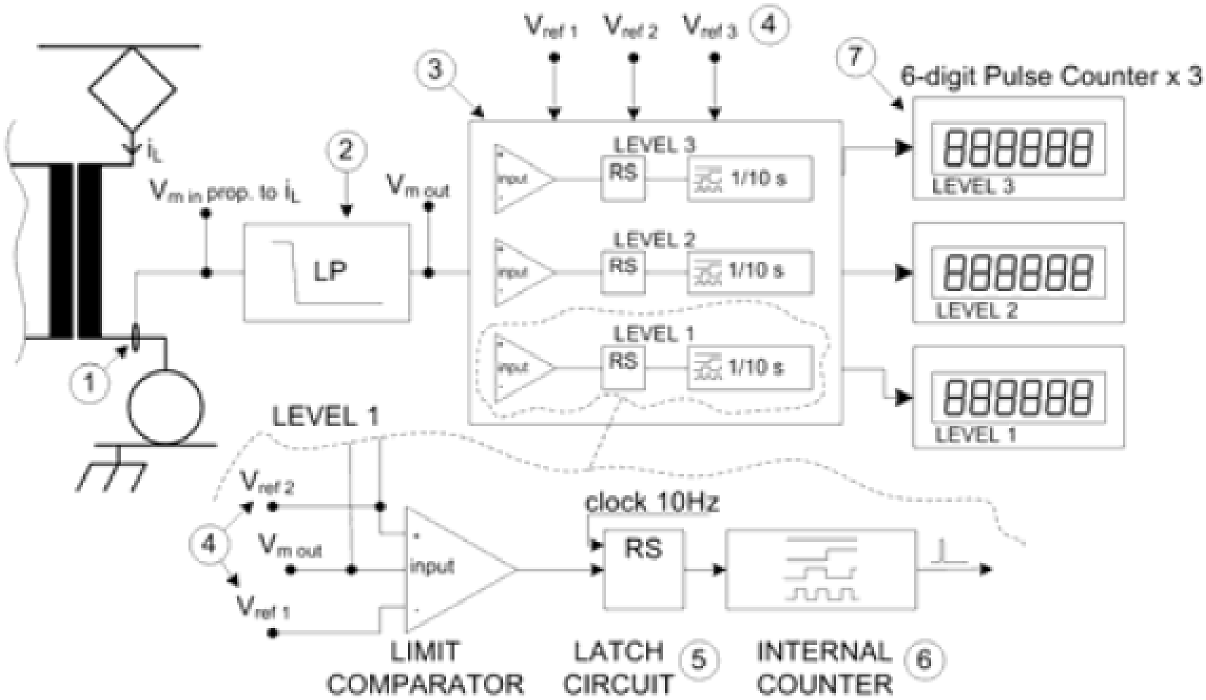

Figure 5: Schematic overview of logger device

The number corresponds to the number in the figure.

1. The current transducer is a Hall-effect closed loop current transducer from LEM, LF 505-S. The current transducer utilizes low offset current, high accuracy and high bandwidth. Primary nominal current, I_{pn} = 500 A and secondary nominal current, I_{sn} = 100 mA gives the conversion ratio of 1:5000. The current transducer is mounted on the cable from the primary low voltage side of the locomotive transformer.

2. The low pass filter is an active 8th order Butterworth. It is designed for a cut frequency of f_c = 2 Hz.

3. Three level limit comparator with internal counter, counting presence of I_{kc} with a 1/10 s resolution. Output signal from this block is a pulse to the 6-digit pulse counter when one second of I_{kc} has been registered.

4. Reference voltages

- $V_{ref\,1}$ sets the threshold for detecting and counting the DC component for the lowest interval, level 1
- $V_{ref\,2}$ is the higher limit for level 1 as well as the lower limit for level 2
- $V_{ref\,3}$ is the higher limit for level 2 as well as the lower limit for level 3

5. Latch circuit. If V_m out is within the level limits of the limit comparator, the output signal will trigger the latch circuit. The clock resets the latch circuit every 100 ms.

6. Internal counter. At the same instant as the latch is triggered, the internal counter counts one step. The internal counter both resets and send a pulse to the display counter on the tenth count representing one second of DC component.

7. The Pulse Counters are displaying the time in seconds with DC component in the locomotive current for the different levels.

When implementing logging of the DC component in the locomotive current for condition measuring of the contact strip there are two possible solutions. Either, on-board analysis can be used by implementing the calculation in the automatic regulation system of pantograph pneumatic mechanism system.

Figure 6. shows a structure of the mathematical model of the control system with proposed the current logger in MATLAB/Simulink

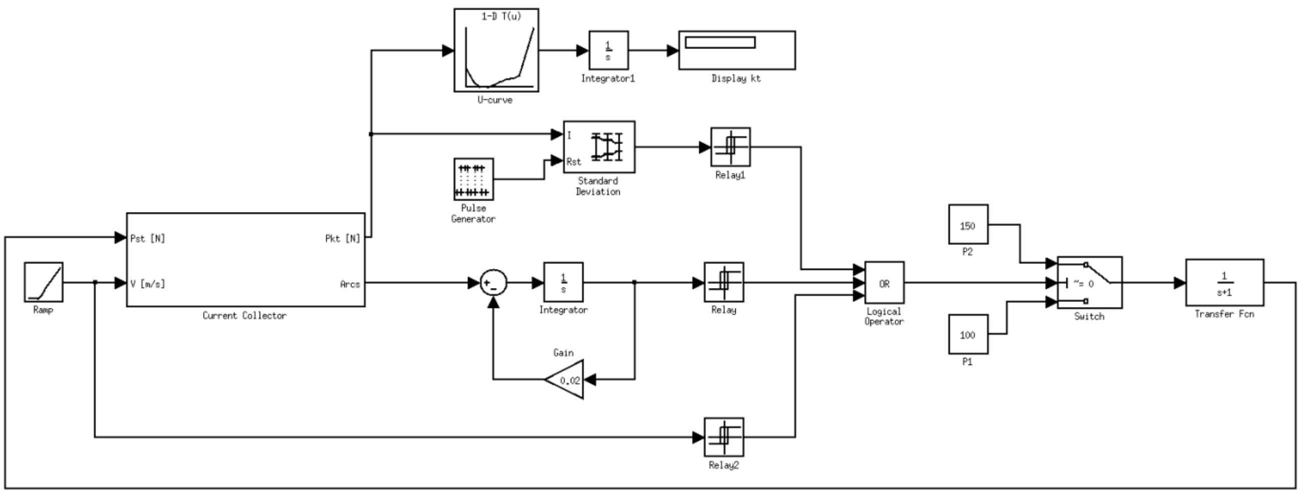

Figure 6. Scheme of mathematical model of automatic control of a pantograph with proposed the current logger in the Simulink environment.

3. 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 measured the process of current collection during acceleration of electric rolling stock up to the maximum speed. Figure 7 shows results of the measurements of current collection with automatic control system. Changes of static contact force F_{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 $F_{c\ opt}$, 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 $F_{c\ min}$. [N].

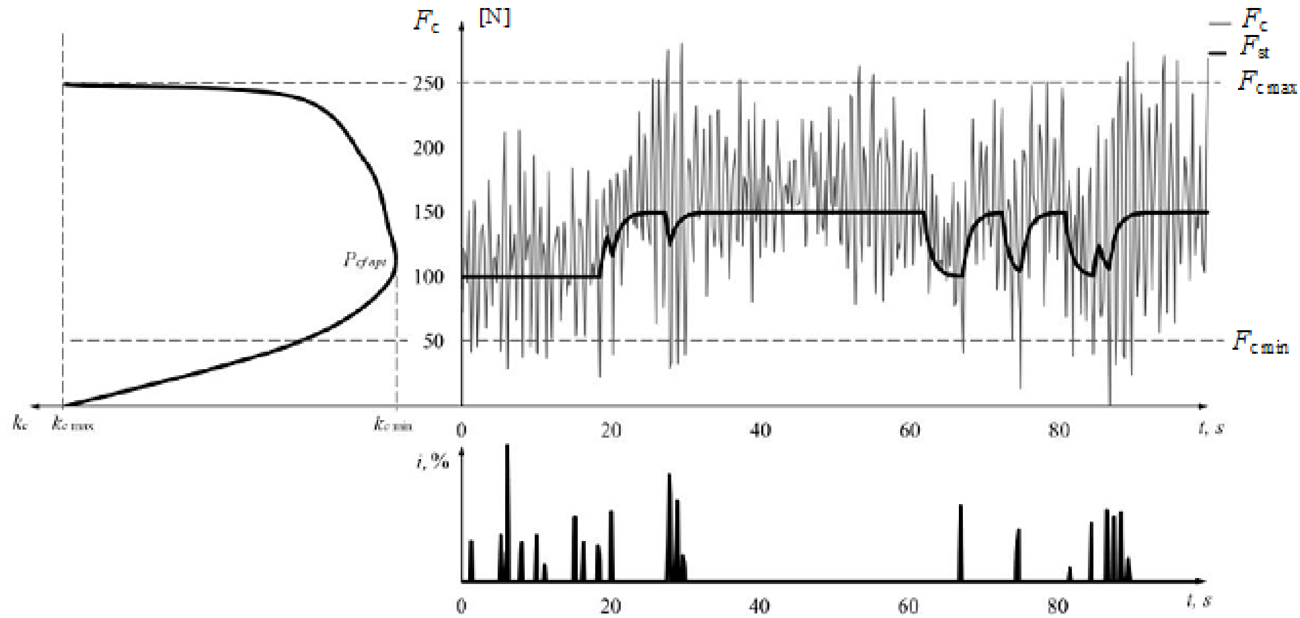

Figure 7. The results of simulation of automatic control system of pantograph: k_c – quality criterion of current collection, F_c – contact force, F_{st} – static contact force, i(t) – intensity the DC component of the locomotive current

The measured 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. For evaluation of simultaneous work of control systems we may conducte a series of experiments with different combinations of threshold values of contact force deviation and arcing rate [19]. For evaluation of simultaneous work of control subsystems we may conducte a series of experiments with different combinations of threshold values of contact force deviation and arcing rate.

The experimental results show that the use automatic control system in design of pantographs can improve the quality and reliability of the current collection with ice or rime frost on the overhead line. Using movement DC component of the locomotive current (I_{kc}) as input signal for control system can be almost as effective as using direct contact force measurement.

4. CONCLUSIONS

The paper has outlined improvement of automatic control system for current collectors. To verify the approach field tests in winter climate has been carried out. These field tests have been combined with a simple statistical analysis. The field test has shown that:

• A DC component in the locomotive current can be used as an indication of arcing.

• There is no correlation between train speed and the DC component due to arcing.

• There is a dependency between the RMS value of the locomotive current and the DC component. The DC component increases with increasing RMS current. Above 200 A, the DC level seems to reduce slightly.

The method requires an estimate of the specific mechanical wear as well as the additional contribution due to arcing. As an initial approach a simple statistical estimation of the wear has been made. This initial estimation will be calibrated from on-going long term tests.

Of great importance for the implementation of the method is to what extent the wear of the contact strip is influenced by the intensity of the arcing and thus the level of the DC component. If so the dependence between the level of the DC component and the wear has to be more accurately explored.

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 with ice or rime frost on the overhead line. Use DC component of the locomotive current 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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ПРОЕКТИРАНЕ НА АВТОМАТИЧЕН РЕГИСТРАТОР ЗА ЕЛЕКТРИЧЕСКИ ТОК ЗА АВТОМАТИЧНА СИСТЕМА ЗА УПРАВЛЕНИЕ ЗА ТОКОПРИЕМНИЦИ С ЛЕД ИЛИ СКРЕЖ ПО КОНТАКТНАТА МРЕЖА

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Здравка Челара 14, Белград, СЪРБИЯ

Ключови думи: *автоматична система за управление, контактна лента, постоянен ток, образуване на електрическа дъга*

Резюме: *Статията третира начините за регулиране на пантографите, така че да се осигурят качество и надеждност на токоприемане. С цел оценяване въздействието на това регулиране е предложен интегрален критерий за качеството на токоприемане, вземайки предвид ефективността и надеждността на експлоатацията на пантографа. При осъществяване на контрол на контактната лента е възможно да се използва фактът, че образуването на електрическа дъга между контактната лента и контактната мрежа генерира постояннотоков компонент в променливия електрически ток на локомотива. Докладът представя автоматична система за управление, която регулира контактната сила между пантографа и контактния проводник с оглед на условията на процеса на взаимодействие. Износването на контактната лента се предвижда с помощта на контролиране на дължината на пробег на пантографа, както и на постояннотоковия*

компонент на променливия електрически ток на локомотива. Експерименталните резултати свидетелстват, че прилагането на автоматична система за управление при проектирането на пантографи може да подобри качеството и надеждността на токоприемането при наличието на лед или скреж по контактната мрежа. Използването на постояннотоковия компонент при движение на тока в локомотива (I_{kc}) като входен сигнал за системата за управление може да е почти толкова ефективно колкото прилагането на измерване на правата контактна сила.