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SPECIAL SECTION

Influence of contact gaps on the conditions of vehicles supply and wear and tear of catenary wires in a 3 kV DC traction system

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Abstract. Short-term contact losses between a pantograph and a contact wire are not included in the standards nor are they taken into account in evaluating pantograph-contact wire interaction. These contact losses, however, accelerate wear and tear as well as disturb operation of vehicles' drive systems. The article presents the effects of short-term contact breaks as well as an analysis of impact of contact breakages on a vehicle's current at 3 kV DC power supply. Results of voltage and current oscillations measured in real conditions when pantograph of a DC driven chopper vehicle was running under isolators were presented. Then a simulation model of a vehicles with ac motors and voltage inverters was derived to undertake simulation experiments verifying operation of such a vehicle in condition similar to those measured in real condition.

Key words: pantograph, overhead line, pantograph-catenary interaction, contact losses, traction drive.

1. Introduction

Despite rapid development of electric road vehicles, rail network traction power supply system is still dominating among transport systems using electric traction. Electric rail vehicles are supplied from a substation through a fixed catenary, which is in dynamic contact with a sliding current collector strip, and the circuit is closed by the return circuit using rails and a cable system. It is a basic solution for the transfer of power to a moving traction vehicle – both, a tram with speeds of up to 70 km/h and a TGV train, at a record speed of 574 km/h.

Catenary is the least reliable, and practically the only one without reserve, element of a circuit of energy delivery from traction substations to vehicles' pantographs. Condition of this element is a decisive factor as far as reliability and energy quality of a supply system are concerned [1]; especially since the contact wires wear down due to friction and influence of an electric arc. Arcing phenomenon during pantograph lowering was analyzed by Gao et al. [2]

Negative impact of electric arc depends on time of its occurrence as well as current values. Unfavourable weather conditions, icing in particular, also seem to exhibit significant influence [3]. Therefore, it is required to constantly improve the reliability and durability of the operation of the most unreliable elements of the power system circuit. Technical Standards of Interoperability (TSI) as well as standards and regulations developed for the railway lines are dedicated to improve the catenary parameters [4]. However, the phenomenon of short-term contact breaks below 5 ms is not used for evaluating pantograph-catenary interaction. During movements of a pantograph along catenary without ice short-term breaks are not observed.

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Damages to the surface of contact wires, also during short-term contact breaks, cause deformation leading to further difficulties or loss of contact between a current collector and a contact wire (during subsequent trains runs), and, as a result, to rapid point damages of a catenary. So different approaches may be found in literature, to reduce the effect of this problem, with simulation methods of interaction pantograph-contact wire [5, 6], optimization and active control of contact force [7, 8], application of monitoring and diagnostic systems [9], introduction of new types of contact strips at the pantograph pan [10, 11], enhancement of catenary [12, 13] and so on. Moreover, the research done by Shen et al. [14] and Karakose et al. [15] is carried out towards the utilization of image processing techniques to assess the quality of pantograph cooperation with the overhead contact line. Another approach to the issue of the correct cooperation of the pantograph with the contact line is the dynamic analysis of the pantograph-catenary contact force. Liu et al. [16] explores the use of pantograph-catenary contact force for monitoring of the current collection quality by the extraction of the catenary structure wavelength. Wang et al. [17] proposes the technique of detection of contact wire irregularities by spectral analysis of pantograph-catenary contact force.

In this paper authors focused on the influence of contact losses between current collector and contact wire on dynamic operation of a vehicle drive due to disturbances: voltage fluctuations at pantograph and breakage of current flow from catenary to a vehicle. Influence of such phenomena on both: operation of a vehicle's drive and wearing down of contact wire and pantograph strips due to creation of electric arc in the point of contact loss is analysed.

2. Catenary – pantograph interaction

Overhead contact line with catenary suspension is a common solution used on railway lines to supply rail traction vehicles.

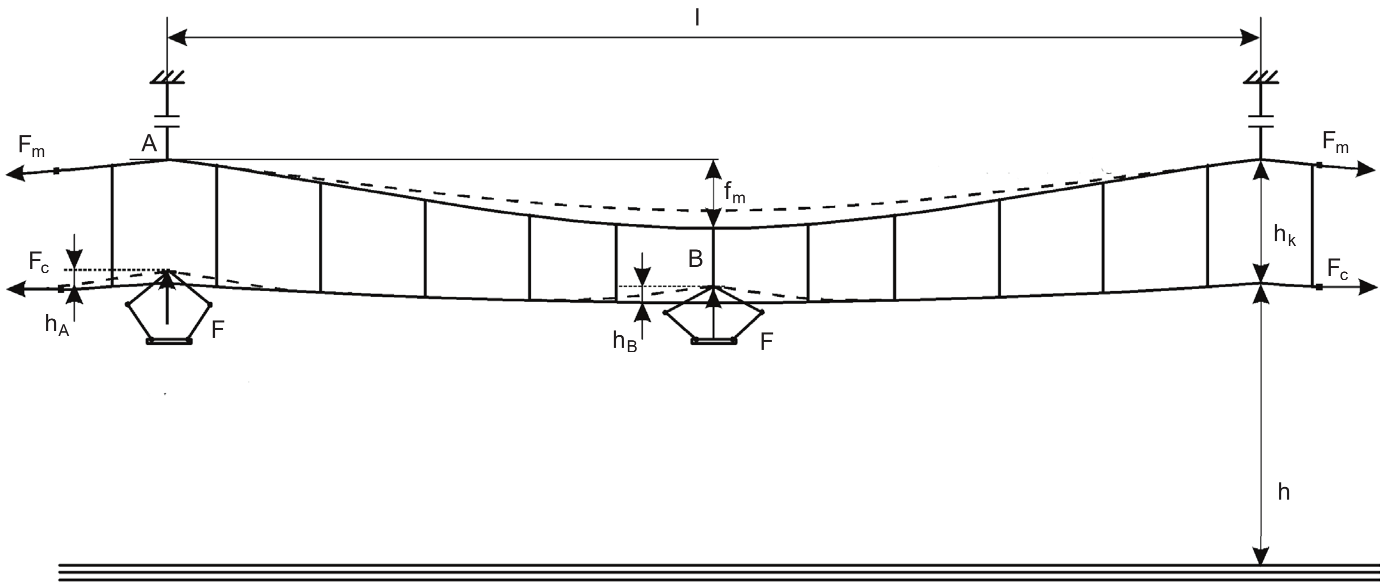


Fig. 1. Overhead contact line with catenary suspension span interacting with a pantograph

The following symbols are used:
A – suspension point of a messenger wire, B – centre of a span, l – span length, h – height of wire suspension,
h_k – design height of a catenary, f_m – messenger wire slack, h_A – rising of a wire by a pantograph at a suspension point,
h_B – rising of a wire by a pantograph middle of a span, F – pressure force of a pantograph contact strip on a contact wire.

Fig. 1 presents catenary raised by a pantograph at various points of the span. Regardless of the design speed, for evaluation of dynamic characteristics and quality of current collection from DC catenary, one uses synthetic parameters, according to TSI (Table 1).

Table 1
Dynamic characteristics and current collection requirements [4]

Standard deviation at maximum speed of line σ_{max} [N]	0.3 Fm
Percentage share of electric arc discharge at a maximum speed of a line, NQ [%] (minimum time of arc duration 5 ms)	≤ 0.2

2.1. Factors influencing wear of catenary wires. To a large extent, durability of a catenary depends on wear down and tear of contact wires. Wear down and tear of wires is related to:
- friction of a collector head strip. The cross-section of a contact wire decreases. Upon attaining minimum admissible values, the wire should be replaced. The decisive factor is the maximum wear down of a wire or average value of a wire cross-section;
- local overheating of a wire as a result of increased contact resistance due to decrease of a pressure force (Fig. 1) or too high current during a stop;
- overheating above the admissible level of temperature leads to copper recrystallization, which decreases its durability;
- occurrence of electric arc during contact losses under the condition of current flow;
- occurrence of mechanical damages at extremely high forces in case of pantograph failure.

In order to obtain good quality of interaction between a current collector and a catenary, it is of high importance to provide optimum, possibly constant value of pressure force. The quality of pantograph-catenary interaction during a vehicle's run is determined by the following parameters [4, 6, 9, 10]:
- variability of pressure force at a contact point;
- the scope of vertical movement of a pantograph during its interaction with a catenary;
- elevation of a wire during a run;
- relative time of contact losses.

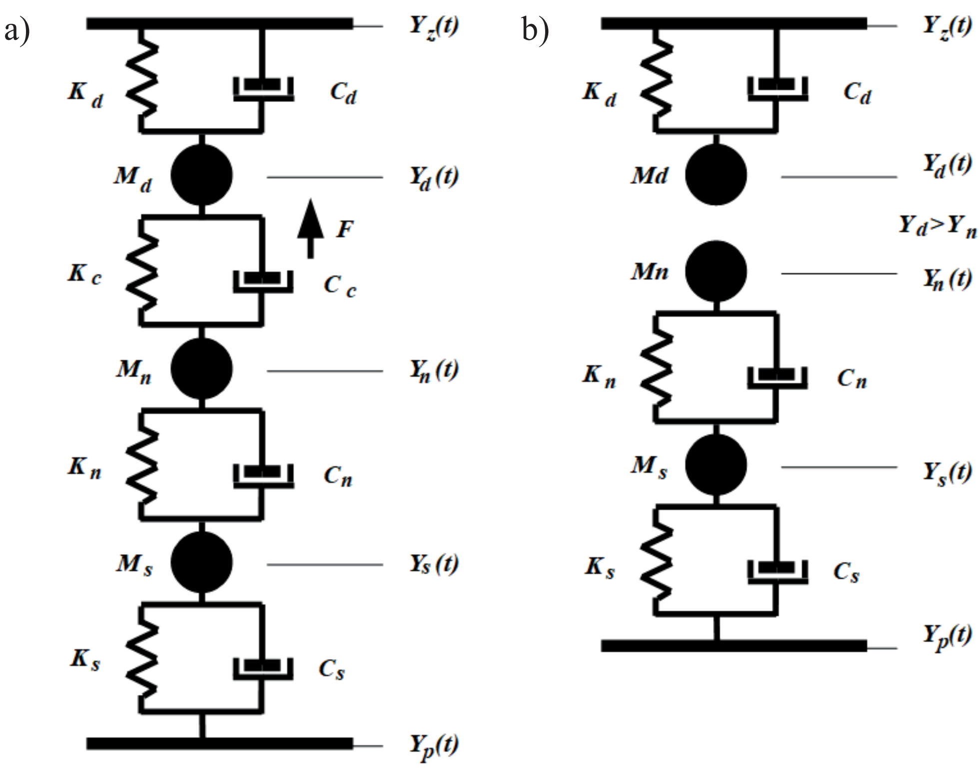
Variable pressure forces are associated with movements of a pantograph's collector head and movements of a catenary during a train run. When a collector is in contact with a contact wire, the collector head strip moves vertically to the level depending on the catenary flexibility, running speed and a static position of the wires. The task of a pantograph is to ensure that during a run, the strip is constantly pressed to the wires. Pressure force at the contact point depends on the constant force of rising a collector head, acceleration acting on a pantograph's collector head and resistances to motion. Acceleration changes and contact force are connected with the square of horizontal movement speed of a vehicle. Increase of operational speed entails the necessity of decreasing the force variability. Stability of forces minimizes wear and tear of wires and a contact strip. Too high contact force causes excessive wear due to friction. Too low force, on the other hand, results in increase of energy losses at the contact point of a strip and wires. When force drops to zero, the contact is lost. Loss of contact (which may be caused, among others, due to ice or hoarfrost on catenary wires [1]) results in current flowing through an electric arc. It entails rapid voltage growth at a contact point, from values below 1 V to values above 40 V. Then, a process of rapid damaging of contact strip and contact wire surfaces occur. Upon melting due to electric arc, the surface of a wire becomes rough. During subsequent runs, pressure forces are more likely to undergo changes on these particular areas. These surfaces suffers grinding during next runs, which accelerates wear of the wire. At places with high run speed, the collector's head strip may more frequently separate from a contact wire, and in short time, it can lead to wear down of wire to a critical point. Therefore, it is of high importance to reduce the number of points of contact loss between a collector head strip and a contact wire as well as decrease its time of contact loss. To a large extent, the durability of a catenary is determined by wear down of contact wires at points of contact loss. The material of a contact strip also has a significant impact on the wearing down of wires. The strip is a part of a pantograph that is subject to constant wear down and tear. Therefore, it requires frequent operational inspection [9, 18]. Excessive wear down of the strip may lead to damaging of a collector and accelerated wear of a catenary. Due to high electrical and thermal conductivity, copper type contact strips were used. However, such copper strips cause fast wear down of contact wires. Under the same operational conditions, the use of graphite strips provides two to three times slower wear of contact wires than in case of copper strips. Currently, on Polish railway and tram lines, only strips based on graphite and graphite-copper sinters are used.

2.2. Mathematical model of a pantograph collector head with a strip interacting with a catenary. For the analysis of interaction of a pantograph contact strip with a catenary, one used a one-dimensional model of a catenary and a collector head. A pantograph frame has only a minimum impact on the interaction of a collector head with a catenary at slight changes of a nominal height of catenary suspension. Mathematical modelling of a catenary and pantographs is a basic method used to analyze their interaction [5, 6, 10, 17]. Such models are characterized by various degrees of complexity. This depends on the required scope of tests and the purpose of their use. For the purpose of analysis of a contact strip interaction with a catenary, in this publication one used a dual-mass model of a pantograph, limited to a collector head and contact strip, and a single mass model of a catenary. Such a model is used for the assessment of the behavior of a contact strip and a catenary during short-term contact losses. Other elements of a pantograph have minimum influence on mechanical short-term phenomena at the contact point.

System of equations (1–5) describing behaviors of the model are presented below.

$$\begin{gathered} M_n \ddot{Y}_n + C_n\left(\dot{Y}_s - \dot{Y}_n\right) + C_s\left(\dot{Y}_s - \dot{Y}_p\right) + \\ + K_n\left(Y_s - Y_n\right) + K_s\left(Y_s - Y_p\right) + M_s g = 0 \end{gathered} \tag{1}$$

where:
g – gravitational acceleration,
M_s – equivalent collector head mass equal to 12 kg,



Elements of a model defined by indexes:
d – a contact wire,
c – a contact surface of a contact wire and a strip,
n – a strip,
s – a collector's head.

Fig. 2. Model of a collector head and a contact wire shown in state of: a) contact b) contact loss [12]

K_s – collector's head suspension rigidity equal to 100 N/mm,
C_s – viscotic damping of collector's head suspension equal to 10 [Ns/m],
Y_s – position of a collector's head,
K_n – rigidity of a contact strip equal to 10^6 N/mm,
C_n – viscotic damping of a contact strip,
Y_n – position of a contact strip,
Y_p – location of the point of collector's head suspension base.

Equation (1) is used for the duration of contact and a contact loss, while equations (2) and (3) are used only for the time of contact.

$$M_d\ddot{Y}_d + C_d(\dot{Y}_d - \dot{Y}_z) + C_c(\dot{Y}_d - \dot{Y}_n) + \\ + K_d(Y_d - Y_z) + K_c(Y_d - Y_n) + M_n g = 0 \tag{2}$$

where:
M_d – contact wire equivalent mass equal to 1 kg,
K_d – rigidity of contact wire suspension equal to 1.5 N/mm,
C_d – viscotic damping of contact wire suspension equal to 10^2 Ns/m,
Y_d – contact wire location,
K_c – rigidity of contact surfaces, strip and wire equal to 10^4 [N/mm],
C_c – viscotic damping of contact surfaces, strip and contact wire equal to 10^5 [Ns/m],
Y_z – location of contact wire suspension.

$$M_n\ddot{Y}_n + C_d(\dot{Y}_n - \dot{Y}_z) + C_c(\dot{Y}_d - \dot{Y}_n) + \\ + K_d(Y_d - Y_n) + K_c(Y_d - Y_n) + M_n g = 0 \tag{3}$$

where:
M_n – contact strip mass equal to 5 kg.

Equations (1), (4) and (5) describe movements in a model during contact loss.

$$M_d\ddot{Y}_d + C_d(\dot{Y}_d - \dot{Y}_z) + K_d(Y_d - Y_z) + M_d g = 0 \tag{4}$$

$$M_n\ddot{Y}_n + C_n(\dot{Y}_n - \dot{Y}_s) + K_n(Y_n - Y_s) + M_n g = 0 \tag{5}$$

The model employs typical parameters described in the literature [9] and own analyses. Flexibility of a contact strip and a contact wire material has been taken into account as well. Strip movements in relation to a contact wire are shown in Fig. 3 and waveform of forces in Fig. 4. Value Y_n larger than value Y_d occurs for contact of a strip with a contact wire and pressing of surface layer of a strip. At the same time what occurs are the contact forces higher than zero. Contact loss appears for $Y_n < Y_d$. Vibrations of a collector's head-catenary system were analysed; they cause short-term contact breaks with a duration time of milliseconds. After separation of a contact strip and a contact wire for the time of tens of milliseconds, the process of contact restoration takes multiple stages. The strip is further detaching from a contact wire, which results in additional contact losses. Contact forces during restoration of contact are several times higher than the static contact force up to 100 N.

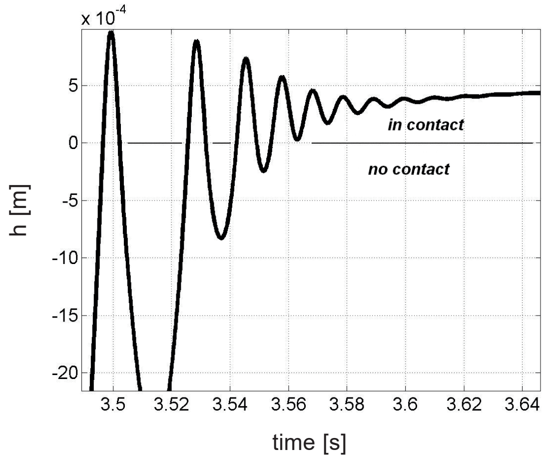


Fig. 3. Motion of a strip in relation to wire during restoration of contact

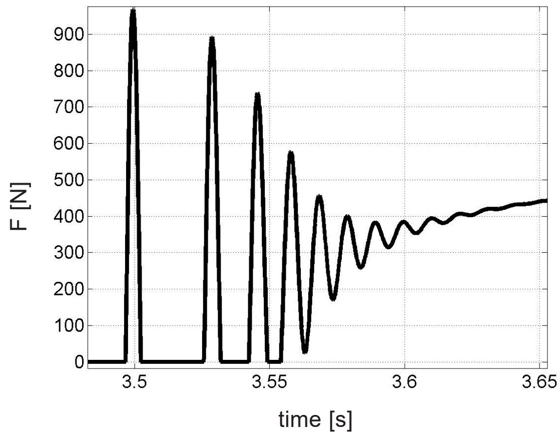


Fig. 4. Waveform of forces occurring between a strip and a wire during restoration of contact

3. Impact of current flow during contact losses

In tram traction, contact losses occur even at a speed of several km/h. This is related to the fact that the structure has many points of weakened flexibility – connectors, insulators and crossings. This turns short-term contact breaks or reduction of a downforce to zero, which as well causes melting of wires. For the purpose of assessing the phenomenon, the effect of an electric arc has been examined. Two tests were performed in laboratory conditions for 1 [m/s] with short-term currents of two values: 396 [A] (the first test) and 612 [A] (in the second test) which were forced to flow within 2 [ms]. The strip was moving horizontally in relation to wire presented in the photos. Short-term exposure to electric arc causes melting of the wire surface. Graphite dust from strip material also appeared on the surface of the contact wire. Horizontal length of an arc crater depends on a vehicle's speed and duration of an electric arc. Higher current values increase the width of a crater (across the wire). The arc craters with different values of current are shown in Fig. 5.

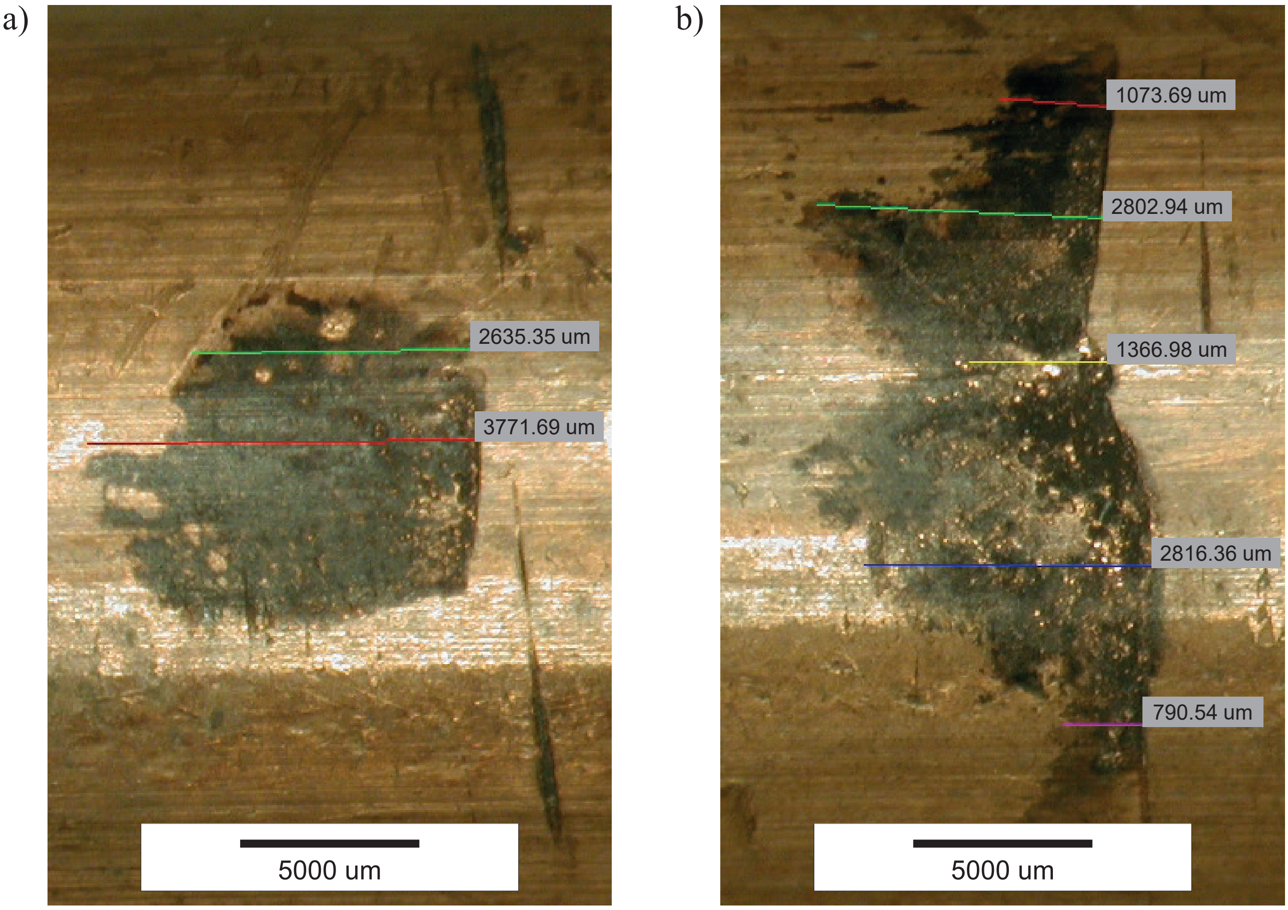


Fig. 5. Arc craters for two values of current flowing in time of 2 [ms] (research of the Authors) a) the first test – current 396 [A], b) the second test: current 612 [A]

Under normal operating conditions, short-term contact losses occur quite frequently and are acceptable. However, during current flow, they cause the deteriorating influence of a current arc. Minor irregularities occur on the surface of wires. A single instance of a strip losing contact with a wire in a time exceeding several dozens of ms causes additional short-term contact losses during restoration of contact. Maximum temporary value of a contact force is much higher comparing to a static force value. Each contact loss during current flow causes the melting of a contact wire, occurrence of surface irregularities related to the arc crater. Even short-term contact losses lasting several milliseconds can significantly deteriorate the surface of a wire and contact strip. The area of damages increases with the increase of contact loss duration and the value of current. In case of a railway catenary, if a contact loss occurs at high speed, damage will be shallow. In case of relatively slow tram vehicles, the occurrence of even short-term contact losses (several ms) leads to damaging significant parts of a wire. It is due to higher current values in case of tram traction than in case of railway traction and a lower speed of arc movement on the surface. Duration of arc at the same point is several times longer for tram traction. Since the weakest point influences the necessity to replace the whole contact wire, local damages to the contact wire of a catenary are considered to be of high importance. It is essential to eliminate, especially in case of a tram traction, each point of contact losses, regardless of the duration of a single contact loss.

4. Examples of measurement results during contact losses when a vehicle is passing an insulator

Even though modern rolling stock with AC motors has been put into operation, vehicles with DC motors are and will be operating on Polish railway lines supplied by 3 kV DC voltage. A part of them undergoes re-engineering, while maintaining DC motors and applying chopper starting instead of resistors. During rolling stock examination after re-engineering, one conducted measurements of catenary and motors currents as well as voltages at the current collector and filter under various operational states of a traction unit (several dozens of measurements), and the characteristics for occurrence of collector separation or run under insulators were selected. The waveforms were registered by a LeCroy type oscilloscope and represented as screenshots from the oscilloscope together with a description of parameters and a scale of four waveforms. Examples of the measurement results are summarised below (Fig. 6, 7 and 8).

*Ch*1 – voltage at a pantograph (510 V/div),
*Ch*2 – catenary current (210 A/div),
*Ch*3 – filter's voltage (510 V/div),
*Ch*4 – motor's current (100 A/div), time – 100 ms/div

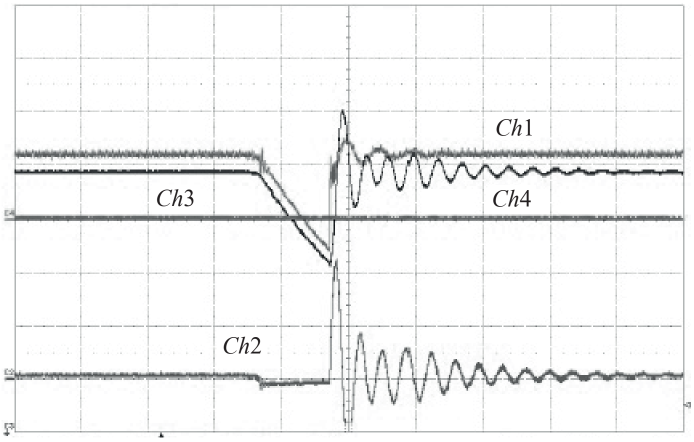


Fig. 6. Pantograph-catenary wire contact loss – no current taken by motors, voltage drop Ch1, Ch3 during loss of contact, oscillations of Ch2 and Ch3-charging input filter capacitance when contact returns

*Ch*1 – voltage at a pantograph (510 V/div),
*Ch*2 – catenary current (210 A/div),
*Ch*3 – filter's voltage (510 V/div),
*Ch*4 – motor's current (100 A/div), time – 100 ms/div

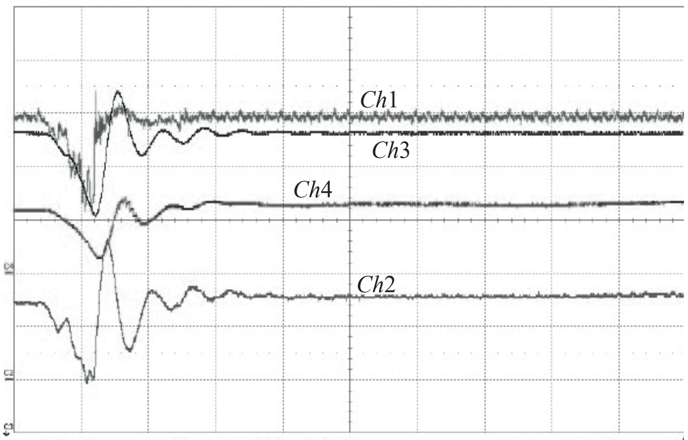


Fig. 7. Pantograph-catenary wire contact break during coasting

In Figs. 6–8 it can be observed that current oscillations appear in both states: when current is taken by the vehicle from catenary for traction drives and when current is taken only for auxiliary circuit. Mentioned low frequency current oscillations are the result of charging input filters' capacitance used in on-board vehicles with DC motors fed by choppers and, similarly when equipped with AC motors fed by inverters.

Considerable current peaks appearing in the phase of re-establishing contact (Fig. 6 and 7) cause increased damages to the surface of a contact strip and wire. An example of the impact

*Ch*1 – voltage at a pantograph (510 V/div),
*Ch*2 – catenary current (210 A/div),
*Ch*3 – filter's voltage (510 V/div),
*Ch*4 – motor's current (100 A/div), time – 100 ms/div

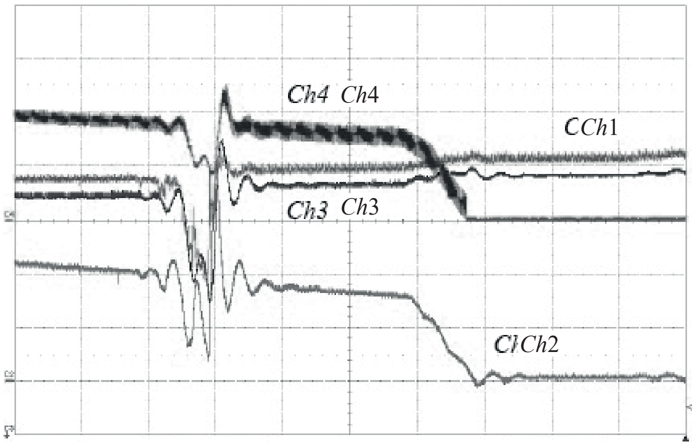
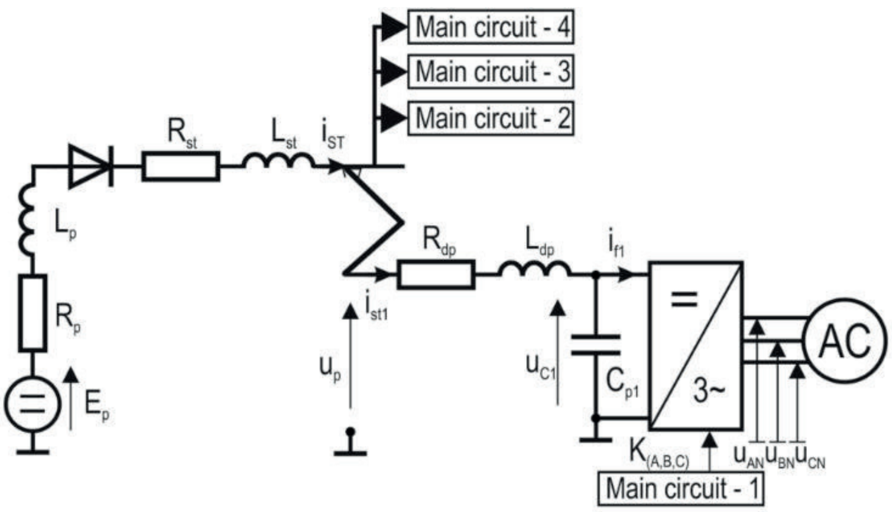


Fig. 8. Pantograph-catenary wire contact break during a run under an insulator with current taken by a vehicle from catenary

of short-term contact loss is a run through an insulator, during which a value of current drawn from a catenary does not fall to zero (Fig. 8). The conducted tests with registration of current and voltage curves in the main circuit of the units show correct cooperation that a drive system and a supply system, both under operational conditions and disturbed conditions caused by a bouncing collector or a run under an insulator. Current and voltage oscillations occurring under such conditions were vanishing, usually just after several cycles, which indicates the stability of operation of a chopper control system within series DC motors. The presented results are similar to those analyzed and discussed in [19], where there are described electrical characteristics of influence of elements of infrastructure (DC side filters, catenary parameters, location of a vehicle) on electric arc and currents during breaking contact between a pantograph and a contact wire.

5. Influence of contact losses on operation of a drive with AC motors

5.1. Mathematical model of a system. For the purpose of the analysis, a unilateral catenary supply system was adopted. Voltage source (E_p), resistance (R_p) and inductance (L_p) connected in series as a model of a substation. An ideal diode was connected into the series, and it imitates a rectifier in a traction substation. Catenary was modelled with parameters $R_{st}(l)$, $L_{st}(l)$, whose values depend on the length of a catenary between a substation and a traction vehicle. The main circuit of the modelled vehicle consists of four circuits in parallel that consist of a *LC* network, voltage inverter (*FN*) supplying one asynchronous motor AC (individual supply). In order to conduct simulation tests, one assumed that loads of four motors are the same. The motors operate according to the same control algorithms, input



A list of main designations in Fig. 9:
E_p – substation source voltage,
i_{f1} – inverter input current,
i_{ST1} – current in a catenary,
u_{C1} – voltage at a capacitor C_{p1},
u_p – voltage at a vehicle's pantograph,
L_{dp}, R_{dp}, C_{p1} – respectively: inductance, resistance, vehicle's LC filter choke capacity,
L_{ST}(l) – inductance of a catenary depending on the section length,
L_p – substitute inductance of a traction substation,
R_p – traction substation substitute resistance,
R_{ST}(l) – resistance of a catenary depending on the section length.

Fig. 9. Functional diagram of a simplified model of a traction system

voltages and input currents are equal. Functional diagram of the analyzed system [20–23] is presented in Fig. 9.

5.2. Voltage source inverter. A voltage source inverter is a power electronic device, whose static and dynamic properties depend mainly on the type of controllers and the type of power of electronic elements (GTO thyristors, IGBT transistors) that form switching devices (valves). A common feature of all these switching devices is their ability to operate under two conditions resulting from non-linear characteristics: on-state – in which even at very high currents flowing through a switching device, voltage drop is limited to several volts, and off-state – in which even at low voltages at a switching device, flowing current does not exceed milliamperes [24, 25]. A mathematical description assumes an electrical switching device to be a lossless switch between two states: a lossless on-state state and an off-state. Possible states of switching devices in three inverter legs are represented by variables K_A, K_B, K_C. Each of these variables may assume the value of 1 or 0. By selecting an appropriate method for activating switching devices, one can influence appropriate shaping of waveforms of three-phase voltages supplying motor, with respect to both: a value of fundamental voltage component and the content of higher harmonics as well. Inverter's output voltage $U_{AN}(t)$, $U_{AN}(t)$, $U_{AN}(t)$ is a value resulting from variables K_A, K_B, K_C, and a value of voltage at a filter capacitor C_f, described by the formula:

$$\begin{bmatrix} U_{AN}(t) \\ U_{BN}(t) \\ U_{CN}(t) \end{bmatrix} = \begin{bmatrix} K_A \\ K_B \\ K_C \end{bmatrix} \left[u_c(t) \right]. \tag{6}$$

5.3. Model of an asynchronous motor. A drive motor of a traction vehicle is fed with a non-sinusoidal voltage from an inverter. To describe dynamics of the asynchronous motor supplied by distorted voltage, one used a description of a motor in a fixed system of coordinates (α, β) related to a stator. The elements of the state matrix depend on the current value of mechanical angular speed of motor's rotor Ω_m. The equations will assume the following form [20]:

$$\dot{\boldsymbol{X}}_{\boldsymbol{e}} = \boldsymbol{A}_e(\Omega_m)\boldsymbol{X}_e + \boldsymbol{B}_e\boldsymbol{U}_{\boldsymbol{e}} \tag{7}$$

- state matrix $A_e(\Omega_m)$

$$\boldsymbol{A}_e = \begin{bmatrix} 0 & 0 & -R_s & 0 \\ 0 & 0 & 0 & -R_s \\ Z_2 & Z_3 & Z_1 & -p_b\Omega_m \\ -Z_3 & Z_2 & -p_b\Omega_m & Z_1 \end{bmatrix} \tag{8}$$

where: L_S, L_r, i L_m – inductances of a stator, rotor (expressed as stator's windings) and mutual inductance of windings, R_s, R_r – respectively, stator's circuit resistance and rotor's circuit resistance (recalculated to stator's windings), p_b – is a number of motor's poles pairs, ω_K – synchronous pulsation of motor's supply voltage, Ω_m – mechanical angular speed of rotor's, m_s – number of motor's phases.

$$\begin{aligned} \sigma_1 &= 1 - \frac{L_m^2}{L_r L_s} \\ Z_1 &= \frac{1}{\sigma_1}\left(\frac{R_s}{L_s} + \frac{R_r}{L_r}\right) \\ Z_2 &= \frac{R_r}{\sigma_1 L_r L_s} \\ Z_3 &= \frac{p_b\Omega_m}{\sigma_1 L_s} \end{aligned} \tag{9}$$

- state vector $\boldsymbol{X}_e$

$$\boldsymbol{X}_e = \left[\Psi_{s\alpha} \;\; \Psi_{s\beta} \;\; i_{s\alpha} \;\; i_{s\beta} \right]^T \tag{10}$$

- control matrix B_e

$$\boldsymbol{B}_e = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ \frac{1}{\sigma_1 L_s} & 0 \\ 0 & \frac{1}{\sigma_1 L_s} \end{bmatrix} \tag{11}$$

- control vector $\boldsymbol{U_e}$

$$\boldsymbol{U}_e = \begin{bmatrix} u_{s\alpha} & u_{s\beta} \end{bmatrix}^T \tag{12}$$

Control vector of a motor $\boldsymbol{U}_e$ depends on inverter's supply circuit voltage u_C and control signals $K_{(A,\,B,\,C)}$.

$$\boldsymbol{U}_e = \boldsymbol{T}_u u_{c1} \begin{bmatrix} K_A \\ K_B \\ K_C \end{bmatrix} \tag{13}$$

Matrix T_u describes dependencies between output voltages of an inverter and voltage components in a vector of motor's supply.

$$\boldsymbol{T}_u = \begin{bmatrix} \frac{2}{3} & \frac{-1}{3} & \frac{-1}{3} \\ 0 & \frac{1}{\sqrt{3}} & \frac{-1}{\sqrt{3}} \end{bmatrix} \tag{14}$$

Phase current of a motor is calculated on the basis of the formula:

$$\begin{bmatrix} i_A(t) \\ i_B(t) \\ i_C(t) \end{bmatrix} = \boldsymbol{T}_p \begin{bmatrix} i_{s\alpha}(t) \\ i_{s\beta}(t) \end{bmatrix} \tag{15}$$

where:

$$\boldsymbol{T}_p = \frac{1}{2} \begin{bmatrix} 2 & 0 \\ -1 & \sqrt{3} \\ -1 & -\sqrt{3} \end{bmatrix} \tag{16}$$

Matrix T_p describes relations between output currents of an inverter and current components in a vector of a motor's state, when the condition is fulfilled: $i_A + i_B + i_C = 0$.

5.4. Model of a catenary and a vehicle. Differential equations describing current waveforms in a catenary $i_{ST}(t)$ and voltage waveforms $u_C(t)$ at a capacitor C_p have the following form:

$$\begin{aligned} L_z i_{st} + R_z i_{st} + u_c - E_0 = 0 \\ 4C_p \dot{u}_c - i_{st} - 4i_f = 0 \end{aligned} \tag{17}$$

where:

$$L_z = L_d + L_{st}(l) + \frac{L_{dp1}}{4}; \; R_z = R_d + R_{st}(l) + \frac{R_{dp1}}{4} \tag{18}$$

input current $i_f(t)$ for the presented circuit is described by the formula

$$i_f(t) = i_A K_A + i_B K_B + i_C K_C. \tag{19}$$

Voltage source inverters used in traction vehicles have to allow for control of frequency and fundamental voltage component amplitude. Furthermore, it is necessary to minimize phase current distortions in order to reduce parasitic torques influencing negatively on operation of vehicles and current harmonics in a catenary. In order to do so, one applies various techniques for impulse width modulation. The described mathematical model of the electromechanical system converting energy supplied to a traction vehicle with asynchronous drive is a non-linear system. It means that there is no general, analytical solution for the described system. However, it is possible to obtain a similar solution by using numerical methods. The model assumed parameters typical for a vehicle's structure. The values of parameters described in the model have been selected on the basis of literature analysis. Simulation experiments conducted by the authors allow for analysis of the selected dynamic features of the considered electromechanical energy conversion system. A characteristic feature of the described system is the variability of the values of electric parameters as the function of pantograph vibrations. Figures 10–13 presents curves of the selected electromagnetic and mechanical values during long-term contact loss. It includes lowering pressure force with contact loss longer than 100 ms and short-term contact losses occurring during restoration of contact. Tests were conducted for a constant speed of a tram. It allowed for examination of electromagnetic and mechanical curves in an open system without the influence of current regulators.

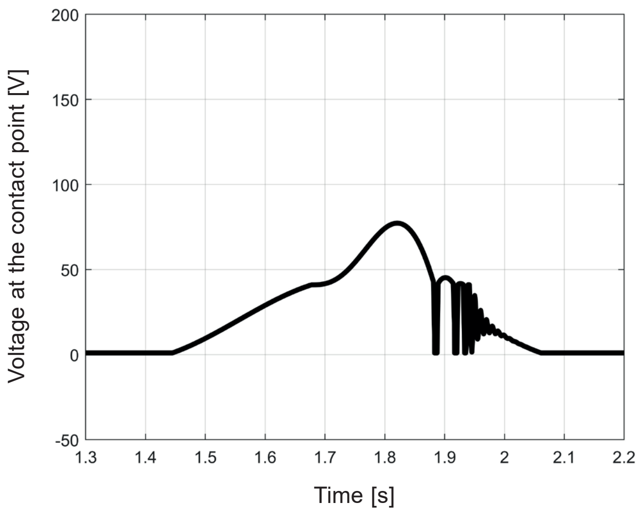


Fig. 10. Waveform of voltage at a contact point of a pantograph and a contact wire

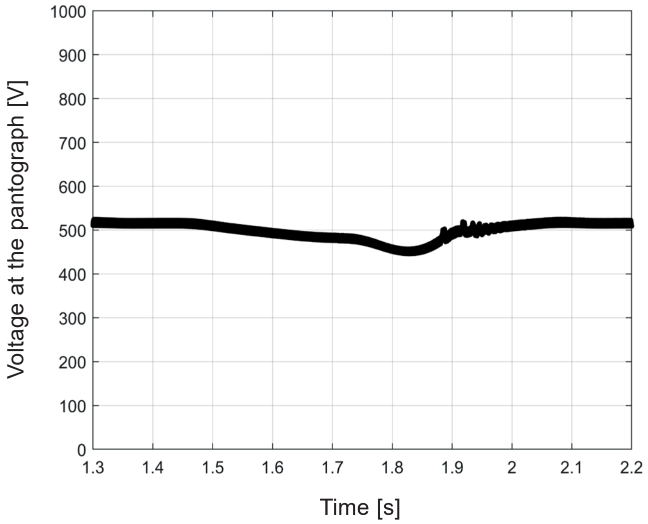


Fig. 11. Waveform of voltage at a vehicle's pantograph

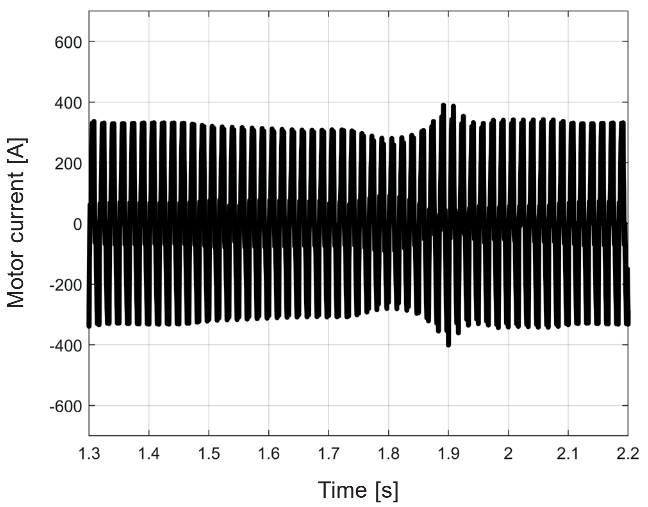


Fig. 12. Asynchronous motor current waveform

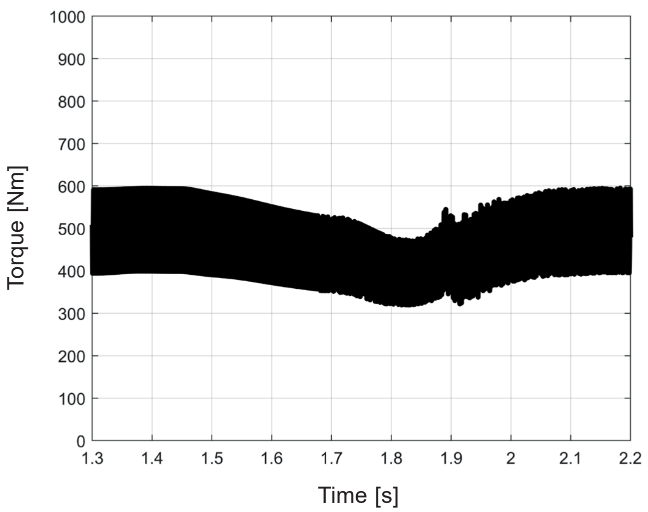


Fig. 13. Waveform of electromechanical torque of an asynchronous motor

The results of the conducted simulations indicate:

- a considerable decrease of voltage at the contact point of a contact strip of a pantograph with a contact wire, even before a contact loss has occurred;
- a decrease (of approx. 10%) of voltage at the pantograph, even though an input filter has been applied;
- value of a motor's current decreases;
- drive torque decreases;
- during restoration of contact, despite short-term character of the process and reduced voltage at the pantograph, what occurs is current rush exceeding the set values and short-term oscillation of drive torque.

Contact losses decrease drive torque for a period longer than the duration of a contact loss. They also cause additional voltage and current oscillations, which transfer into drive torque; their amplitude is, however, quite low. Filters used in the main circuit as well as inductance of a supply circuit: a catenary, choke and rectifier unit provide damping of electric and mechanical oscillations. However, if these oscillations would be longer and had higher amplitudes they could influence harmonic spectra of current flowing in rails, which could have a disturbing effect on the operation of track circuits [21, 22].

6. Conclusions

The article presents the results of analyses and research regarding the influence of pantograph contact losses on conditions of power supply of vehicles supplied with 3 kV DC voltage. Contact losses, long-term (time of occurrence exceeding 50 ms) as well as short-term (several ms), if rare, do not change operation of a drive system significantly, both in drive systems with DC motors supplied from a chopper (Chapter 4 – measurements) and in case of supply of vehicles equipped with AC motors (Chapter 5 – simulations). Due to their short duration in comparison to the time of a run and slight changes of drive torque, they do not require response from a drive control system. Use of control for current increment in order to reduce a voltage drop and drive torque of motors would be an unfavourable solution, since it would increase current in an electric arc and cause increased damage of a contact wire and collector's head. This could also lead to oscillations appearing in the main circuit of a vehicle's drive, and consequently, even mechanical oscillations and vibrations. Occurrence of contact losses significantly influences the durability of the structure, especially if losses appear multiple times at the same points of a catenary. Effects of the electric arc (appearing in such cases) cumulate and lead to rapid local damages of a contact wire, which significantly reduces the lifespan of a catenary. It also generates the need for frequent repairs at the points of incorrect interaction of the pantograph and a catenary. Furthermore, atmospheric phenomena of winter period, such as ice and rime, have an adverse impact on the interaction and on the occurrence of short-term contact losses.

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