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 dependencies 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.

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) 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

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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 technique, the current of the fundamental harmonic 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 trolley \( I_t \) is determined from the condition of the permissible voltage losses in the working section of the crane operation, according to the relationship [6, 11]:

\[
I_t = \frac{\Delta U_{\text{max}}}{I_t \cdot \Delta U_{l1}} = \frac{\Delta U_{\text{max}}}{\sqrt{3} \cdot I_t \cdot R_t \cdot \left(\cos \phi_1 + \tan \phi_1 \cdot \sin \phi_1\right)};
\]

where \( \Delta U_{\text{max}} \) are the permissible voltage losses and voltage losses per 1 m of trolley section length, respectively, at a given trolley current; \( I_t \) is the working length of the trolley; \( I_{\text{max}} \), \( I_t \) are the maximum current of the system and feed bus, respectively; \( \tan \phi_1 = X_0 / R_1 \); where \( X_0 \), \( R_1 \) are the inductive and active resistance of the trolley for the fundamental harmonic with frequency of 50 Hz; \( \phi_1 \) is the shift angle of the fundamental harmonic.

To ensure the permissible voltage losses \( \Delta U_{\text{max}} \leq 5\% \), 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 \( n \)**

\[
\gamma_n = \frac{Z_{sn}}{Z_{tn}} = \frac{R_{sn}}{R_{tn}} \left[1 + \tan^2 \phi_{sn}\right]^{1/2},
\]

where \( Z_{sn} = \sqrt{R_{sn}^2 + X_{sn}^2} \) is the impedance of the corresponding conductor (s – bus, t – trolley) for \( n \) harmonic; \( X_{tn} = X_{tn}^* + X_{tn}^\prime + X_{tn}^\prime\prime \). \( X_{tn}^* = X_{tn}^\prime + X_{tn}^\prime\prime \) is the inductive resistance: \( X^* \) – internal; \( X^* \) – external; \( X^\prime \) 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 | R_{ts}, \ Omega/km | X_{ts}, \ Omega/km | Z_{ts}, \ Omega/km | X_{t1} + X_{t1}^*, \ Omega/km | X_{t1}^*, \ Omega/km | \tan \phi_{t1} | \gamma_n, p.u. |
|----------------------------------------|----------------|------------------|-----------------|------------------|-----------------------------|------------------|----------------|--------------|
| Steel corner                           | 50×50×5 mm     | 1.65             | 1,263           | 2,08             | 0,339                       | 0,924            | 0,765          |              |
| Aluminum bus                           |                | R_{ts}, \ Omega/km | X_{ts}, \ Omega/km | Z_{ts}, \ Omega/km | X_{t1} + X_{t1}^*, \ Omega/km | X_{t1}^*, \ Omega/km | \tan \phi_{t1} | \gamma_n, p.u. |
| 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            | —                           | —                | —              | 1,646         | 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:

\[
I_n^* = K_n \cdot \frac{I_n}{I_t} = K_n \cdot \frac{1}{n} = K_n \cdot \frac{1}{f_n^*},
\]

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 \( L_d = \infty \) \( K_n = 1 \)); \( I_n, I_t \) 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:

$$
R_{sn} = R_{s1}, \quad X_{sn} = X_{s1} f_n^*;
$$

$$
\gamma_{sn} = \frac{X_{sn}}{R_{sn}} = \frac{X_{s1} f_n^*}{R_{s1}}.
$$

(4)

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

$$
R_{sn} = R_{s1} \sqrt{f_n^*}; \quad X_{sn} = (X_{s1}' + X_{sn}'' + X_{sn}^3) f_n^*;
$$

$$
\gamma_{sn} = \frac{X_{sn}}{R_{sn}} = \frac{X_{s1}' + 0,56 R_{s1} \sqrt{f_n^*} + X_{sn}^3}{R_{s1}}.
$$

(5)

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

$$
I_{pmax}^* = \sqrt{\frac{\sum_{k=0}^{n=6k \pm 1} K_n^2 f_n^{*2}}{\sum_{k=0}^{n=6k \pm 1} K_n^2 f_n^{*2}}},
$$

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:

$$
\gamma_n = \frac{R_{s1}}{R_{s1} \sqrt{f_n^*}} \frac{1 + (\gamma_{s1} f_n^*)^2}{1 + (X_{s1}' + 0,56 R_{s1} \sqrt{f_n^*} + X_{s1}^3)^2} f_n^*.
$$

(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 $f_n^* \geq 7$, relationship (7) with sufficient accuracy can be reduced to the form:

$$
\gamma_n = \frac{X_{s1}'}{0,56 R_{s1} \sqrt{f_n^*}}.
$$

(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, $\gamma_n$ 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:

$$
I_{sn}^* = \frac{I_{sn}}{I_{pmax}} = \frac{1}{1 + \gamma_n} \frac{1}{f_n^*};
$$

$$
I_{tn}^* = \frac{I_{tn}}{I_{pmax}} = \frac{\gamma_n}{1 + \gamma_n} \frac{1}{f_n^*}.
$$

(9)

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.

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

| Bus sizes, mm | $I_{s1}^*$ | $I_{s1}^{\infty}$ | $I_{tn}^{\infty}$ | $I_{tn}^*$ | $I_{tn}^{\infty}$ | $I_{tn}^*$ |
|--------------|------------|-----------------|-----------------|------------|-----------------|------------|
| 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 $I_{tn}^*$ significantly decreases including the decrease in the high-frequency component $I_{tn}^{\infty}$.

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 $\Delta U_{lt}$ is determined taking into account expressions (1), (9):
losses in the trolley with a feed bus as a function of frequency *10% and 5%, respectively.

THDI harmonic, and the relative values of 22% and 16% of the voltage losses at the fundamental frequency is shown in Fig. 4 at cosφ = 0.5 increase significantly which is explained by the influence of the component (cosφ + tgφ1 sinφ1) in expression (10). An increase in ΔUn* is noted for n≥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 I1* and high-frequency components In≥f. 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 cosφ = var, made of the corner 50 × 50 × 5 mm for some combinations of feed at f≤25.

| cosφ, mm | 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  |

As follows from Fig. 4, the relative values of the voltage losses ΔUn* for n≥5 harmonic components at cosφ = 0.5 increase significantly which is explained by the influence of the component (cosφ + tgφ1 sinφ1) in expression (10). An increase in ΔUn* is noted for n≥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 I1* and high-frequency components In≥f. This ratio increases as the cross-section of the feed bus decreases.

Analysis of Table 3 shows that the relative value of the voltage losses of the corner at cosφ = 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 cosφ = 0.5: with 20 × 3 mm bus it increases by 2.022 times, and with 80 × 5 mm bus – by 3.1 times. Therefore, ΔUn in expression (1) should be reduced by an appropriate value.

Dependences ΔU1* = f(cosφ1) in the trolley with feed bus are shown in Fig. 5.

Analysis of the dependence ΔU1* = f(cosφ1) for the trolley with feed bus shows that with a decrease in cosφ1, 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 \( \cos \phi_1 \), 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 \( \Delta P_t \) and in the feed bus \( \Delta P_b \), which are equal, respectively:

\[
\Delta P_t = 3 \cdot \sum_{k=0}^{n=6k+1} R_n I_{in}^2 \quad \text{and} \quad \Delta P_b = 3 \cdot \sum_{k=0}^{n=6k+1} R_s I_{sn}^2 .
\]

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

\[
\Delta P^* = \frac{\Delta P_t^* + \Delta P_b^*}{\Delta P_1^*} = \sum_{k=0}^{n=6k+1} K_n^2 \left( \frac{y_n}{1 + y_n} \right)^2 + \frac{R_1}{R_1} \sum_{k=0}^{n=6k+1} \left( \frac{1}{1 + y_n} \right)^2 K_n^2
\]

(12)

where \( \Delta P_1^* = 3R_1I_{in}^2 \) are the losses in trolleys without feed.

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

![Dependences \( \Delta P^* \) in the trolley with feed bus](image)

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

| Parameter, p.u. | \( \Delta P_{t1}^* \) | \( \Delta P_{t2}^* \) | \( \Delta P_{t3}^* \) | \( \Delta P_{b}^* \) | \( \Delta P_{b2}^* \) | \( \Delta P_{b3}^* \) |
|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Bus sizes, mm  | -              | -              | -              | -              | -              | -              |
| 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         | 0.18             | 0.135          |
| 80×5           | 0.0084         | 0.0044         | 0.0084         | 0.038          | 0.0018         | 0.039            | 0.047          |

Analysis of Table 4 shows that to the first harmonic of the system current, the power losses in the induction feed systems \( \Delta P \) 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 \( (\Delta P_{t2} + \Delta P_{b2}) \) 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 \( n \leq 7 \). 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 mm² 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 \( \cos \phi_1 = 1.0–0.5 \) 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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