Simulation of non-sinusoidal modes in railway power supply systems during movement of high-speed trains

A V Kryukov, A V Cherepanov, A R Shafikov and E S Bezridnyj

1Transport Electric Power Engineering department, Irkutsk State Transport University, 15, Chernyshevsky St., Irkutsk, 664074
2Power Supply and Electrical Equipment department, Irkutsk National Research Technical University, 83, Lermontov St., Irkutsk, 664074

E-mail: and_kryukov@mail.ru, smart_grid@mail.ru, alshaficov1@mail.ru, bezrik4471@mail.ru

Abstract. Rectifier locomotives have non-linear current-voltage characteristics and generate higher harmonics (HH) in the power supply networks, which is accompanied by the following negative effects: reduced equipment service life, distortion of electricity metering, occurrence of resonant processes, etc. Therefore, the problem of reducing the levels of harmonic distortion in the networks adjacent to the traction substations of the AC railways is of increased relevance. The level of HH generation depends on the design features of electric locomotives. Electric stock with zone-and-phase regulation creates high harmonic distortions, which results in increased losses, increased electromagnetic effects on adjacent power and telecommunication lines and reduced reliability of power supply. Electric locomotives with asynchronous traction motors (ATM) connected via 4q–S converters virtually do not distort the sinusoidality of the current curve. To measure the degree of reduction of harmonic distortion during the movement of locomotives with ATM, simulation modeling of non-sinusoidal modes of a typical 25 kV traction power supply system was carried out for two variants of the locomotives used: 1) VL-80R with DC motors; 2) UTY–1 with asynchronous traction motors. The methodology for determining non-sinusoidal modes is based on the technology of modeling electric power systems (EPS) in phase coordinates; at the same time, the models of EPS elements were formed as lattice schemes characterized by a fully connected topology. The parameters of these circuits can be recalculated to the frequencies of HH. The proposed approach is universal and can be used to study non-sinusoidal modes in existing and future traction power supply systems. The simulation results showed that the problem of increased harmonic distortion in the networks feeding the traction substations can be completely solved by replacing the acting locomotives with new-generation electric locomotives with asynchronous electric drives and four-quadrant converters.

1. Introduction

Rectifier locomotives have non-linear current-voltage characteristics and generate higher harmonics (HH), which can penetrate into external networks and areas of power supply to non-traction consumers [1]. The flow of HH currents is accompanied by the following negative effects [2–16]:

• additional heat insulation of transformer windings, leading to their service life reduction;
• accelerated thermal aging of the insulation of stator windings of asynchronous electric motors;
- increase in measurement errors of power consumption parameters, which can result in an unacceptable degradation in the accuracy of electricity metering;
- a breakage of the neutral wire due to contact burning-off with a significant level of harmonics with numbers that are multiples of three; this can result in the failure of some power consuming units due to the emergence of increased voltages at their terminals;
- resonant effects at higher harmonic frequencies, creating severe problems for electrical equipment;
- increased levels of induced voltages in power and communication lines passing near the railway.

Therefore, the problem of reducing the levels of harmonic distortion in the networks adjacent to the traction substations (TS) of the AC railways is of increased relevance.

The level of HH generation depends on the design features of electric locomotives. To illustrate this position, Fig. 1 shows the harmonic spectra of VL-80R electric locomotives with zone-and-phase regulation and most advanced UTY-1 with asynchronous engines and four-quadrant converters [17].

Electric stock (ES) with DC engines and zone-and-phase regulation creates significant harmonic distortion; this increases the power loss in the electric traction network (ETN), which results in additional heating of the equipment and the deterioration of energy performance.

Electric locomotives with ATM, equipped with 4q – S converters, virtually do not distort the sinusoidal current, have lower reactive power consumption and reduce the levels of harmonic voltage components at the nodal points of the supply networks, which contributes to their energy efficiency.

To measure the degree of reduction of harmonic distortion during the movement of locomotives with ATM, simulation modeling of non-sinusoidal modes of a typical 25 kV traction power supply system was carried out for two variants of the locomotives used: VL-80R with DC motors and zone-and-phase regulation; UTY–1 with asynchronous traction motors connected to four-quadrant (4q – S) converters.

![Figure 1. VL-80R and UTY-1 spectra comparison](image)

2. The simulation technique
The method of determining non-sinusoidal modes is based on the technology of modeling electric power systems (EPS) in phase coordinates [18–23]; at the same time, the models of EPS elements were formed as lattice schemes were characterized by a fully connected topology. The parameters of these circuits can be recalculated to the frequencies of HH.

During simulation modes at HH frequencies, there are systems of equations of fairly high dimension to be solved [20]:

$$\mathbf{F}[\mathbf{X}(f_i)]=\mathbf{0}; \; \mathbf{Y}(f_1)\mathbf{U}(f_2)=\mathbf{I}(f_2); \; \mathbf{Y}(f_3)\mathbf{U}(f_4)=\mathbf{I}(f_3); \cdots \; \mathbf{Y}(f_m)\mathbf{U}(f_n)=\mathbf{I}(f_n),$$
where \( f_i \) is the higher harmonic frequencies, \( i = 2, 3, ..., 40; f = f_0 = 50 \text{ Hz} \); \( Y(f_i) \) is the matrix of the conductivities of the design model of the power supply system, whose elements are determined by the frequencies \( f_i \); \( U(f_i) \) is the desired voltage at the nodal points of the network; \( I(f_i) \) is the vector of current HH sources.

Determination of short circuit (SC) and idle run (IR) parameters of transformers at higher harmonic frequencies has some unique features. The scattering reactances that are defined for \( f = 50 \text{ Hz} \) must be recalculated for the HH frequencies. Short-circuit losses are also corrected in proportion to the frequencies \( f_i \). Idle run losses are inexpedient to increase, as induction decreases in the magnetic circuit with frequency growth, which leads to loss reduction.

One of the schemes for the loads proposed in [8] is used when calculating HH. It is parallel with the resistances, which are determined by the formulas:

\[
R_p = \frac{U^2}{P}, \quad X_p = \nu \frac{U^2}{Q},
\]

where \( U \) is the voltage at the load terminals at \( f = 50 \text{ Hz} \), \( \nu \) is the harmonic number.

To calculate the currents of stationary sources of harmonics, one can use the following expression [8]:

\[
I_v = \frac{2\sqrt{3} I_d}{\pi k_v \nu}
\]

where \( \nu = kp \pm 1 \); \( p = 6, 12 \) or 24 is the number of transducer pulsations, \( k = 1, 2, 3 ... \).

For a single-phase rectifier converter \((p = 2)\) harmonic currents are calculated based on the ratio:

\[
I_v = \frac{4I_d}{\pi k_v \nu},
\]

where \( I_d \) is the rectified current, which is determined based on the set value of the main harmonic current; phase angles of current harmonics are calculated as follows:

\[
\psi_v = \nu \psi,
\]

where \( \psi \) is the phase of the main frequency current.

It is possible to set the currents of stationary sources of harmonics on the basis of reference data or measurement results.

In accordance with the requirements of GOST 32144-2013, 40 harmonics are taken into account when calculating non-sinusoidal modes. The voltage and current waveforms are calculated using the expression:

\[
u(t) = \sum_{k=1}^{40} \sqrt{2} U_k \sin(\omega k t + \psi_k).
\]

3. Simulation results

The simulation was carried out using the Fazonord software package for a typical 25 kV traction power supply system (Fig. 2). A double-track section with a length of 120 km was considered. The traction power supply system included three intersubstation zones 40 km long.

The simulation was carried out with the movement of four up and down freight trains weighing 6384 tons in two options:

1) locomotives VL-80R with DC engines and zone-and-phase regulation are used for the movement of trains;
2) UTY-1 locomotives with ATM and four-quadrant converters are used [17].

Schematic diagrams of electric stock are shown in Fig. 3. The train schedule is shown in Figure 4, and the dependences characterizing the current consumption of trains are shown in Fig. 5. Non-sinusoidal indicators were determined on 110 kV buses of the traction substation number 4.

The results based on the modeling are shown in table 1 and in fig. 6, 7.
Figure 2. Railway power supply system scheme

Figure 3. ES schemes [17]: a – VL-80R; b – UTY-1; T – transformer; B – rectifying installation; I – smoothing inductor; DCTM is DC traction motor; ATM – asynchronous traction motor; AVI-PWM – autonomous voltage inverter with pulse-width modulation; 4q-S – four-quadrant converter; C is capacitive filter

Figure 4. Train movement schedule
Figure 5. Current consumption of trains weighing 6384 t: a – down trains; b – up trains

Table 1. Total harmonic coefficients on 220 kV buses TP -4

| Phase | VL-80R | UTY-1 | γk_U |
|-------|--------|-------|-------|
|       | Average value | Maximum | Average value | Maximum | Average value | Maximum |
| A     | 6.61   | 9.25  | 0.43  | 0.81  | 15.39  | 11.48  |
| B     | 13.21  | 25.61 | 0.70  | 1.68  | 18.74  | 15.24  |
| C     | 12.24  | 21.44 | 0.53  | 1.14  | 23.11  | 18.82  |

The analysis of results presented in table 1 and fig. 7 allows for the following conclusions:

1. During train traffic with locomotives VL-80R, the levels of harmonic components on 110-kV TP-4 buses far exceed the maximum permissible values of 3 %. To reduce the non-sinusoidality, the use of expensive means is required, such as passive and active filters [18].

2. During train traffic with UTY-1 electric locomotives, the values k_U do not exceed the values of 2 % normally acceptable by GOST 32114-2013. Harmonic distortion levels, in comparison with the movement of electric locomotives VL-80R, are reduced 11..25 times.
Figure 6. Coefficients $k_U$ on 110kV TP-4 buses in time: a – phase A; b – phase B; c – phase C
Figure 7. Voltage waveforms on 110 kV TP-4 buses: a – phase A; b – phase B; c – phase C

Thus, the problem of increased harmonic distortion level in the networks adjacent to the traction substations of main railways can be completely solved by replacing the existing electric stock to most advanced electric locomotives with asynchronous electric drives and four-quadrant converters.

4. Conclusion
Based on computer simulation of non-sinusoidal modes of a typical 25 kV power supply system in the Fazonord-APC software package, it was shown that, using most advanced electric stock with asynchronous motors and four-quadrant converters, the harmonic distortion levels in the networks, adjacent to the traction substations, do not exceed standard values.
References

[1] Marquardt K G 1982 Electric power supply of electrified railways (Moscow: Transport Publ.)
[2] Timofeev D V 1965 Modes in electrical systems with traction loads (Moscow, Leningrad: Energija Publ.)
[3] Steimel A 2008 Electric traction motive power and energy supply. Basics and practical experience. (Munchen: Oldenbourg Industrieverlag)
[4] Biesenack H, Braun E, George G et al 2006 Energieversorgung elektrischer bannen (Wiesbaden: B.G. Teubner Verlag)
[5] Arrilaga D, Bradley D and Bodger P 1990 Harmonics in electrical systems (Moscow: Energoatomizdat Publ.)
[6] Dolinger S Yu et al 2013 Assessment of additional power losses from the reduction of the quality of electric energy in the elements of power supply systems Omsk Scientific Herald 2(120) 178–83
[7] Zhezhelenko I V, Saenko Yu L and Gorpinich A V 2008 The impact of power quality on electrical equipment service life reduction and the reliability deterioration Electrical engineering 3 14–20
[8] Zhezhelenko I V 2000 Higher harmonics in power supply systems of industrial enterprises (Moscow: Energoatomizdat Publ.)
[9] Kargin S V, Krasnova A N and Bekbulatov R R 2012 Energy quality management in general purpose distribution networks (Moscow: Energopress Publ.)
[10] Kartashov I I and Zuev E N 2000 Power quality in power supply systems. Ways to control and ensure it. (Moscow: MEI Publ.)
[11] Kartashov I I et al 2006 Electricity Quality Management (Moscow: MEI Publ.)
[12] Tretyakov E A 2013 Quality management of electrical energy in the railway distribution networks (Omsk: OmGUPS Publ.) 195 p
[13] Shidlovsky A K and Kuznetsov V G 1985 Improving the quality of energy in electrical networks (Kiev: Naukova Dumka Publ.)
[14] Shidlovsky A K, Novsky V A and Kaplychnyy N N Stabilizing electrical energy parameters in distribution networks (Kiev: Naukova Dumka Publ.)
[15] Dolgov A P, Kandakov S A and Zakaryukin V P 2011 Improving the electric power quality in the systems of external power supply of the Eastern Siberia railways (St. Petersburg: Electrification and development of the infrastructure for train traction power supply in rail transport) pp 37–8
[16] Sudnova V V 2000 Electric power quality (Moscow: Energoservis Publ.)
[17] Burkov A T and Mirsaitov M M 2016 Modes of electric traction network in operation of electric locomotives VL-80R and UTY-1 Modern technologies for transport 2 pp 146–60
[18] Zakaryukin V P, Kryukov A V and Cherepanov A V 2018 Intelligent Traction Power Supply System Advances in Intelligent Systems and Computing 692 91–9
[19] Cherepanov A V Zakaryukin V P and Kryukov A V 2018 Modeling of traction power supply systems for movement of high-speed trains MATEC Web of Conf.: Polytransport Systems-2018 216(02006) 1–7
[20] Zakaryukin V P and Kryukov A V 2005 Complex non-symmetrical modes in electrical systems (Irkutsk: Irkutsk university Publ.)
[21] Zakaryukin V P, Kryukov A V, Avdienko I M and Bezridniy E S 2017 Modeling modes of traction power supply systems when driving high-speed trains Modern technologies System analysis Modeling 3 126–35
[22] Zakaryukin V P, Kryukov A V and Avdienko I M. 2016 Elimination of asymmetry in electrical networks supplying traction substations of railways Modern technologies System analysis Modeling No 1 189–95
[23] Zakaryukin V P and Kryukov A V 2013 Multifunctional approach to modeling of electric power systems Modern technologies System analysis Modeling 4100–7