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Alternating Traction Current Dynamics in Track Lines of Double-Track Hauls

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Abstract—The operational stability of track circuits and continuous cab signaling in electrified railway sections is disturbed most often by traction current noises in the track line. They are generated when asymmetrical traction current is produced at the points where track circuit equipment is connected to the tracks or under sending cab coils of continuous cab signaling. From the standpoint of traction current flows, a single-track haul track line can be considered a solitary double-wire circuit with two reciprocally induced single-wire electric circuits. As a result, traction current asymmetry becomes easier to calculate. In the case of double-track hauls, this problem is much more difficult to solve, because the traction network in these hauls additionally includes electrified trackways of adjacent tracks, second contact wire, and longitudinal power supply lines laid on catenary supports. These lines are reciprocally inductive with the considered trackways. The considered hauls are characterized by different distances from each trackway to additional electric lines, for which reason the reciprocal inductances inversely related to these distances are different as well. According to the analysis of the proposed procedure of calculating the traction current asymmetry in the track line, this asymmetry depends not only on electric resistances and specific reciprocal inductances of interlinked single-wire electric power lines, but also on the ratio of currents in these lines. It has been established that the absolute value of traction current asymmetry at a particular point of the track lines is indicated more adequately by the level of impact of traction current asymmetry on the operational stability of track circuits than by the traction current asymmetry factor. The time course of the traction current asymmetry in the track line depends on variations in the ambient temperature, traction current in the rails, and electric resistances in the junctions of parts of track bonds, choke jumpers, and ground circuits of catenary line supports. Additional changes in the traction current asymmetry under sending cab coils occur during train traffic and depend on the inbound resistances of track line sections ahead, as well as on any uneven longitudinal track magnetization.

Keywords: traction current, track lines, electric and magnetic properties of the traction network, track circuits, continuous cab signaling, traction current asymmetry dynamics

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Noises in track circuits (TCs) and continuous cab signaling (CCS) in ac railway sections are generated mainly by the traction current in the trackways (TWs) of the track traction network [1]. Newly designed systems for this purpose can be given the required stability by more advanced coding procedures [2, 3].

To make the currently used TCs and CCS more reliable, it is necessary to develop new procedures for analyzing test data on traction current variations to identify the nature of pulse noises in this current [4]. This is very important for analysis and synthesis of noise-immune receivers in TCs and CCS. Another subject of interest is the study of the generation of these noises, which makes it possible to devise efficient measures aimed at reducing noise levels [5].

Traction current trackways are single-wire electric power lines reciprocally inductive with other TWs and contact and power line wires [6, 7]. The noises in TCs and CCS are generated by traction currents in track lines only in the case of traction current difference in points at which TC equipment is connected to the tracks or under CCS sending cab coils. This difference is referred to as "traction current asymmetry in the track line."

Traction current asymmetry in the track line originally results from longitudinally or transversally asymmetrical resistance in the TW. According to analysis of noises formed by alternating traction current in single-track hauls, the traction current asymmetry and level of asymmetry-induced noises are largely affected by reciprocal inductances among the electric power lines of the traction network [5]. With adjacent tracks in hauls or stations, noise generation becomes far more complicated.

To calculate traction current asymmetry, we need to determine the current in each TW of the TL. The

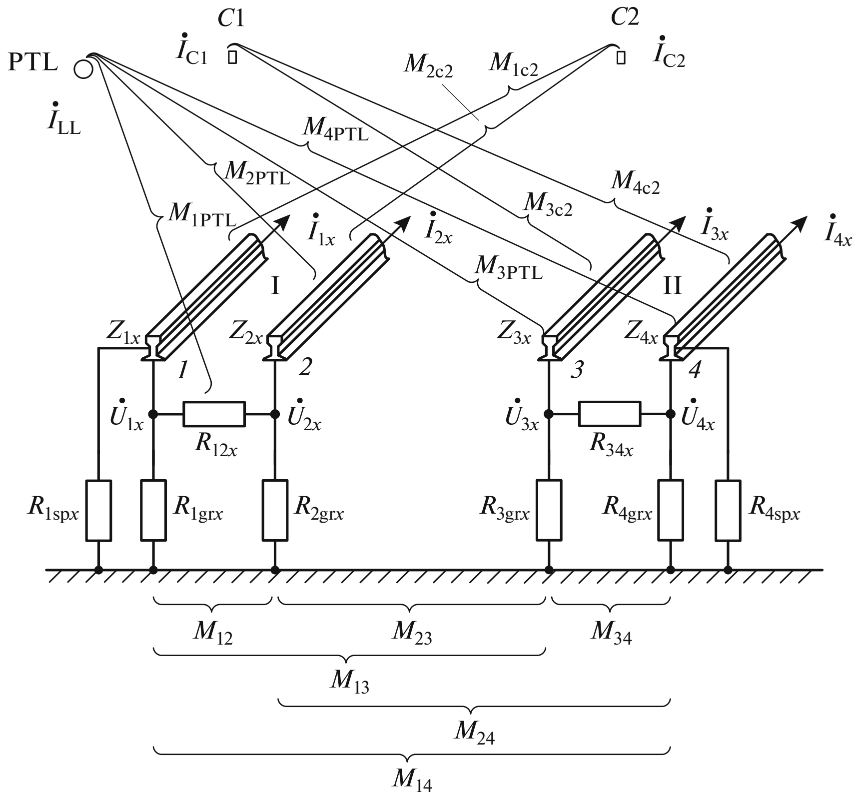

Fig. 1. Electric and magnetic parameters of the track lines of a double-track electrified railway section.

traction network design procedure aimed at determining the traction current in the track line without considering its distribution along the trackways does not apply to this calculation [6]. It is, thus, necessary to devise a procedure for calculating traction current asymmetry in track lines of double-track hauls.

Let us consider a double-track haul of an ac haulage section with track circuits of length l_{tc}. The TCs are limited by insulated junctions with impedance bonds (IBs). The drops of traction voltage U_{TC} on the trackways of these TCs are identical and equal to the voltage between the middle points of IBs.

In Fig. 1, we see the electric and magnetic parameters of the track lines of an electrified double-track railway section, as well as the reciprocal inductances of these parts. The track lines and contact wires are numbered from left to right.

Trackway resistances Z_{1x}, Z_{2x}, and Z_{3x} include longitudinal and transversal electric resistances, which generally vary along track line length x [1]. Longitudinal TW resistances include resistances of blank rails, conductor bonds, choke jumpers, and sections of main IB windings and vary over time due to damage to and wear of conductor bonds and choke jumpers.

Transversal track line resistances include crosstie and metaling surface resistances R_{12x} and R_{34x}; track-to-ground resistances R_{1grx}, R_{2grx}, R_{3grx}, and R_{4grx}; and inbound resistances of catenary network support ground circuits R_{1spx} and R_{4spx}. The power losses in the track traction network are reduced and the traction currents in the track lines are evened out by mounting intertrack junctions along the haul (they are not shown in Fig. 1) [4]. Resistances R_{12x} and R_{34x} vary with impairments of the state of electrical insulation parts of reinforced concrete crossties or with surface dampening of dirty wooden crossties. Resistances R_{1grx}, R_{2grx}, R_{3grx}, and R_{4grx} depend on the state of metaling. Resistances R_{1spx} and R_{4spx} decrease with impairments in the state of electric insulation parts in catenary network support ground circuits.

Trackway traction currents $\dot{I}_{1x}$, $\dot{I}_{2x}$, $\dot{I}_{3x}$, and $\dot{I}_{4x}$ vary along the TW length at variations in the intensity with which traction currents are discharged from the tracks to the ground. This happens with variations in the ratio of the longitudinal and transversal TW resistances to the TW length. The traction currents in contact wires $C1$ and $C2$ are referred to as $\dot{I}_{C1}$ and $\dot{I}_{C2}$, whereas the longitudinal PTL current is indicated as $\dot{I}_{LL}$. All these currents vary over time.

The reciprocal inductances between the trackways of the primary and the adjacent tracks are indicated as M_{12}, M_{13}, M_{14}, M_{23}, M_{24}, and M_{34}; the reciprocal inductances between the TWs and the contact wires of the adjacent tracks are indicated as M_{1c2}, M_{2c2}, M_{3c1}, and M_{4c1}; and the reciprocal inductances between respective TWs and PTL wires are indicated as M_{1PTL}, M_{2PTL}, M_{3PTL}, and M_{4PTL}. The symmetrical reciprocal inductances between the contact wires and the TWs of the primary track lines M_{1c2}, M_{2c1} and M_{3c2}, M_{4c2} are omitted in Fig. 1 so as to make the diagram less complicated.

If we ignore as relatively insignificant in comparison with the considered distances equivalent wire radii equal to section perimeters of tracks, contact wires, or PTL wires, specific reciprocal inductances of electric power lines can then be found in H/km, taking into account [7] and according to

$$M_{12} = \left[1 + 2\ln\frac{2}{1.78 l_{ij}\sqrt{4\pi\sigma f}} - j\frac{\pi}{2}\right]\times 10^{-4}, \qquad (1)$$

where f is the frequency of a respective traction current harmonics; l_{ij} is the distance between reciprocally inductive interfering line i and electric power line j; and σ is the specific ground conductivity, S/m.

The specific reciprocal inductance of electric power lines is inversely related to the distance between these; however, this inductance decreases at a far slower pace than the considered distance increases.

For instance, the specific TW inductance at a traction current frequency of 50 Hz and a distance between the trackways with P50 rails of 1.52 m is $1.35e^{-j7}$ mH/km [8]. In the same conditions, the specific reciprocal inductance between the contact wire and the trackway at a height of the contact wire above the rail head of 6.55 m is $1.07e^{-j79}$ mH/km [8]. Consequently, when the distance between single-wire electric power lines increases by 4.31 times, the reciprocal inductance between these lines will decrease by only 26% at a frequency of 50 Hz.

The specific reciprocal inductance resistances of electric power lines i and j are found as $z_{M_{ij}} = j\omega M_{ij}$, where ω is the frequency of a respective traction current harmonic. The distances between TWs of adjacent tracks and from contact wires and PTLs to each TW of a respective track line are different; thus, we also find different respective specific reciprocal inductance resistances $z_{M13} \neq z_{M14}$, $z_{M23} \neq z_{M24}$, $z_{M1c2} \neq z_{M2c2}$, $z_{M1ptl} \neq z_{M2ptl}$, $z_{M3c2} \neq z_{M4c2}$, and $z_{M3ptl} \neq z_{M4ptl}$.

The traction current leak from the tracks to the ground can be ignored for dry or frostbound metaling. In this case, only the longitudinal TW resistance asymmetry in the track lines can be considered. Then, taking into account $z_{M12} = z_{M21}$ and $z_{M1c1} = z_{M2c1}$, we can record the corresponding equations to consider the voltage drop distribution among the parts of TW1 and TW2 for TCs limited by block joints with an IB as

$$\begin{aligned}\dot U_{tc} &= [(z_{tr} + r_{jr1})l_{tc} + (0.5z_{IB} + z_{CHJ1}) \\ &+ (R_{BI1} + R_{BF1})]\dot I_{1x} + (\dot I_{2x}z_{M12} + \dot I_{3x}x_{M13} \\ &+ \dot I_{4x}z_{M14} + \dot I_{c1}z_{M1c1} + \dot I_{c2}z_{M2c2} + \dot I_{LL}z_{M2ptl})l_{tc},\end{aligned} \qquad (2)$$

$$\begin{aligned}\dot U_{tc} &= [(z_{tr} + r_{jr2})l_{tc} + (0.5z_{IB} + z_{CHJ2}) \\ &+ (R_{BI2} + R_{BF1})]\dot I_{2x} + (\dot I_{1x}z_{M12} + \dot I_{3x}x_{M23} \\ &+ \dot I_{4x}z_{M24} + \dot I_{c1}z_{M1c1} + \dot I_{c2}z_{M2c2} + \dot I_{LL}z_{M2ptl})l_{tc},\end{aligned} \qquad (3)$$

where z_{tr} is the specific resistance of blank tracks and conductor bond resistances; r_{jr1} and r_{jr2} are the specific resistances of wire-to-sleeve and sleeve-to-track junctions in the conductor bonds in TW1 and TW2; z_{IB} is the resistance of the sections of the main IB coils for traction current; z_{chj1} and z_{chj2} are the choke jumper resistances in TW1 and TW2; R_{BI1}, R_{BF1}, R_{PI2}, and R_{PF2} are the resistances of bridges between wires and plug contacts and between plug contacts and tracks in the choke jumpers in the initial and final sections of TW1 and TW2; z_{M12}, z_{M13}, and z_{M14} are the specific resistances of reciprocal inductance between TW1 and TW2, TW3, and TW4; z_{M21}, z_{M23}, and z_{M24} are the specific resistances of reciprocal inductance between TW2 and TW1, TW3, and TW4; z_{M1c1} and z_{M2c1} are the specific resistances of reciprocal inductance between TW1 and TW2 and contact wire $C1$; z_{M1c2} and z_{M2c2} are the specific resistances of reciprocal inductance between TW1 and TW2 and contact wire $C2$; and z_{M1ptl} and z_{M2ptl} are the specific resistances of reciprocal inductance between the TW1, TW2, and PTL wires.

Taking into account (2) and (3), the resistances of TW1 and TW2 for traction current are found as

$$\begin{aligned}Z_{TW1} &= \frac{\dot U_{tc}}{\dot I_{1x}} = (z_{tr}l_{tc} + 0.5z_{IB} + z_{CHJ}) \\ &+ (r_{JR1}l_{tc} + R_{BI1} + R_{BF1}) \\ &+ \left(\frac{\dot I_{2x}}{\dot I_{1x}}z_{M12} + \frac{\dot I_{3x}}{\dot I_{1x}}z_{M13} + \frac{\dot I_{4x}}{\dot I_{1x}}z_{M14}\right. \\ &+ \left.\frac{\dot I_{c1}}{\dot I_{1x}}z_{M1c1} + \frac{\dot I_{c2}}{\dot I_{1x}}z_{M1c2}\frac{\dot I_{LL}}{\dot I_{1x}}z_{M1ptl}\right)l_{tc},\end{aligned} \qquad (4)$$

and

$$\begin{aligned}Z_{TW2} &= \frac{\dot U_{tc}}{\dot I_{2x}} = (z_{tr}l_{tc} + 0.5z_{IB} + z_{CHJ}) \\ &+ (r_{JR2}l_{tc} + R_{BI2} + R_{BF2}) \\ &+ \left(\frac{\dot I_{1x}}{\dot I_{2x}}z_{M12} + \frac{\dot I_{3x}}{\dot I_{2x}}z_{M23} + \frac{\dot I_{4x}}{\dot I_{2x}}z_{M24}\right. \\ &+ \left.\frac{\dot I_{c1}}{\dot I_{1x}}z_{M1c1} + \frac{\dot I_{c2}}{\dot I_{1x}}z_{M1c2} + \frac{\dot I_{LL}}{\dot I_{1x}}z_{M1ptl}\right)l_{tc},\end{aligned} \qquad (5)$$

respectively.

Let us consider the case of $\dot{I}_{1x} > \dot{I}_{2x}$ in the first track line. The traction current asymmetry factor for this line is then found as

$$k_{Al1} = (\dot{I}_{1x} - \dot{I}_{2x})/(\dot{I}_{1x} + \dot{I}_{2x}).$$

In case of no leaks to the ground, the TW traction currents are inversely related to their resistances. Taking this into account, the traction current asymmetry factor is found as

$$k_{Al1} = \frac{Z_{\mathrm{TW2}} - Z_{\mathrm{TW1}}}{Z_{\mathrm{TW1}} + Z_{\mathrm{TW2}}}. \quad (6)$$

The traction current asymmetry factor is a dimensionless value. Its use in finding RW resistances does not result, therefore, in any inaccuracies.

Taking into account (4) and (5), the equation to find the numerator of (6) is recorded as

$$\begin{aligned} Z_{\mathrm{TW2}} - Z_{\mathrm{TW1}} &= (r_{\mathrm{JR2}} - r_{\mathrm{JR1}})l_{\mathrm{tc}} + (R_{\mathrm{TW2}} - R_{\mathrm{TW1}}) \\ &+ (R_{\mathrm{BF2}} - R_{\mathrm{BF1}})\Bigg[\left(\frac{\dot{I}_{1x}}{\dot{I}_{2x}} - \frac{\dot{I}_{2x}}{\dot{I}_{1x}}\right) z_{M12} \\ &+ \left(\frac{\dot{I}_{3x}}{\dot{I}_{2x}} z_{M23} - \frac{\dot{I}_{3x}}{\dot{I}_{1x}} z_{M13}\right) + \left(\frac{\dot{I}_{4x}}{\dot{I}_{2x}} z_{M24} - \frac{\dot{I}_{4x}}{\dot{I}_{1x}} z_{M14}\right) \quad (7) \\ &+ \left(\frac{\dot{I}_{\mathrm{c1}}}{\dot{I}_{2x}} - \frac{\dot{I}_{\mathrm{c1}}}{\dot{I}_{1x}}\right) z_{M\mathrm{1c1}} + \left(\frac{\dot{I}_{\mathrm{c2}}}{\dot{I}_{2x}} z_{M\mathrm{1c2}} - \frac{\dot{I}_{\mathrm{c2}}}{\dot{I}_{1x}} z_{M\mathrm{1c2}}\right) \\ &+ \left(\frac{\dot{I}_{\mathrm{LL}}}{\dot{I}_{2x}} z_{M\mathrm{2ptl}} - \frac{\dot{I}_{\mathrm{LL}}}{\dot{I}_{1x}} z_{M\mathrm{1ptl}}\right) l_{\mathrm{tc}}. \end{aligned}$$

The equation that holds for the denominator of (6) is

$$\begin{aligned} Z_{\mathrm{TW2}} - Z_{\mathrm{TW1}} &= (2z_{\mathrm{tr}}l_{\mathrm{tc}} + Z_{\mathrm{IB}} + 2Z_{\mathrm{IB}}) \\ &+ (r_{\mathrm{JR1}} - r_{\mathrm{JR2}})l_{\mathrm{tc}} + (R_{\mathrm{BI1}} - R_{\mathrm{BI2}}) \\ &+ (R_{\mathrm{BF2}} - R_{\mathrm{BF1}})\Bigg[\left(\frac{\dot{I}_{1x}}{\dot{I}_{2x}} + \frac{\dot{I}_{2x}}{\dot{I}_{1x}}\right) z_{M12} \\ &+ \left(\frac{\dot{I}_{3x}}{\dot{I}_{2x}} z_{M23}\right) + \left(\frac{\dot{I}_{4x}}{\dot{I}_{2x}} z_{M24} + \frac{\dot{I}_{4x}}{\dot{I}_{1x}} z_{M14}\right) \quad (8) \\ &+ \left(\frac{\dot{I}_{\mathrm{c1}}}{\dot{I}_{2x}} - \frac{\dot{I}_{\mathrm{c1}}}{\dot{I}_{1x}}\right) z_{M\mathrm{1c1}} + \left(\frac{\dot{I}_{\mathrm{c2}}}{\dot{I}_{2x}} z_{M\mathrm{2c2}} + \frac{\dot{I}_{\mathrm{c2}}}{\dot{I}_{1x}} z_{M\mathrm{1c2}}\right) \\ &+ \left(\frac{\dot{I}_{\mathrm{LL}}}{\dot{I}_{2x}} z_{M\mathrm{2ptl}} + \frac{\dot{I}_{\mathrm{LL}}}{\dot{I}_{1x}} z_{M\mathrm{1ptl}}\right) l_{\mathrm{tc}}\Bigg]. \end{aligned}$$

It follows from (7) that the absolute traction current asymmetry in the track line is determined by the difference in junction resistances r_{sr}, R_{BI}, and R_{BF} in the line TWs; differences in the resistance of reciprocal inductance of these trackways with other single-wire electric power lines; and ratio of currents in corresponding single-wire electric power lines.

Aging and damage increase junction resistances r_{jr1}, r_{jr2}, R_{ji1}, R_{jf1}, R_{ji2}, and R_{jf2} at a different rate in different TWs. The variations in the ratios of currents in the considered single-wire electric power lines occur irrespective of the availability or absence of rolling stock on the TC.

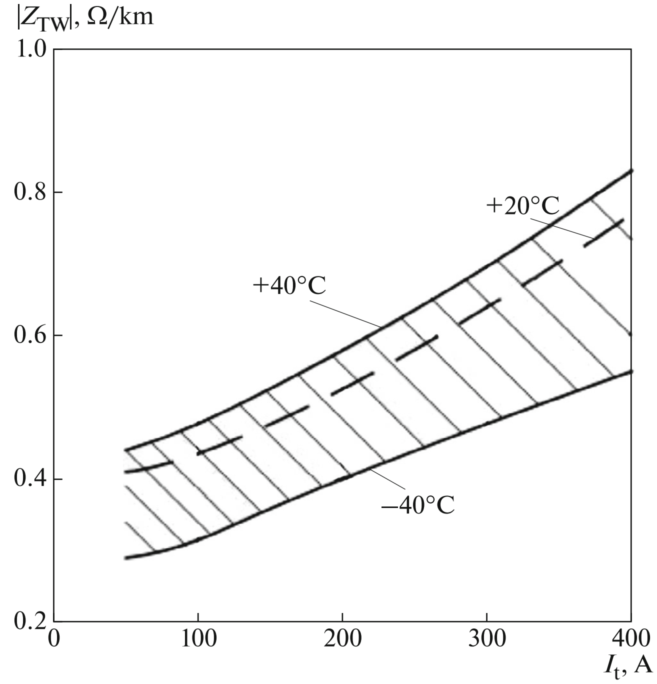

Fig. 2. Range of variations in the specific TW resistance module under track temperature and traction current variations.

The resistances contained in the first parentheses in (8) also vary in time. The specific resistance of blank rails, including bond conductor resistances r_{jr}, as well as steel jumper resistances Z_{chj}, depend on the ambient temperature and the traction current flow along the TWs. Copper choke jumper resistance Z_{chj} varies under ambient temperature variations. Resistance Z_{chj} of main coil sections to the traction current varies upon magnetization of IB cores due to traction current asymmetry. As a result, variations are possible in the traction current asymmetry factor, whereas the absolute traction current asymmetry in the TW remains unchanged.

In Fig. 2, the range of variations in specific TW resistance module $|z_{\mathrm{tw}}|$ is shown at a track temperature of from –40 to 40°C and at a 50-Hz traction ac in rails of up to 400 A. The ambient temperature varies quite slowly; however, rapid variations in the traction current and its harmonic structure in the track lines can be observed in the case of noises from external sources and changes in the handling mode of trains between traction substations. In these conditions, the specific TW electric resistance module varies by 2.87 times from 0.29 to 0.89 Ω/km.

The decreasing specific TW electric resistance under constant differences in value between respective resistances r_{CB} and R_{CHJ} of junctions between parts of conductor bonds and choke jumpers in the track line TW increases the traction current asymmetry factor in the TW.

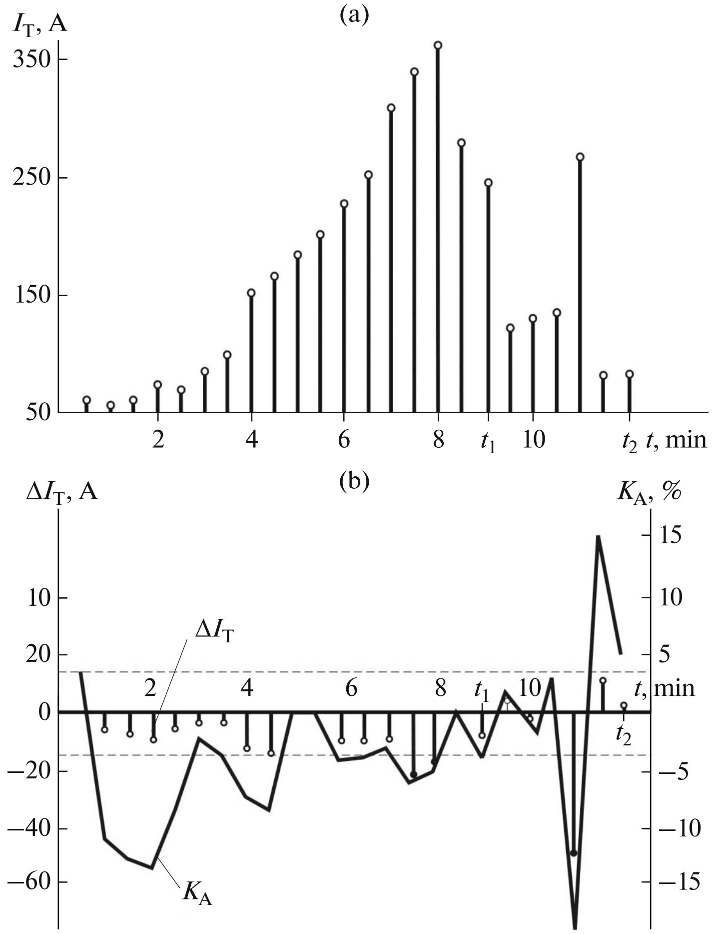

Fig. 3. (a) Traction current variations in the tracks and (b) traction current asymmetry dynamics when the train comes close to the point of measurement.

In these instances, the numerator found by (7) remains unchanged, whereas the denominator found by (8) decreases. As a result, e.g., while the traction current in the rails remains unchanged at a frequency of 50 and 150 Hz, respectively, the asymmetry of the specific resistance of TWs with P65 rails upon a drop in the temperature of the tracks from 40 to –40°C increases by 50%.

This accounts for the increasing intensity of operational failures in TCs and CCS upon a decrease in temperature and insignificant changes in the train weight and the traffic intensity and speed. In addition, this accounts for the increasing traction current asymmetry factor under decreasing traction current flow in the track line.

Longitudinal and transversal TW resistances are subject to random variations in time and along the track line length. For this reason, there are also random variations in the TW resistance asymmetry and the traction current asymmetry at the points at which TC equipment is connected to the tracks or under CCS sending cab coils.

During train movement, random variations may also occur in the resistance of the part of the track line from the first pair of wheels to the end of the TC, which is limited by block joints with an IB. This leads to stochastic variations in the traction current asymmetry under CCS sending cab coils.

The inferences drawn from the studies are confirmed by analyzing the results of measurements in the operating environment (Fig. 3). They were arranged in the summer in one of the hauls of the Trans-Siberian Railway and taken every minute on the receiver end of the TC with an IB with block joints as the train came close to the point of measurement.

In Fig. 3a, the dynamics of variations in traction ac $\dot{I}_m$ in the track line is shown, whereas the plots of percentage variations in absolute traction current asymmetry $\Delta\dot{I}_m$ and traction current asymmetry factor K_A are shown for the given period of time in Fig. 3b. The limits of tolerance for the traction current asymmetry factor of 4% are shown with a dashed line. The absolute traction current asymmetry that corresponds to this factor is 12 A at a track line current of 300 A.

In the first minutes of the measurements, the track current in the point of measurement was low because most of the electric locomotive traction current leaked from the tracks to the ground and did not reach that point. In the last minute of the procedure, the driving motors of the electric locomotive were shut down.

It follows from Fig. 3 that the traction current asymmetry factor under a low traction current in the rails and its low absolute asymmetry was very high, whereas the absolute traction current asymmetry fell within the tolerance range.

The increased traction current in the tracks and their accordingly increased resistance resulted in closer numerical values of the asymmetry factor and the absolute traction current asymmetry used to find the resistances of the trackways in the track line. Henceforth, the absolute value of the traction alternating current in the tracks is a more adequate standard for evaluating the impact of the traction current on the operational stability of the TC and the CCS.

Noises in the CCS sending cab coils are additionally generated when a train travels along the tracks with uneven longitudinal magnetization. These noises vary in level and frequency with variations in the train speed. The physical processes observed in this case are analyzed in [1].

The elaborated procedure makes it possible to find time-dependent numerical values of traction current asymmetry in track lines of double-track hauls at points at which track circuit equipment is connected to the tracks or at any point on the track circuit under CCS sending cab coils.

REFERENCES

1. Shamanov, V.I., *Elektromagnitnaya sovmestimost' sistem zheleznodorozhnoi avtomatiki i telemekhaniki* (Electromagnetic Compatibility of Railway Automatic and Telemechanic Systems), Moscow: Uchebn.-metod. tsentr po obrazovaniyu na zheleznodorozhnom transporte, 2013.
2. Sapozhnikov, V.V., Sapozhnikov, Vl.V., and Efanov, D.V., The way to research properties of Hamming codes and their modification in functional control systems, *Avtomat. Transporte,* 2015, vol. 1, no. 3.
3. Kravtsov, Yu.A., Arkhipov, E.V., and Bakin, M.E., Promising ways for coding rail circuits with tone frequency, *Avtomat. Transporte,* 2015, vol. 1, no. 2.
4. Bestem'yanov, P.F., A method of statistical modeling of electromagnetic interference in automatics and telemechanics channels in railway transport, *Russ. Electr. Eng.,* 2015, vol. 86, no. 9, p. 503.
5. Shamanov, V.I., The magnetic properties of rail lines and level of interferences for the apparatus of automatic control and telemechanics, *Russ. Electr. Eng.,* 2015, vol. 86, no. 9, p. 548.
6. Markvardt, K.G., *Elektrosnabzhenie elektrifitsirovannykh zheleznykh dorog* (Electric Power Supply for Electrified Railways), Moscow: *Transport*, 1982.
7. Vakhnin, M.I., Penkin, N.F., et al., Signals and interlocking devices for AC electric traction, in *Tr. VNIIZhT* (Scientific Works of All-Union Scientific-Research Institute of Railway Transport), Moscow: Transzheldorizdat 1956, issue 126.
8. Arkatov, V.S., Kravtsov, Yu.A., and Stepenskii, B.M., *Rel'sovye tsepi. Analiz raboty i tekhnicheskoe obsluzhivanie (Rail Circuits. Operation Analysis and Technical Support)*, Moscow: Transport, 1990.

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