Methodological approach to assessing additional active power losses in overhead power lines at non-sinusoidal modes

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Abstract. Non-sinusoidal voltage in electrical networks is one of the most pressing problems in the field of power quality. In non-sinusoidal modes in electrical networks, in addition to losses of active power at the fundamental frequency, i.e. at the 1-st harmonic, active power losses occur at frequencies that are multiples of the fundamental frequency, corresponding to harmonics from 2 to 40. Additional harmonic active power losses increase losses in electrical networks, creating economic damage for both energy companies and consumers. The paper provides a review of the literature on the topic under consideration. A methodological approach is proposed to assess additional active power losses in overhead power lines. Based on the methodological approach, an analysis of the power quality indicators characterizing the non-sinusoidal mode, measured at the point of connection of 110 kV transmission line to the electrical network, was carried out, additional active power losses were determined.

1 Introduction

In the last few years, the federal authorities have begun to actively discuss issues of power quality in Russian electrical networks and adopt legislative documents, which, of course, is caused by the low power quality and the associated economic damage. In 2008, the economic damage caused by the poor power quality, according to a minimum estimate, amounted to 25 billion dollars [1]. Government Decree No. 2425 dated December 23, 2021 [2] indicates that electrical energy is subject to mandatory certification for compliance with the requirements of GOST 32144-2013 [3]. At the beginning of 2022, the Section for Legislative Regulation of Energy Efficiency and Energy Saving of the Expert Council under the State Duma Committee on Energy proposed “Rosseti” PJSC to hold a seminar on amending the Federal Law “On Electric Power Industry” [4, 5]. One of the proposals concerned the establishment of requirements for the power quality and the responsibilities of electricity industry entities and consumers to comply with them. In 2022, the law on amendments to the Federal Law “On Electric Power Industry” was adopted [5]. According to experts from the State Duma, “resolving issues of the power quality will lead to a significant economic effect for power industry entities and consumers, a reduction in irrational spending of budget funds, and an increase in resources that can be directed to the technological modernization of electrical networks” [4]. High power quality is necessary for the digital economy, the task of creating which was set in [7]. The number of electronic equipment, which requires high power quality on the one hand, and, on the other hand, degrades it, is rapidly increasing [8–10]. One of the pressing problems in the field of power quality is voltage non-sinusoidality. The values of power quality indicators, characterizing the distortion of the voltage curve shape, exceed the standards established in [3]. One of the negative consequences of non-sinusoidal voltages is additional losses of active power and energy in power transmission lines. To assess their magnitude, the methodological approach is required. It includes: analysis of measured indicators of power quality and operating parameters characterizing the non-sinusoidal mode at the point of connection of the power transmission line to the electrical network, determination of the resistance of the power transmission line at harmonics from 2 to 40, taking into account changes in temperature environment; determination of the maximum, average and total values of additional active power losses in the power transmission line and other issues. The application of the methodological approach is illustrated by the assessment of additional active power losses in the three-phase 110 kV power transmission line “Mogocha-Davenda” in Trans-Baikal Territory.

2 Review of literature on the assessment of additional active power losses in overhead power lines under non-sinusoidal modes

Power lines are an element of electrical networks. In non-sinusoidal modes, harmonic currents flow in them not only of the 1-st, corresponding to the fundamental frequency, but also of harmonics that are multiples of it. As in any other electrical equipment, that is the element of electrical networks, harmonic currents in power lines cause additional active power losses. Many publications are devoted to determining the value of
active power losses in power transmission lines under non-sinusoidal modes due to the relevance of the problem [10–14].

In [10] it is indicated that when a load with a nonlinear current-voltage characteristic (nonlinear load) is powered from a source with a sinusoidal voltage, the flow of active power of the 1-st harmonic is directed into it. Most of this power is consumed by the load to perform useful work, which in [11] was proposed to be called “working power”. Part of the active power of the 1-st harmonic is converted by the nonlinear load into active powers of harmonics with numbers $n>1$ [10]. In [11], it is proposed to call such harmonic active powers “harmful powers”.

In [9], the question is raised about additional financial losses of the supply network and consumers associated with active harmonic powers. In [12] the accounting of electrical energy in non-sinusoidal modes is considered and the misunderstandings that arise between energy supply organizations and consumers when paying for electrical energy are pointed out. Electric energy meters measure the active energy of not only the 1-st, but also other harmonics. For this reason, energy supply organizations and consumers incur additional costs when paying for electrical energy.

The authors of [13] note that additional harmonic active power losses in electrical system networks can amount to several percent of losses with sinusoidal voltage. In networks of industrial enterprises and in networks of electrified railway transport, losses can reach 10–15%. In [14] the values of active power losses at the fundamental frequency and additional losses at harmonic frequencies are given based on the values of current harmonics measured during the day in a 110 kV power transmission line at “Buryatenergo”. At some points in time, additional losses amounted to 30% of losses at the fundamental frequency. The level of additional active power losses per day amounted to 13.1% of electrical energy losses at the 1-st harmonic.

The authors of [15–19] examined the influence of current harmonics and ambient temperature on the value of resistance of the power transmission line wire.

### 3 Methodological approach to assessing additional active power losses in overhead power lines

In non-sinusoidal modes, the voltage and current in one phase of the electrical network are represented by the expressions

$$u(t) = \sum_{n=1}^{40} U_{un} \sin(n \omega t + \varphi_{un}) ,$$  \hspace{1em} (1)

$$i(t) = \sum_{n=1}^{40} I_{in} \sin(n \omega t + \varphi_{in}) ,$$  \hspace{1em} (2)

where $u(t)$, $i(t)$ – instantaneous values of voltage and current; $n$ – harmonic number; $U_{un}$, $I_{in}$ – amplitude values of voltage and current of the $n$-th harmonic; $\omega = 2\pi f$ – angular frequency, where $f=50$ Hz; $\varphi_{un}$, $\varphi_{in}$ – phase angles of voltage and current of the $n$-th harmonic.

Active power at non-sinusoidal voltage and current in one phase of the electrical network in accordance with [15] is represented as

$$P = U_i I_1 \cos \varphi_1 + \sum_{n=2}^{40} U_{in} I_{in} \cos \varphi_{in} ,$$  \hspace{1em} (3)

or

$$P = P_1 + \sum_{n=2}^{40} P_n = I_1^2 R_1 + \sum_{n=2}^{40} I_{in}^2 R_n ,$$  \hspace{1em} (4)

where $P_1$ – the active power of the 1-st harmonic, $P_n$ – the active power of the $n$-th harmonic; $\varphi_1 = \varphi_{11} - \varphi_{1h}$, $\varphi_n = \varphi_{1n} - \varphi_{nh}$ – the angles between the current and voltage of the 1-st and $n$-th harmonics; $I_1$, $I_n$ – effective values of currents of the 1-st and $n$-th harmonics; $R_1$ and $R_n$ – resistance of the wire for the 1-st and $n$-th harmonics.

Additional losses of active power transmitted through one phase of the power transmission line for one of the harmonics, including the 1-st, are determined by the expression

$$\Delta P_n = I_n^2 R_n ,$$  \hspace{1em} (5)

where $I_n$ – the effective value of the current flowing through the wire of one phase; $R_n$ – the resistance of the wire. The total active losses at harmonics from 2 to 40 can be calculated by the expression

$$\Delta P_{nc} = \sum_{n=2}^{40} I_{in}^2 R_n .$$  \hspace{1em} (6)

The reference literature provides the values of the resistance of the wires for the 1-st harmonic currents. When determining active power losses in the power transmission line for harmonics with number $n>1$, it is necessary to take into account the change in the resistance of the wire caused by the electromagnetic field of different frequencies [20]. When transmitting electrical energy, alternating electric current is distributed unevenly across the cross-section of the wire. The current density has the highest values on the surface of the wire and decreases with distance from the surface into the depth of the wire. The phenomenon of surface effect occurs in the wire, as a result of which the resistance increases. The change in the value of resistance is characterized by the surface effect coefficient. Taking into account the surface effect, expression (6) takes the form

$$\Delta P_{nc} = \sum_{n=2}^{40} I_{in}^2 k_{sh} R_n ,$$  \hspace{1em} (7)

where $k_{sh}$ – the surface effect coefficient at the $n$-th harmonic.

There are various proposals in the literature for calculating the surface effect coefficient [13, 15–17]. In [13, 15, 16], the value of the surface effect coefficient is proposed to be determined as

$$k_{sh} = \frac{0.47}{n} .$$  \hspace{1em} (8)

In [17], under the assumption of a sharp manifestation of the surface effect, i.e. when the length of the electromagnetic wave in the wire is significantly less than the cross-sectional radius of the wire [20], it is proposed to accept that

$$k_{sh} = \frac{1}{n} .$$  \hspace{1em} (9)

In [10] it is noted that the resistance of the power transmission line is influenced by climatic conditions
and line load. However, since power lines are only one of the elements of the electrical network, the parameters of which are constantly changing, “it is hardly necessary to calculate the ultra-precise value of the surface effect that has influence on the characteristics of a limited number of elements.” The author proposes to take a simplified value of the coefficient for practical calculations. In [14], the surface effect is calculated using expression (9).

Publications [18, 19] note that when calculating the parameters of electrical network modes, it is necessary to take into account the influence of the ambient temperature, since the resistance of power transmission line wires changes with temperature changes. As the temperature increases, the resistance of the wire increases, and as the temperature decreases, it decreases. The reference literature provides information for determining the resistance of wires at a temperature of 20°C. For other temperature values, the value of the resistance of the wire is determined by the expression from [18, 19]

\[ R_t = R_{20} + \alpha_T (t - 20), \]

where \( R_{20} \) – the wire resistance at a temperature of 20°C; \( \alpha_T \) – the wire resistance at ambient temperature; \( t \) – the ambient temperature.

Thus, additional active power losses in power line wires under non-sinusoidal modes must be determined taking into account the influence of the surface effect and ambient temperature. The mathematical expression for determining the resistance of the wire, taking into account these two factors, takes the form

\[ R = \sqrt{n} [R_{20} + \alpha_T (t - 20)]. \]

To estimate the value of the total additional losses arising in non-sinusoidal modes, relative to the active power losses of the 1-st harmonic, it is proposed to calculate as

\[ \Delta P_{\alpha n} = \Delta P_{\alpha 1} / R_{20} \times 100\%. \]

The sign \( \Sigma \) means the summation of active power losses, which are calculated from indicators and parameters measured in accordance with [3] at intervals of 10 minutes for seven days. Additional active power losses due to harmonics can be used to calculate possible electrical energy losses for one year as a forecast.

Thus, the proposed methodological approach for assessing and analyzing additional active power losses in the overhead power transmission line in non-sinusoidal mode should include the points below.

1. Analysis of measured indicators of power quality and mode parameters. In accordance with [3], to assess the power quality, measurements are carried out within seven days. The analysis uses: \( K_{\Sigma} \) – total harmonic distortion in phases A, B, C, %; \( K_{f(n)} \) – coefficient of the \( n \)-th harmonic component of voltage in phases A, B, C, %; \( K_{f(n)} \) – coefficient of the \( n \)-th harmonic component of the current in phases A, B, C, %; \( I_1 \) – root mean square value of the positive sequence current of the 1-st harmonic, A.

The current values \( I_n \) for harmonics from 2 to 40 are determined as

\[ I_n = \frac{K_{f(n)} I_1}{100}. \]  

2. Determination of the resistance of the wire, taking into account the surface effect for harmonics from 2 to 40 and the range of changes in ambient temperature.

The values of resistances are calculated using expression (11). Resistance \( R_{20} \) is calculated as

\[ R_{20} = \rho L /\ell, \]

where \( \rho \) – the resistance of the wire at the temperature of 20°C, Ohm/km; \( L \) – length of the power transmission line, km.

3. Calculation of additional active power losses for harmonics from 2 to 40 for the ambient temperature range.

Additional active power losses at each harmonic are calculated using expression (4). The resistance \( R \) of the wire used in (4) is determined by (10), the current \( I_1 \) by (13).

4. Calculation of active power losses of the 1-st harmonic.

Additional losses of active power of the 1-st harmonic for each temperature of a given interval are calculated as

\[ \Delta P_{1} = I^2 R_{1}. \]

5. Calculation of the relative value of the additional active power losses.

The relative value of additional active power losses \( \Delta P_{\alpha 1} \) is determined by (12), where \( \Delta P_{\alpha 1} \) is calculated by (6), \( \Delta P_{1} \) by (15).

6. Calculation of the amount of additional losses of electrical energy per year.

In accordance with [3], the measurement of one indicator of the power quality, characterizing the non-sinusoidal mode, is carried out over the time interval of 10 minutes, which represents 1/6 of an hour. The amount of electrical energy at one time interval is determined as

\[ A W = (1/6) \Delta P_{\alpha n}. \]

Within seven days, 1008 measurements of power quality indicators are made. The amount of electrical energy for seven days will be determined as

\[ A W_{1008} = (1/6) \sum_{i=1}^{1008} \Delta P_{\alpha n(i)}. \]

The predicted value of electrical energy losses for the year can be calculated using the expression

\[ A W = (52/6) \sum_{i=1}^{1008} \Delta P_{\alpha n(i)}. \]
4 Assessment of additional active power losses in the 110 kV power transmission line

The analysis and assessment of additional active power losses in non-sinusoidal mode was carried out for the overhead power transmission line “Mogocha – Davenda”, connected to the 110 kV buses of the Verhnyaya Davenda substation. A fragment of a network diagram with the power transmission line is shown in Fig. 1. Measurements of power quality indicators and mode parameters were carried out at node 73. The following designations are used in the figure: OSG – open switchgear, CSG – closed switchgear. The measurements were carried out with the Resurs-UF2M device [21]. The three-phase 110 kV power transmission line “Mogocha – Davenda” has a length of 41.5 km, made with the SA-95 wire [22]. The ambient temperature during the measurements varied in the range from +19°C to +23°C.

Over the period of seven days, the following indicators were measured in three phases: \( K_U \), \( K_{U(n)} \), \( K_{I(n)}, I_1 \). In Fig. 2 shows the measured values of the indicator \( K_U \) and the standard values \( (K_{U95}, K_{U100}) \) established for it in [3] for 95% and 100% of the measurement time. From the given graphs, it is clear that in all phases the measured indicators exceed both standard values throughout the entire measurement time.

Figure 3 shows a diagram of the values in three phases for odd harmonics for 95% of the measurement time (95% A, 95% B, 95% C), maximum values (max A, max B, max C) and standard values \( (K_{U(n)95}, K_{U(n)100}) \) established for them in [3]. The diagram shows that the standard values are significantly exceeded at the 3-rd, 5-th, 7-th, 9-th, and 11-th harmonics.

Figure 4 shows the measured values of the indicator \( K_{I(n)} \). Standard values for current indicators are not established in [3].
Figure 5 shows the measured values of the positive sequence current of the 1-st harmonic.

Based on the measured values of the indicators $K_{I_1(n)}$ and the current $I_1$, the values of the current harmonics in three phases were determined using expression (11).

The resistance of the wire of one phase of the power transmission line is determined for the ambient temperature range with the step of 20° and for the odd harmonics from 1 to 17. The table shows that with increasing temperature and harmonic number, the resistance of the line increases.

Table 1. Resistance of the power line, Ohm.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Ambient temperature, °C</th>
<th>$n$</th>
<th>$-40$</th>
<th>$-20$</th>
<th>$0$</th>
<th>$+20$</th>
<th>$+40$</th>
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<tbody>
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</tr>
<tr>
<td>$I_1$</td>
<td></td>
<td>1</td>
<td>10.162</td>
<td>11.340</td>
<td>12.517</td>
<td>13.695</td>
<td>14.873</td>
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<td></td>
<td></td>
<td>5</td>
<td>22.723</td>
<td>25.355</td>
<td>27.989</td>
<td>30.623</td>
<td>33.257</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7</td>
<td>26.886</td>
<td>30.000</td>
<td>33.117</td>
<td>36.234</td>
<td>39.350</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9</td>
<td>30.486</td>
<td>34.017</td>
<td>37.551</td>
<td>41.085</td>
<td>44.619</td>
</tr>
<tr>
<td></td>
<td></td>
<td>11</td>
<td>33.704</td>
<td>37.607</td>
<td>41.514</td>
<td>45.421</td>
<td>49.328</td>
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<tr>
<td></td>
<td></td>
<td>13</td>
<td>36.640</td>
<td>40.883</td>
<td>45.131</td>
<td>49.378</td>
<td>53.625</td>
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<td></td>
<td></td>
<td>15</td>
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<td>43.916</td>
<td>48.478</td>
<td>53.041</td>
<td>57.603</td>
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<td>17</td>
<td>41.899</td>
<td>46.752</td>
<td>51.609</td>
<td>56.466</td>
<td>61.323</td>
</tr>
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</table>

Table 2 presents the calculated additional power losses in three phases of the power transmission line $P_{d12}$, $P_{d12}$, $P_{d12}$, as well as $P_{n-max}$, $P_{n-avg}$ – the maximum and average value of harmonic active power losses from the 2-nd to the 40-th of 1008 values for seven days.

Table 2. Additional active power losses, W, %.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Ambient temperature, °C</th>
<th>$n$</th>
<th>$-40$</th>
<th>$-20$</th>
<th>$0$</th>
<th>$+20$</th>
<th>$+40$</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>0.1637</td>
<td>0.1732</td>
<td>0.1820</td>
<td>0.1930</td>
<td>0.2016</td>
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<tr>
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<td>5</td>
<td>165.070</td>
<td>174.640</td>
<td>184.200</td>
<td>194.100</td>
<td>203.260</td>
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<td></td>
<td>9</td>
<td>1.7300</td>
<td>1.8311</td>
<td>1.9310</td>
<td>2.0317</td>
<td>2.1320</td>
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<tr>
<td></td>
<td></td>
<td>11</td>
<td>1744.700</td>
<td>1845.80</td>
<td>1946.90</td>
<td>2048.00</td>
<td>2149.10</td>
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<tr>
<td></td>
<td></td>
<td>17</td>
<td>523.750</td>
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<td>536.640</td>
<td>533.930</td>
<td>549.910</td>
</tr>
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<td>1.93140</td>
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<td>2.1320</td>
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<td>12</td>
<td>1744.700</td>
<td>1845.80</td>
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<td></td>
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<td>19</td>
<td>1744.700</td>
<td>1845.80</td>
<td>1946.90</td>
<td>2047.90</td>
<td>2149.10</td>
</tr>
</tbody>
</table>

Additional active power losses on harmonics in phase A amount to 9.5% of the active power losses on the 1-st harmonic, in phase B 16.3%, in phase C 17.5%. To predict the amount of electrical energy spent on additional active power losses per year, it is necessary to carry out calculations according to (17). At a temperature of +20°C, active power losses are equal to: $\Delta P_{L12} = 222.47$ W, $\Delta P_{L12} = 382.84$ W, $\Delta P_{L12} = 340.57$ W, total losses are 945.87 W. Electrical energy losses for the year will be 50.32 kW·hour. For the power transmission line 41.5 km long, losses are insignificant. If we determine the total losses of electrical energy due to harmonics in 110 kV overhead power lines in Russia, the length of which is almost 200 thousand km, and non-sinusoidal voltage occurs in
all 110 kV electrical networks [9], then their value will be enormous.

**Conclusion**

Reducing additional active power losses in electrical networks is possible by improving the power quality, which requires the adoption of documents regulating the reduction of the generation of current harmonics by nonlinear loads in the electrical network.

At the design stage of power supply systems, it is already necessary to provide for the installation of equipment to eliminate the harmonics of nonlinear load currents.

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