Calculation of balancing and filter compensating devices of the power supply system

A S Lukovenko\textsuperscript{1,2}, V V Kukartsev\textsuperscript{2,3}, V S Tynchenko\textsuperscript{2,3}, A S Mikhalev\textsuperscript{3}, V A Kukartsev\textsuperscript{1} and K A Bashmur\textsuperscript{2}

\textsuperscript{1}The branch of JSC «FGC UES» Krasnoyarsk enterprise MES Siberia, 105/5, Pogranichnikov, Krasnoyarsk, 660111, Russian Federation
\textsuperscript{2}Reshetnev Siberian State University of Science and Technology, 31, Krasnoyarsky Rabochy Av., Krasnoyarsk, 660037, Russian Federation
\textsuperscript{3}Siberian Federal University, 79, Svobodny pr., Krasnoyarsk, 660041, Russian Federation

E-mail: anlukov2.0@mail.ru, vadimond@mail.ru, vlad_saa_2000@mail.ru

Abstract. The problem of reducing the quality of electricity is increasingly arising in the process of increasing energy capacities. The decrease in the quality of electricity can be caused by many different factors that manifest themselves under certain circumstances, and therefore have different solutions for their elimination. The most acute problem is the impact of the electricity quality on the energy parameters of electrical equipment and power receivers in the metallurgical industry and on the railway. The article discusses the features of calculating the asymmetry of currents in a traction AC network. The main moments of calculating the settings of balancing devices are determined. The initial calculation data for balancing devices were taken from the dynamic parameters of one of the operating modes of a power transformer TDTNZh 40 MVA, to which two single-phase loads with a capacity of 17 MVA are connected to terminals AB and 10 MVA to terminals BC. The current of the negative sequence and the coefficient of the negative sequence are calculated, and the filter compensating device is also calculated using the parameters of the balancing device. Based on the calculations, the magnitude of the negative sequence current asymmetry was established and the calculation procedure for the balancing device connected to the traction winding of the transformer with the connection group Y/Δ-11 was implemented.

1. Introduction

In recent years, there have been big problems with the issue of electricity quality, which are caused by non-linear loads of the electric network. When applied directly from a general-purpose network, the electrical system has non-linear loads that have non-sinusoidal harmonic currents [1-2].

Power electronics equipment, such as adjustable drives, controlled rectifiers, arc induction furnaces, electric rolling stocks of railways, are the main non-linear and parametric loads that lead to poor-quality electricity. In addition, the proliferation of non-linear household electrical appliances is growing every day.

Non-sinusoidal harmonic currents that occur when an applied non-linear load can lead to significant distortion of the linear voltage and the shape of the current curve [3-4].
In addition, harmonics can interfere with control, communications or protection, causing an error in the electricity meter, additional losses and a decrease in the life of electrical equipment. Harmonic distortion degrades power factor [2, 5].

Home appliances (relatively low-power receivers) summarized can represent a source of harmonic distortion, because electrical appliances can be used for a long period of time.

2. Calculation of the balancing devices installation

Connecting single-phase consumers to a three-phase network, in which the load is distributed unevenly over the phases, leads to a deterioration in the use of all elements of the three-phase circuit (generators, transformers, power lines, electric motors) [6-8].

It is possible to reduce the load asymmetry and the related asymmetry of voltage and currents if the single-phase load is distributed more evenly between the phases of the three-phase circuit or special balancing devices are used (figure 1) [9, 10].

![Figure 1. K2I(n) dependency graph for a traditional transformer.](image)

Figure 1 shows the dependence K2I(n) without turning on the compensating device (CD) and with the inclusion of CD. The graph corresponds to the condition $\cos \varphi_{\text{lag}} = \cos \varphi_{\text{adv}} = 0.8$, the average value $n = 0.25$ and 4, typical for traction transformers of a single-track section, the inclusion of single-phase CD allows to reduce the asymmetry of currents by 20% [11].

Balancing devices (BD) - technical means that can minimize the currents components of the reverse and zero sequences that occur during asymmetric operating modes of electric networks [12].

The main point in calculating the installation of balancing devices is to determine the voltage of the negative sequence according to formula 1.

$$
\hat{U}_2 = \hat{I}_2 \sum \cdot \frac{z_2 \sum}{2}.
$$

where $\hat{I}_2 \sum$ - equivalent negative sequence current due to unbalanced loads;

$\frac{z_2 \sum}{2}$ - resistance of the network’s reverse sequence.
The negative sequence current $I_2$ and its initial phase $\varphi_{I2}$ when connecting three single-phase loads to the line voltage $AB$, $BC$, $CA$ in the traction power supply system can be determined from formulas 2 and 3.

$$I_2 = I_{2\Sigma} = \frac{\sqrt{3}}{3} \cdot \sqrt{I_{AB}^2 + I_{BC}^2 + I_{CA}^2 - I_{AB} \cdot I_{BC} - I_{BC} \cdot I_{CA} - I_{CA} \cdot I_{AB}},$$ \hspace{1cm} (2)

$$\varphi_{I2} = \arctg \frac{\sqrt{3}}{3} \cdot \frac{I_{AB} + I_{BC} - 2 \cdot I_{CA}}{I_{AB} - I_{BC}}.$$ \hspace{1cm} (3)

When setting the full load powers, expressions (2) and (3) are converted to:

$$I_2 = \frac{\sqrt{3}}{3 \cdot U_{NOM}} \cdot \sqrt{S_{AB}^2 + S_{BC}^2 + S_{CA}^2 - S_{AB} \cdot S_{BC} - S_{BC} \cdot S_{CA} - S_{CA} \cdot S_{AB}},$$ \hspace{1cm} (4)

$$\varphi_{I2} = \arctg \frac{\sqrt{3}}{3} \cdot \frac{S_{AB} + S_{BC} - 2 \cdot S_{CA}}{S_{AB} - S_{BC}}.$$ \hspace{1cm} (5)

In the presence of significant asymmetry, for example, when two single-phase loads on the line voltage $AB$ and $BC$ are turned on, these expressions can be converted to a simpler form:

$$I_2 = I_{2\Sigma} = \frac{\sqrt{3}}{3 \cdot U_{NOM}} \cdot \sqrt{S_{AB}^2 + S_{BC}^2 - S_{AB} \cdot S_{BC}},$$ \hspace{1cm} (6)

$$\varphi_{I2} = \varphi_{I2\Sigma} = \arctg \frac{\sqrt{3}}{3} \cdot \frac{S_{AB} + S_{BC}}{S_{AB} - S_{BC}}.$$ \hspace{1cm} (7)

Using the obtained expressions and the asymmetry data of the traction substation currents, the balancing devices could be calculated in order to reduce the asymmetry current in the traction network. The source data is the dynamic parameters of one of the operating modes of the power transformer TDTNZH 40 MVA, to which two single-phase loads with a capacity of 17 MVA are connected to terminals $AB$ and $10$ MVA to terminals $BC$; the loads are connected to the line voltage of the transformer $U_{AB}$ and $U_{BC}$ respectively. The voltage on the transformer tires is 27.5 kV. For the given parameters, the value of the asymmetry coefficient $\varepsilon_2$ and the parameters of the balancing device could be calculated.

According to expressions (6) and (7), the current of the negative sequence of the asymmetric load is:

$$I_2 = I_{2\Sigma} = \frac{\sqrt{3}}{3 \cdot 27.5} \cdot \sqrt{17000^2 + 10000^2 - 17000 \cdot 10000} = 296 \, \text{kA},$$

$$\varphi_2 = \varphi_{I2\Sigma} = \arctg \frac{\sqrt{3}}{3} \cdot \frac{17 + 10}{17 - 10} = 115.7^\circ \approx 116^\circ.$$

Then the coefficient of the negative sequence will take the value:

$$\varepsilon_2 = \frac{\sqrt{3} \cdot I_2 \cdot U_{NOM}}{S_K} \cdot 100\% = \frac{\sqrt{3} \cdot 296 \cdot 27.5}{40000} \cdot 100 = 35\%.$$
To eliminate the asymmetry, we will calculate the capacity of the capacitor bank (CB):

\[ Q_\Sigma = \sqrt{3} \cdot I_2 \cdot U_{NOM} \cdot (\sqrt{3} \cdot \sin \phi_\Sigma - \cos \phi_\Sigma) = \sqrt{3} \cdot 296 \cdot 27.5 \cdot (\sqrt{3} \cdot \sin 116^\circ - \cos 116^\circ) = 29478 \ \text{var} \]

\[ \cos 116^\circ = 29.48 \ \text{K var} = 29.48 \ \text{M var} \]

We determine the distribution of the capacitance of the capacitor bank to completely eliminate the asymmetry:

\[ Q_{BC} = \frac{2}{3 - \sqrt{3} \cdot \text{ctg} \phi_\Sigma} \cdot Q_\Sigma = \frac{2}{3 - \sqrt{3} \cdot \text{ctg} 116^\circ} \cdot 29.48 = 15.34 \ \text{M var} \]

\[ Q_{CA} = Q_\Sigma - Q_{BC} = 29.48 - 15.34 = 14.14 \ \text{M var} \]

Perform a validation of the solution. To do this, we determine the current of the negative sequence of the balancing device:

\[ I_{2CB} = \frac{\sqrt{3}}{3} \cdot U_{NOM} \cdot \sqrt{Q_{BC}^2 + Q_{CA}^2 - Q_{BC} \cdot Q_{CA}} = \frac{\sqrt{3}}{3} \cdot 27.5 \cdot \sqrt{15340^2 + 14140^2 - 15340 \cdot 14140} = 295.53 \ \text{kA} \]

The initial phase of the current balancing device:

\[ \phi_{2CB} = \arctg \frac{\sqrt{3}}{3} \cdot \frac{2 \cdot Q_{CA} - Q_{BC}}{Q_{BC}} - \phi_{cb} = \arctg \frac{\sqrt{3}}{3} \cdot \frac{2 \cdot 14.14 - 15.34}{15.34} + 90^\circ = 115.31^\circ \]

\[ \phi_{2CB} - \phi_2 = 115.31^\circ - 115.7^\circ = -0.39^\circ \]

3. Calculation of filter compensating devices

Let’s calculate the filter compensating device using the parameters of the balancing device.

Let’s take harmonic currents, for example, \( I_5 = 145 \ \text{A}, I_7 = 122 \ \text{A} \). Let the relative values of the higher harmonics (HG) voltages \( U_{5r} = 5.8\%, U_{7r} = 4.9\% \).

The selected capacitors are included in the filters included on the voltage of the AC and CA and tuned to the harmonic frequency \( \nu_p = 5 \).

To determine the residual voltage of the 9th harmonic, we find the values of the coefficients \( \rho_{BC} \) and \( \rho_{CA} \):

\[ k_{p_{BC}} = \frac{Q_{BC}}{S_k} = \frac{15.34}{40} = 0.38 \]

\[ k_{p_{CA}} = \frac{Q_{CA}}{S_k} = \frac{14.14}{40} = 0.35 \]

\[ \rho_{BC} = \frac{1}{1 + \frac{3 \cdot k_{p_{BC}} \cdot \nu_p^2}{1 - \nu_p^2}} = \frac{1}{1 + \frac{3 \cdot 0.38 \cdot 5^2}{1 - 5^2}} = 0.024 \]
\[
\rho_{CA} = \frac{1}{1 + \frac{3 \cdot k_p \cdot \rho_{CA}}{1 - v_{q_p}^2}} = \frac{1}{1 + \frac{3 \cdot 0.35 \cdot 5^2}{1 - \left(\frac{5}{7}\right)^2}} = 0.026.
\]

7th harmonic residual voltage:
\[
U_{7_{AB}} = \frac{\sqrt{3 \cdot \left(\rho_{BC}^2 + \rho_{CA}^2 + \rho_{BC} \cdot \rho_{CA}\right)}}{1 + \rho_{BC} + \rho_{CA}} \cdot U_7, \quad U_7 = \frac{\sqrt{3 \cdot (0.024^2 + 0.026^2 + 0.024 \cdot 0.026)}}{1 + 0.024 + 0.026} \cdot 0.49 = 0.35\%.
\]
\[
U_{7_{BC}} = \rho_{BC} \cdot \frac{\sqrt{3 \cdot (1 + \rho_{CA} + \rho_{CA}^2)}}{1 + \rho_{BC} + \rho_{CA}} \cdot U_7 = \frac{0.024 \cdot \sqrt{3 \cdot (1 + 0.026 + 0.026^2)}}{1 + 0.024 + 0.026} \cdot 0.49 = 0.20\%.
\]
\[
U_{7_{CA}} = \rho_{CA} \cdot \frac{\sqrt{3 \cdot (1 + \rho_{BC} + \rho_{BC}^2)}}{1 + \rho_{BC} + \rho_{CA}} \cdot U_7 = \frac{0.026 \cdot \sqrt{3 \cdot (1 + 0.024 + 0.024^2)}}{1 + 0.024 + 0.026} \cdot 0.49 = 0.21\%.
\]

The fraction of current flowing through each filter arm:
\[
\sigma_{7_{BC}} = \frac{1 + 0.5 \cdot (\rho_{CA} + \rho_{CA}^2)}{1 + \rho_{BC} + \rho_{CA}} = 0.96,
\]
\[
\sigma_{7_{CA}} = \frac{1 + 0.5 \cdot (\rho_{BC} + \rho_{BC}^2)}{1 + \rho_{BC} + \rho_{CA}} = 0.96.
\]

Total harmonic current flowing through the filter:
CB power must satisfy the condition:
\[
Q_{BC(CA)} \geq 1,2 \cdot U_{NOM \ CB} \cdot I_{v \sum}^{BC(CA)}, \quad (8)
\]
\[
2 \cdot 27.5 \cdot 0.186 = 0.01023 \ M \ var.
\]

According to the condition for choosing the CB \(Q_{BC} = 15.36 \ Mvar, \ Q_{CA} = 14.14 \ Mvar\), it satisfies condition (8), the calculation of the current of the negative sequence \(I_2\) and its initial phase \(\phi_{I2}\) satisfies the verification of the correctness of the solution, there is no current overload of the CB and the balancing device is selected correctly.

4. Conclusion
When passing heavy trains there is a strong current consumption, which leads to asymmetry of currents and voltages in the traction network, additional losses, heating of conductors. This mode adversely affects the operation of the power transformer traction substation.

When using the developed model for calculating the negative sequence current, the magnitude of the currents and voltages asymmetry in the AC traction network decreases, and the power of the capacitor bank must satisfy the condition \(Q_{BC(CA)} \geq 1,2 \cdot U_{NOM \ CB} \cdot I_{v \sum}^{BC(CA)}\), that is achieved by turning on the balancing device.
Connecting a balancing device allows us to reduce the negative sequence current, adjust the balancing device to 7 harmonic currents and compensate reactive power without changing the connection diagram of the star-delta power transformer.

References
[1] Iagar A, Popa G and Dinis C 2014 The influence of home nonlinear electric equipment operating modes on power quality WSEAS Transactions on Systems 13 357-67
[2] Tarasov E V, Bulyga L L, Ushakov V Ya and Kharlov N N 2015 Additional energy losses from asymmetric and non-sinusoidal current in an electrical facility and methods of their reduction MATEC Web of Conferences 37 173-9
[3] Chizhikova N V 2013 The influence of the asymmetric mode of the electric network on the work of consumers of electric energy Bulletin of the IGEU 6 1-5
[4] Dickson K 2009 Reduction of power losses using phase load balancing method in power networks Proceedings of the World Congress on Engineering and Computer Science 1 124-9
[5] Khalilov A Zh 2016 Analysis and modeling of asymmetrical operating modes of arc steel-smelting furnaces Young scientist 23 106-9
[6] Khristinich R M and Lukovenko A S 2015 Calculation of asymmetric modes of traction AC network Scientific problems of transport in Siberia and the Far East 2 192-5
[7] Bochev A S 2002 Symmetrization of electric traction loads using compensating devices Bulletin of the Rostov State Transport University 1 55-7
[8] Naumov I V, Shpak D A and Ivanov D A 2008 Control of the operating modes of an induction motor in conditions of asymmetry of the supply voltage Bulletin of the Irkutsk State Agricultural Academy 30 90-5
[9] Marquardt C G 1982 Electricity supply of electrified railways (Moscow, Transport)
[10] Seronosov V V 2006 Improving the conditions for balancing three-phase current loads at traction substations of single-track sections Bulletin of the Rostov State University of Railway Engineering 4 123-7
[11] Naumov I V, Podyachikh S V and Ivanov D A 2011 Optimization of power of balancing devices in distribution networks 0.38 kV Bulletin of the Irkutsk State Agricultural Academy 42 93-9
[12] Yagup V G 2014 Calculation of the parameters of a balancing device for an alternating current traction substation on a visual model East European Journal of Advanced Technologies 8(70) 23-8