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RESEARCH OF OPERATING MODES OF CONDUCTORS IN POWER SUPPLY SYSTEMS OF CRANES WITH INDUCTION FEED, TAKING INTO ACCOUNT THE INFLUENCE OF HIGHER HARMONICS OF THE CURRENT

Purpose. *Investigation of the influence of higher harmonics of current on current distribution, voltage and power losses in the supply systems of crane trolleys and development of a calculation method for practical use.* ***Methodology.*** *The analytical method and the results of the modeling method were used for research.* ***Results.*** *Analytical relationships have been obtained that make it possible to determine the current distribution, voltage and power losses in the systems of induction feeding of crane trolleys, taking into account the composition and amplitude of the higher harmonics of the current.* ***Originality.*** *For the first time, analytical dependences are obtained that take into account the effect of changing the trolley parameters on the frequency in the feed systems. Numerical values have been determined for the most commonly used induction feed systems for cranes. It is shown that with an increase in the cross-section of the feed bar there is a decrease in the main, and especially additional, losses.* ***Practical value.*** *Theoretical relationships have been obtained that can be used to calculate the optimization of induction feed systems in the presence of higher harmonic currents arising in power systems during operation of crane semiconductor controlled electric drives.* References 13, tables 4, figures 6.

Key words: **induction feed system, trolleys, feed bus, current distribution, power and voltage losses.**

У статті викладена методика розрахунку розподілу струму по струмопроводам, втрат напруги і потужності з урахуванням вищих гармонік струму в системах живлення кранів з індукційним підживленням. Отримані необхідні аналітичні залежності, що пов'язують параметри струмопроводів з відносними значеннями частоти вищих гармонійних і визначають їх вплив на струморозподіл, втрати напруги та потужності. Показано, що зі збільшенням перетину шин підживлення відбувається зниження втрат напруги і додаткових втрат, в тому числі і від струмів вищих гармонік, за рахунок перерозподілу цих струмів і втрат від них в шину подачі, що має практично незалежний від частоти активний опір. Показано, що основна частина додаткових втрат визначається амплітудами гармонік з порядком n≤7. Методика може бути застосована для систем живлення залізничного транспорту і розподільних систем, виконаних з застосуванням сталемідних і сталеалюмінієвих струмопроводів. Бібл. 13, табл. 4, рис. 6.

Ключові слова: **система індукційного живлення, тролея, шина живлення, розподіл струму, втрати потужності та напруги.**

В статье изложена методика расчёта токораспределения по токопроводам, потерь напряжения и мощности с учётом высших гармоник тока в системах питания кранов с индукционной подпиткой. Получены необходимые аналитические зависимости, связующие параметры токопроводов с относительными значениями частоты высших гармонических и определяющие их влияние на токораспределение, потери напряжения и мощности. Показано, что с увеличением сечения шин подпитки происходит снижение потерь напряжения, потерь мощности, в том числе и от токов высших гармоник, за счёт перераспределения этих токов и потерь от них в шину подпитки, обладающей практически независимым от частоты активным сопротивлением. Показано, что основная часть добавочных потерь определяется амплитудами гармоник с порядком n≤7. Методика применима для систем питания железнодорожного транспорта и распределительных систем, выполненных с применением сталемедных и сталеалюминиевых токопроводов. Библ. 13, табл. 4, рис. 6.

Ключевые слова: **система индукционной подпитки, троллея, шина подпитки, токораспределение, потери мощности и напряжения.**

Introduction. Energy saving in electrical networks is a priority area, both worldwide and in Ukraine. The widespread introduction of semiconductor converters leads to an increase in higher harmonics of current and voltage distortion, which increases voltage and power losses in electrical networks and leads to a deterioration in power quality indicators [1-3], and also has a significant impact on the operation of converters connected to these networks [4]. Determination of the composition and amplitude of the higher harmonics of the current is carried out by calculation, experimental and modeling methods [5-9]. To determine the influence of higher current harmonics on the supply network, it is necessary to know the parameters of the equivalent circuit. For low-voltage workshop networks, the values of active and inductive resistances are determined mainly by an analytical method. For complex wired conductor systems containing ferromagnetic elements and protective shields, analytical calculations are difficult. For these cases, modeling methods are used [5, 10].

For the most common and typical circuits, as a rule, analytical methods for calculating voltage and power losses are used [2, 11]. Such circuits include crane installations where variable frequency drives (VFDs) are used when modernizing old ones or designing new ones. The use of VFDs with semiconductor converters in crane power systems leads to a significant content of higher harmonic currents in the supply network, which are taken into account by the total harmonic distortion (THD_I) in accordance with the requirements of the International Standards IEEE 519-1992, IEC 61000-3-12:2012 and IEC 61000-3-12:2004. Higher harmonic currents lead to additional voltage and power losses in shop networks [6]. This circumstance attracts more and more attention to the study of operating modes of nonlinear loads, taking into account the higher harmonics of the current [4-9, 12, 13].

The implementation of the requirements for limiting the generation of higher harmonics in the network required research and development of circuit solutions for converters, passive active filters [1, 3]. From an economic point of view, the power distortion compensation is carried out at the load nodes: switchgear 6, 10 kV or switchgear 0.4 kV. However, in shop networks supplying electrical receivers with converters, the influence of higher harmonics turns out to be significant [5] and requires its solution.

In [6, 7], the authors proposed a method for studying the influence of higher harmonics of current in power supply systems of crane installations using steel trolleys and aluminum buses for the current conductor. It is shown that the presence of higher harmonics of the current leads to an increase in voltage losses by 3.2–4 times and power losses by 1.26–1.43 times in comparison with sinusoidal current for steel trolleys.

In the power supply system of heavy duty cranes and relatively long working spans, to ensure the operating voltage within the permissible limits, the main trolley is fed. The most widely used induction feed system is the least expensive. With induction feeding, an aluminum bus is usually laid in parallel to the trolleys [11].

The presence of higher harmonics of current in the power supply systems of the cranes leads to a change in the impedances of individual conductors and, accordingly, in the current distribution in them.

The goal of the paper is to investigate the influence of higher harmonics of currents on current distribution, voltage and power losses in the conductors of the induction feed system of cranes, and offer recommendations for reducing losses from higher harmonics.

Main research material.

Initial data. According to the generally accepted technique, the current of the fundamental harmonic of the trolleys I_t is determined from the condition of the permissible voltage losses in the working section of the crane operation, according to the relationship [6, 11]:

$$\begin{cases} I_t = \dfrac{\Delta U_{\max}}{l_t \cdot \Delta U_{t1}} = \dfrac{\Delta U_{\max}}{\sqrt{3} \cdot l_t \cdot R_t \cdot \left(\cos\varphi_1 + \mathrm{tg}\varphi_{t1} \cdot \sin\varphi_1\right)}; \\ I_s = I_{\max} - I_t, \end{cases} \quad (1)$$

where $\Delta U_{\max}$, ΔU_{t1} are the permissible voltage losses and voltage losses per 1 m of trolley section length, respectively, at a given trolley current; l_t is the working length of the trolley; $I_{\max}$, I_s are the maximum current of the system and feed bus, respectively; $\mathrm{tg}\varphi_{t1} = X_{t1}/R_{t1}$; where X_{t1}, R_{t1} are the inductive and active resistance of the trolley for the fundamental harmonic with frequency of 50 Hz; φ_1 is the shift angle of the fundamental harmonic.

To ensure the permissible voltage losses $\Delta U_{\max} \le 5$ %, an aluminum bus is laid parallel to the trolley in the working area of the crane operation. The current distribution along the conductors in the feed system is determined by the ratio of the impedances at the fundamental harmonic [11].

Ratio of currents in conductors using the superposition method for components with harmonic n

$$\gamma_n = \frac{Z_{sn}}{Z_{tn}} = \frac{R_{sn}}{R_{tn}} \cdot \sqrt{\frac{1 + tg^2\varphi_{sn}}{1 + tg^2\varphi_{tn}}}, \quad (2)$$

where $Z_{s(t)n} = \sqrt{R^2_{s(t)n} + X^2_{s(t)n}}$ is the impedance of the corresponding conductor (s – bus, t – trolley) for n harmonic; $X_{tn} = X'_{tn} + X''_{tn} + X'''_{tn}$; $X_{sn} = X'_{sn} + X'''_{sn}$ is the inductive resistance: X' – internal; X'' – external; X''' is the resistance to mutual inductance of the trolley and the feed bus.

The parameters of the conductors of the most common induction feed systems are given in Table 1 for distance between trolleys of 250 mm, made with a corner of 50 × 50 × 5 mm.

The inductive resistance of the conductors is indicated taking into account the mutual inductance of the trolley and the feed bus [11].

Table 1

Parameters of conductors of feed systems

Dimensions, mm	Parameters						
Steel corner 50×50×5 mm	R_{t1}, Ω/km	X_{t1}, Ω/km	Z_{t1}, Ω/km	$X'_{t1}+X'''_{t1}$, Ω/km	X''_{t1}, Ω/km	tgφ_{t1}	γ_1, p.u.
	1,65	1,263	2,08	0,339	0,924	0,765	
Aluminum bus	R_{s1}, Ω/km	X_{s1}, Ω/km	Z_{s1}, Ω/km	—	—	tgφ_{s1}	
20×3	0,513	0,277	0,583	—	—	0,54	0,28
30×3	0,342	0,253	0,425	—	—	0,74	0,204
40×3	0,256	0,237	0,348	—	—	0,926	0,161
50×3	0,205	0,225	0,32	—	—	0,11	0,147
60×4	0,128	0,213	0,248	—	—	1,664	0,119
80×5	0,077	0,195	0,21	—	—	2,53	0,101

The most common sources of higher harmonics are uncontrolled (for variable frequency drives) and controlled (for DC drives) rectifiers. The relative values of the n-order harmonics of the input current of the bridge rectifier are determined from the relationship:

$$I_n^* = K_n \cdot \frac{I_n}{I_1} = K_n \cdot \frac{1}{n} = K_n \cdot \frac{1}{f_n^*}, \quad (3)$$

where K_n is the coefficient that takes into account the ratio of the ripple amplitude in a real rectifier to an ideal one [6] (with inductance L_d in the rectifier link $L_d = \infty$ $K_n = 1$); I_n, I_1 are the current values of the n-order harmonic and fundamental harmonic in current conductors, respectively; $f_n^* = f_n$ / 50 is the relative frequency of the n-order harmonic.

In [6] it was shown that the resistance of aluminum buses is related by the following ratios for the n harmonic component relative to the main one:

$$\begin{cases} R_{sn} = R_{s1}; \quad X_{sn} = X_{s1} f_n^*; \\ \mathrm{tg}\varphi_{sn} = \dfrac{X_{sn}}{R_{sn}} = \mathrm{tg}\varphi_{s1} f_n^*. \end{cases} \quad (4)$$

The resistance of the steel corners is related by the ratios for the n harmonic component relative to the main one:

$$\begin{cases} R_{tn} = R_{t1}\sqrt{f_n^*}; \quad X_{tn} = (X'_{t1} + X''_{t1} + X'''_{t1}) f_n^*; \\ \mathrm{tg}\varphi_{tn} = \dfrac{X_{tn}}{R_{tn}} = \dfrac{\left(X'_{t1} + 0{,}56 R_{t1}\sqrt{f_n^*} + X''_{t1}\right)\sqrt{f_n^*}}{R_{t1}}. \end{cases} \quad (5)$$

The maximum current taking into account higher harmonics is determined by the relationship [2, 6]

$$I_{\max}^* = \sqrt{\sum_{k=0}^{n=6k\pm1} K_n^2 I_n^{*2}} = \sqrt{\sum_{k=0}^{n=6k\pm1} K_n^2 \frac{1}{f_n^{*2}}}, \quad (6)$$

where k is the series of integers 1, 2, 3, etc. In this case, we assume that the fundamental harmonic is equal to the fundamental harmonic of the sinusoidal current of the trolley without feed.

Research results.

1. Distribution of currents in the feed conductors. Transforming expression (2), taking into account the considered relations (3), we have:

$$\gamma_n = \frac{R_{s1}}{R_{t1}\sqrt{f_n^*}} \sqrt{\frac{1 + \left(\mathrm{tg}\varphi_{s1} f_n^*\right)^2}{1 + \dfrac{\left(X'_{t1} + 0{,}56 R_{t1}\sqrt{f_n^*} + X''_{t1}\right)^2 f_n^*}{R_{t1}^2}}}. \quad (7)$$

Analysis of the relationship (7), taking into account the values of the parameters for calculating the conductors, summarized in Table 1 showed that for f_n^* ≥7, relationship (7) with sufficient accuracy can be reduced to the form:

$$\gamma_n = \frac{X_{s1}}{0{,}56 R_{t1}\sqrt{f_n^*}}. \quad (8)$$

Thus, the distribution of currents along the conductors is practically directly proportional to the inductive resistance of the feed buses at the fundamental harmonic and inversely proportional to the square root of the frequency f_n^*, i.e. with increasing frequency, γ_n decreases monotonically, which indicates an increase in high-frequency components in the feed bus (Fig. 1).

It is not difficult to show, using the second equation in expression (1) and relation (2), that the relative value of the bus current I_{sn}^* and trolley current I_{tn}^* for the n harmonic component has the form:

$$\begin{cases} I_{sn}^* = \dfrac{I_{sn}}{I_{\max}} = \dfrac{1}{1+\gamma_n} \cdot \dfrac{1}{f_n^*}; \\ I_{tn}^* = \dfrac{I_{tn}}{I_{\max}} = \dfrac{\gamma_n}{1+\gamma_n} \cdot \dfrac{1}{f_n^*}. \end{cases} \quad (9)$$

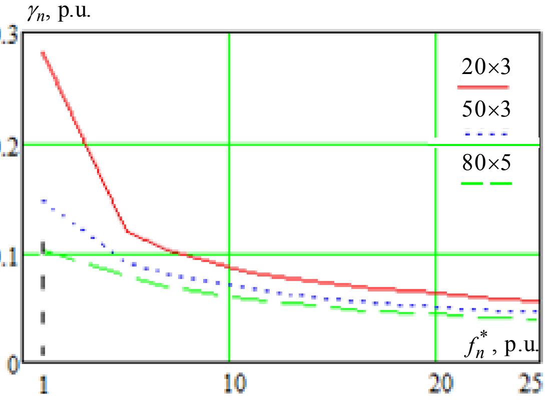

Fig. 1. Dependences $\gamma_n = f(f_n^*)$ for the steel corner 50×50×5 mm with feed bus 20×3, 50×3, 80×5 mm

Figure 2 shows the relative values of the currents in the induction feed system: a corner 50 × 50 × 5 mm with a feed bus 80 × 5 mm for the n harmonic component.

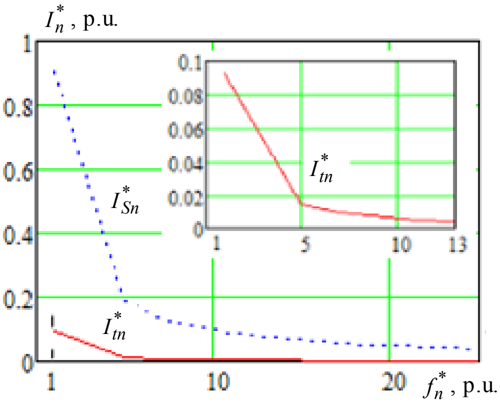

Fig. 2. Dependences $I_n^* = f(f_n^*)$ for the steel corner 50×50×5 mm with feed bus 80×5 mm

Table 2 shows the relative values of the currents in the trolley made of a corner 50 × 50 × 5 mm with a feed bus.

Table 2

Relative values of currents

Bus sizes, mm	Parameter					
	I_{s1}^*, p.u.	$I_{s\Sigma}^*$, p.u.	$I_{sn\Sigma}^*$, n≥5, p.u.	I_{t1}^*, p.u.	$I_{t\Sigma}^*$, p.u.	$I_{tn\Sigma}^*$, n≥5, p.u.
20×3	0,781	0,819	0,024	0,219	0,221	0,026
50×3	0,872	0,908	0,252	0,128	0,13	0,021
80×5	0,908	0,943	0,255	0,092	0,094	0,018

Analysis of Table 2 shows that with an increase in the cross-section of the feed bus, the current of the trolleys $I_{t\Sigma}^*$ significantly decreases including the decrease in the high-frequency component $I_{tn\Sigma}^*$.

2. Voltage losses.

Since the trolleys are selected according to the permissible voltage losses at a given current (1), then we check the influence of higher harmonics for the trolleys.

In the presence of higher harmonics, the relative increase in voltage losses in trolleys relative to the voltage losses at the fundamental harmonic ΔU_{t1} is determined taking into account expressions (1), (9):

$$\Delta U_t^* = \frac{\sqrt{\Delta U_{t1}^2 + \Delta U_{t5}^2 + ... + \Delta U_{t13}^2}}{\Delta U_{t1}} = \sqrt{\sum_{k=0}^{n=6k\pm1} \Delta U_{tn}^{*2}} = \sqrt{1 + \sum_{k=1}^{n=6k\pm1} K_n^* \frac{1}{f_n^*}\left(\frac{\gamma_n}{1+\gamma_n}\right)^2 \left(\frac{1+\gamma_1}{\gamma_1}\right)^2 \frac{\left(\cos\varphi_1 + \mathrm{tg}\varphi_{t1} f_n^* \sin\varphi_1\right)^2}{\left(\cos\varphi_1 + \mathrm{tg}\varphi_{t1}\sin\varphi_1\right)^2}}, \quad (10)$$

where $\Delta U_{t1} = \frac{\sqrt{3} I_{t1} R_{t1} l_t \left(\cos\varphi_1 + \mathrm{tg}\varphi_{t1}\sin\varphi_1\right)}{U_{\text{nom}}} \cdot 100\%$;

$I_{t1} = I_{\max}\left(\frac{\gamma_1}{1+\gamma_1}\right)$; $\mathrm{tg}\varphi_{t1} = X'_{t1} + 0{,}56 R_{t1} + X'''_{t1}$;

U_{nom} is the trolley rated voltage.

For the case of an ideal uncontrolled rectifier $K_n = 1$, $\cos\varphi_1 \approx 1$ which corresponds to a rectifier with an LC filter (distortion factor ν = 0.955 which corresponds to THD_I = 31.05 %)), the voltage losses are:

$$\Delta U_t^* = \sqrt{1 + \sum_{k=1}^{n=6k\pm1} \frac{1}{f_n^*}\left(\frac{\gamma_n}{1+\gamma_n}\right)^2 \left(\frac{1+\gamma_1}{\gamma_1}\right)^2}. \quad (11)$$

The dependence of the relative values of voltage losses in the trolley with a feed bus as a function of frequency f_n^* are shown in Fig. 3.

The relative values of ΔU_{t5}^* and ΔU_{t7}^* are about 22 % and 16 % of the voltage losses at the fundamental harmonic, and the relative values of ΔU_{t11}^* and ΔU_{t25}^* are 10 % and 5 %, respectively.

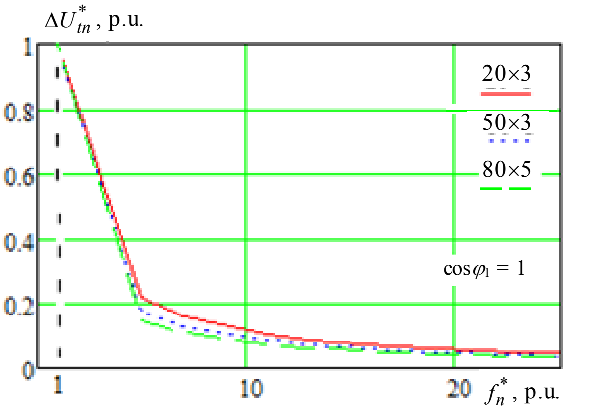

Fig. 3. Dependences $\Delta U_{tn}^* = f(f_n^*)$ in the trolley with feed bus 20×3, 50×3, 80×5 mm; $\cos\varphi_1 = 1$

The dependence of the relative values of the voltage losses in the trolley with feed bus on the frequency is shown in Fig. 4 at $\cos\varphi_1 = 0.5$.

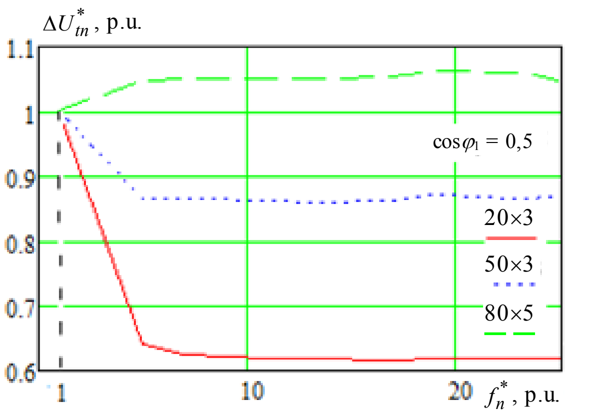

Fig. 4. Dependences $\Delta U_{tn}^* = f(f_n^*)$ in the trolley with feed bus 20×3, 50×3, 80×5 mm; $\cos\varphi_1 = 0.5$

As follows from Fig. 4, the relative values of the voltage losses ΔU_{tn}^* for $n \geq 5$ harmonic components at $\cos\varphi_1 = 0.5$ increase significantly which is explained by the influence of the component ($\cos\varphi_1 + \mathrm{tg}\varphi_{t1} \cdot f_n^* \cdot \sin\varphi_1$) in expression (10). An increase in ΔU_{tn}^* is noted for $n \geq 5$ with an increase in the cross-section of the feed bus which is caused by the redistribution of the ratio of the relative values of the currents of the fundamental harmonic of the trolley I_{t1}^* and high-frequency components $I_{tn\Sigma}^*$. This ratio increases as the cross-section of the feed bus decreases.

Table 3 shows the relative values of the voltage losses in the trolley at $\cos\varphi_1$ = var, made of the corner 50 × 50 × 5 mm for some combinations of feed at $f_n^* \leq 25$.

Table 3

Relative value of voltage losses

bus, mm / $\cos\varphi_1$	20×3	50×3	80×5
1	1,051	1,033	1,025
0,9	1,36	1,63	2,081
0,8	1,54	1,91	2,31
0,7	1,69	2,16	2,53
0,6	1,853	2,39	2,83
0,5	2,022	2,65	3,14

Analysis of Table 3 shows that the relative value of the voltage losses of the corner at $\cos\varphi_1$ = 1 with 20 × 3 mm bus increases by 5.1 %, and with 80 × 5 mm bus – by 2.5 %. The relative value of the voltage losses reaches its maximum value at $\cos\varphi_1$ = 0.5: with 20 × 3 mm bus it increases by 2.022 times, and with 80 × 5 mm bus – by 3.1 times. Therefore, $\Delta U_{\max}$ in expression (1) should be reduced by an appropriate value.

Dependences $\Delta U_t^* = f(\cos\varphi_1)$ in the trolley with feed bus are shown in Fig. 5.

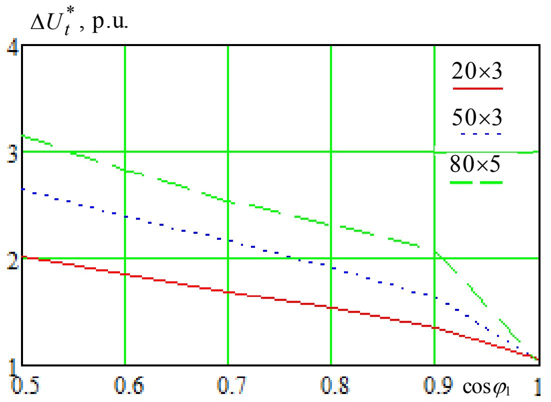

Fig. 5. Dependences $\Delta U_t^* = f(\cos\varphi_1)$ in the trolley with feed bus 20×3, 50×3, 80×5 mm

An analysis of the dependence $\Delta U_t^* = f(\cos\varphi_1)$ for the trolley with feed bus shows that with a decrease in $\cos\varphi_1$, the values of the relative voltage losses in the trolley increase with an increase in the cross-section of the feed bus.

Note that the relative value of the voltage losses in the trolley with feed bus, depending on cosφ_1, is lower in the same trolley without feed bus in the presence of higher harmonics [6].

3. Power losses.

Power losses in the induction feed system have two components: losses in the trolley ΔP_t and in the feed bus ΔP_s which are equal, respectively:

$$\Delta P_t = 3 \cdot \sum_{k=0}^{n=6k\pm1} R_{tn} I_{tn}^2 \quad \text{and} \quad \Delta P_s = 3 \cdot \sum_{k=0}^{n=6k\pm1} R_{s1} I_{sn}^2 .$$

In relative units, power losses are determined taking into account expressions (1), (5), (9):

$$\Delta P^* = \Delta P_t^* + \Delta P_s^* = \frac{\Delta P_t + \Delta P_s}{\Delta P_1} = \sum_{k=0}^{n=6k\pm1} K_n^2 \frac{\sqrt{f_n^*}}{f_n^{*2}} \left(\frac{\gamma_n}{1+\gamma_n}\right)^2 + \frac{R_{s1}}{R_{t1}} \sum_{k=0}^{n=6k\pm1} \left(\frac{1}{1+\gamma_n}\right)^2 \frac{K_n^2}{f_n^{*2}}, \quad (12)$$

where $\Delta P_1 = 3 R_{t1} I_{t1}^2$ are the losses in trolleys without feed.

The relative values of the power losses in the induction feed system are shown in Fig. 6.

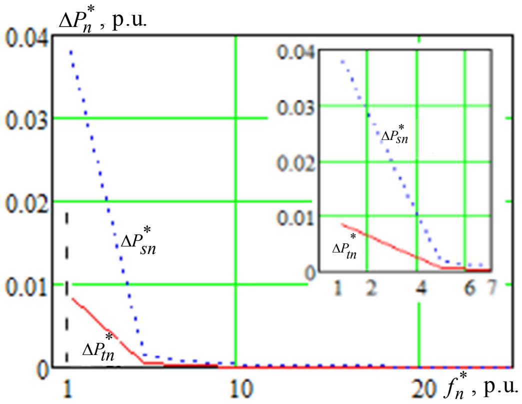

Fig. 6. Dependences $\Delta P_n^* = f(f_n^*)$ in the trolley with feed bus 80×5 mm

The relative values of power losses in the trolley with feed bus for an ideal uncontrolled rectifier K_n = 1 are summarized in Table 4.

Table 4

Relative values of power losses

Bus sizes, mm	Parameter, p.u.						
	ΔP_{t1}^*	$\Delta P_{tn\Sigma}^*$, $n\geq5$	ΔP_t^*	ΔP_{s1}^*	$\Delta P_{sn\Sigma}^*$, $n\geq5$	ΔP_s^*	ΔP^*
20×3	0,048	0,0018	0,0498	0,189	0,012	0,2	0,248
50×3	0,016	0,0007	0,0167	0,118	0,0061	0,118	0,135
80×5	0,0084	0,00044	0,00884	0,038	0,0018	0,039	0,047

Analysis of Table 4 shows that relative to the first harmonic of the system current, the power losses in the induction feed systems ΔP^* decrease depending on the cross-section of the feed buses by 4; 7.4 and 21.3 times, respectively. In this case, the relative additional power losses ($\Delta P_{tn\Sigma}^* + \Delta P_{sn\Sigma}^*$) are 5.5–4.6 % of the total losses.

Analysis of losses from high-frequency components shows that the main share of additional losses is losses from harmonics $n\leq7$. Accounting of the coefficient K_n^2, according to [6], leads to an increase in additional losses by about 1.5 times. Therefore, the calculation of the losses should be made taking into account the real values of the higher harmonics obtained experimentally [8] or by modeling [6].

Note that in order to reduce voltage and power losses in systems with crane installations that operate in heavy duty with a large number of starts, relatively expensive non-inductive feed systems are used, in which the feed bus is made of aluminum wires laid in pipes [11]. Analysis of these feed systems shows that with cross-section of wires of 50–150 mm^2 and with number of cores equal to 3, the inductive resistances decrease by 2–3 times. This leads, according to expression (12), to a decrease in additional voltage and power losses in the trolleys. This circumstance partially or completely compensates the primary capital costs for building a non-inductive feed system, which are determined by a technical and economic calculation.

The proposed technique for calculating voltage and power losses can be used to calculate voltage and power losses in steel-copper and steel-aluminum wires used in railway transport and distribution networks.

A feature of AC power supply systems in railway transport is the significant value of the currents of the 3rd and the 5th harmonics, which reach 60 and 30 % of the fundamental one, respectively [13] which significantly affects the distribution of currents and the value of additional power losses and voltage losses.

Conclusions.

Research results show that in induction feed systems, due to the redistribution of higher harmonic currents between the feed bus and the trolley, there is a decrease in voltage losses, main and additional power losses.

When determining the permissible voltage losses, the reduction factor of the value of the permissible voltage losses 1.051–1.025, and 2.022–3.14 should be used, depending on the change in the power factor in the range of cosφ_1 = 1.0–0.5 and depending on the cross-section of the feed buses, respectively.

The use of an induction feed system allows to reduce the total power losses by 4–21.3 times depending on the cross-section while the relative additional power losses are no more than 5.5 % of the total power losses.

The proposed technique for calculating current distribution, voltage losses and power losses can be used to calculate the modes of steel-aluminum and steel-copper conductors.

Conflict of interests. The authors declare no conflicts of interest.

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