PROBLEMY KOLEJNICTWA
RAILWAY REPORT Issue 188 (September 2020)
INSTYTUT KOLEJNICTWA
DOI: 10.36137/1881E
ISSN 0552-2145 (print) ISSN 2544-9451 (on-line)

Increasing Power Supply Efficiency for "Two Wire-Rail" Line Consumers

Dmytro O. BOSYI[1] , Denys R. ZEMSKYI[2]

Summary

The article is devoted to the problem of non-traction consumers power supply of AC railways. The low efficiency of energy transfer is caused by the design of a non-traction power supply line. The absence of bilateral power is typical for non-traction network 27,5 kV which consist of "two wire-rail" lines. This line is outdated technology, which does not correspond to modern requirements on the power quality, but used on AC railways with three-phase traction transformers. The purpose of the article is to investigate the methods of power supply improvements for non-traction consumers in terms of voltage unbalance, harmonic distortions and energy losses. Connection of the phasing device to delta winding traction transformer for bilateral supplying non-traction customers from network 27,5 kV is suggested in the article. The implementation of a method to increase the efficiency of electricity transmission in the non-traction network power supply allows to reduce power losses from 720 MWh / year to 441 MWh / year, the voltage unbalance from 1,9% to 1,3% and the total harmonic distortion from 8 % to 6 % respectively. Additionally, investment attractiveness of the decision was evaluated.

Keywords: non-traction customers, two wire-rail line, phase coordinates, AC railway, power quality

1. Introduction

The modern stage of social development is accompanied by the introduction in household activities and industry of sensitive to quality power equipment, that are under the electromagnetic impact of devices whit mode impact for voltage balance and harmonic distortion generation [1, 7, 8, 11].

The non-traction power supply is mainly referred to all the power supply subsystems put in place in order to feed all the electrical loads and services not directly related with traction. Such power supply subsystems usually feed [4, 5]:

- signaling and telecoms equipment placed in station buildings or wayside,
- station equipment loads (e.g. lighting),
- depot equipment loads,
- tunnel wayside equipment; other operational,
- auxiliary equipment, water pumping.

The electric supply for non-traction loads is obtained from local distribution grid or from railway distribution power lines. In some cases, the power of the traction load is carried out from the contact network [9].

The design of the non-traction power supply system depends on the principles of railway electrification in different countries. Using three-phase traction transformers is typical for post-Soviet countries, where the traction transformers also feed power to the surrounding region. Their non-traction consumers are owned by the railway as well as by other entities and domestic customers by which the supplier transmits electricity using the railway networks. Therefore, railway companies are often associated with the sale of electricity (for example, JSC "Ukrzaliznytsia", JSCo "RZD"). In other countries, single-phase transformers, Scott transformers, V connection transformers are common in AC traction systems at mains frequency, therefore three-phase transformers are installed there additionally.

Power supply system based on the "two-wire – rail" (TWR) lines is common at the AC railways with a total length of about 30 000 kilometers. Russia, Ukraine,

[1] Assoc. Prof.; Dnipro National University of Railway Transport named after academician V. Lazaryan, Department of Intelligent Power Supply Systems, Dnipro, Ukraine; e-mail: dbs@mm.st.
[2] Postgraduate, Dnipro National University of Railway Transport named after academician V. Lazaryan Department of Intelligent Power Supply Systems, Dnipro, Ukraine; e-mail: d.zemskyi@ukr.net.

Kazakhstan are the first at the top of the longest AC railways in post-Soviet countries list.

The rolling stock of the railways is a source of higher harmonics of the current, and AC railway with a single-phase supply system where used frequency of public grid causes a voltage asymmetry in a three-phase grid for non-traction customers. Often, overhead power lines are mounted on the catenary mast what increases of probability exceeding the quality indicators boundaries. There are longitudinal power line 10 kV and the TWR line 27,5 kV.

The electromagnetic field strongly affects the TWR line voltage due to the short distance to the catenary. In addition, rolling stock current passes through one phase of the TWR line which is rail therefore, the power quality is deteriorating further.

Another drawback of the line is the inability of bilateral power supply to the consumers as a result of different substation connection schemes to the power line (Fig. 1) which is needed to reduce the voltage unbalance in the three-phase grid. In the past, such a situation was advantageous due to savings on the development of the public electricity network, cheap energy resources in the country and planned economy. Today, interest in the problem of electromagnetic compatibility and consumer competence remains growing [11]. The owner of the power grid is obliged to ensure the proper level of electromagnetic compatibility. Otherwise, owner of the power grid will be fined in favor of consumers who are powered by its networks. The Ukrainian railway worsens the quality of electricity with its own equipment (TWR lines and electric locomotives), therefore, it is responsible for the low electromagnetic compatibility of networks with consumers. Following the liberal reform of the electricity market, electricity companies are offering connections to their supply networks. Therefore, the railway runs the risk of losing non-traction consumers due to the unsatisfactory quality of electricity.

There are known studies of the power transmission process by the TWR line which is reduced to the analysis of asymmetry and harmonic distortions voltage problem, leaving open the question of bilateral power supply to consumers [10, 13–15]. Well-known that providing bilateral power supply reduces the loss of energy in the line and the probability of a power interruption.

Therefore, the article's purpose is to increase efficiency transmission of electricity from substation bus 27.5 kV to the non-traction consumers, and efficiency might be estimated by power losses and the degree of power quality poor. So, tasks of investigating should be as follows. Develop a method of providing bilateral power supply to the consumer. Compare the indices of asymmetry, non-sinusoidal voltage, and power losses in the 27.5 kV grid with bilateral and unilateral power supply to the consumer. Determine the estimated payback time of the proposed method.

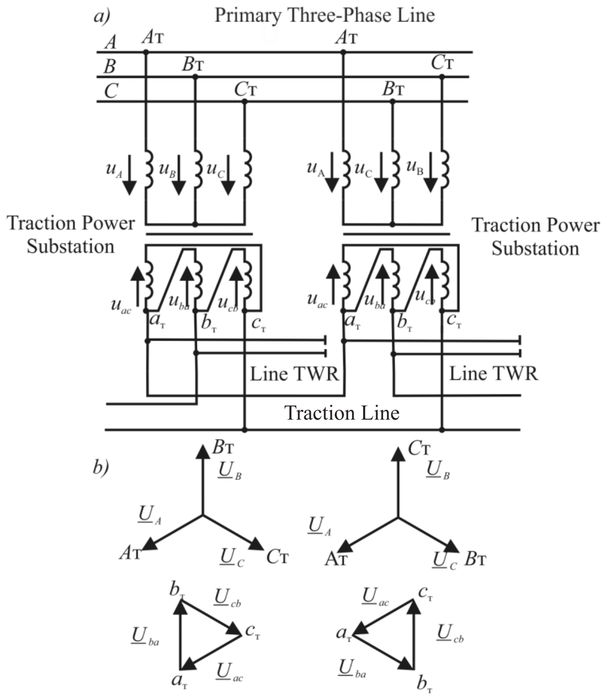


Fig. 1. Railway Electrification System and High Voltage Transmission System: a) schematic diagram b) vector diagrams of transformer windings [author' own work]

2. Method of providing bilateral power to the consumers of TWR lines

The implementation of bilateral power is possible using a phasing device (PD) that converts the systems of voltage vectors at the input terminals to the given type at the output terminals.

Six options for connecting the traction transformers terminals to the power supply network was study, schemes connection is shown in Fig. 2 (1). Vector diagrams of linear voltages at secondary windings in compliance with transformers are shown in Fig. 3 (3). It is proposed to use a transformer as a phasing device (PD), the method of joining the PD to bus 27,5 kV, and the scheme of its windings connection is shown in Fig. 2, 3.

The analysis of change voltage vectors systems during the transformation has shown that PD may be a transformer with star-delta connection windings and a changeable phasor group from 11 to 1. The ratio of turns in the winding is equal to the root of $\sqrt{3}$. The method of providing bilateral power to the consumer is presented as a table (Table 1).

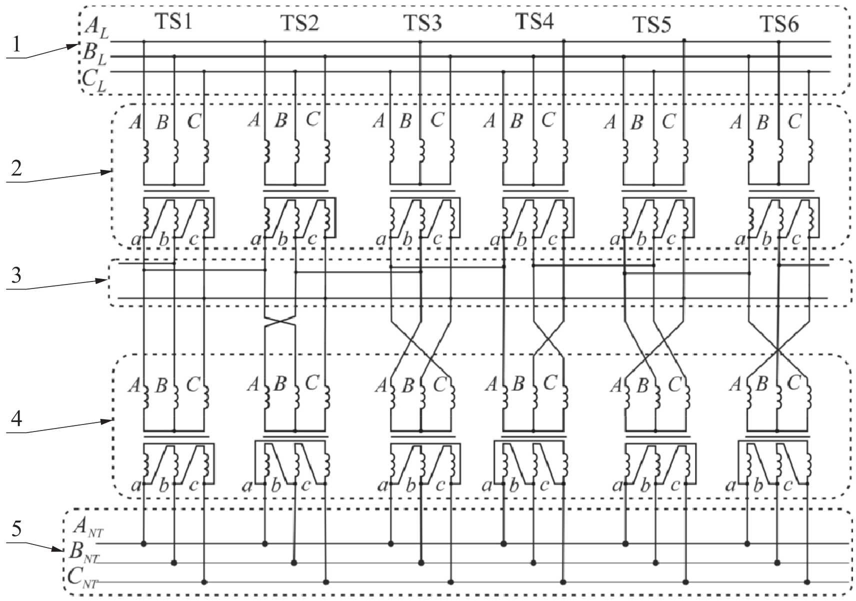


Fig. 2. Connection of the phasing device to delta winding traction transformer: 1) connection schemes of traction substations (TS) to the primary three-phase line (public network), 2) schemes of traction transformers, 3) connection schemes of traction network and to transformer windings, 4) schemes of phasing devices, 5) connection phasing devices and non-traction power supply three-phase line [author’ own work]

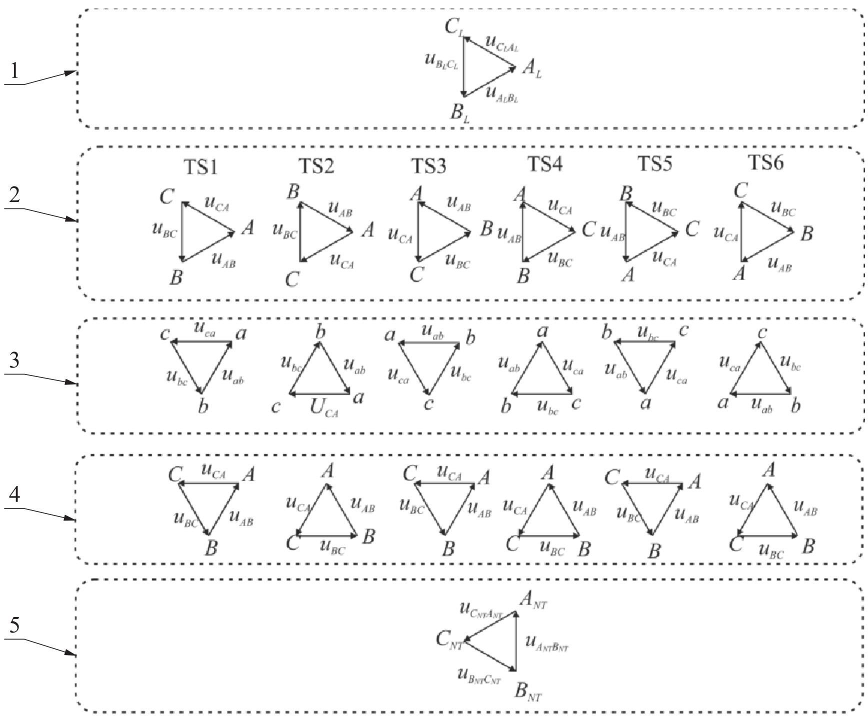
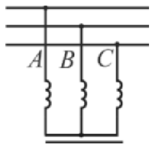
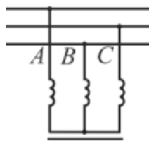
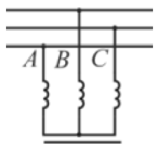
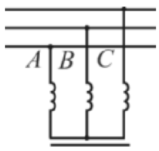
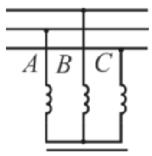
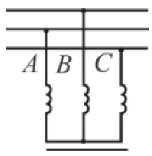


Fig. 3. Phasor diagrams of line voltages at the power supply system with phasing devices: 1) diagram for primary three-phase line, 2) diagram for primary windings transformers, 3) diagram for secondary windings transformers, 4) diagram primary winding phasing devices, 5) diagram secondary winding phasing devices (non-traction power supply three-phase line) [author’ own work]

For example, traction transformer with the first phasor group has connected to the primary three-phase line, as shown in scheme № 1 (Table 1, column 1). Column 7 is used to select the PD scheme of the 11 phasor group. The group of traction transformer is carried out using column 3. Then, the method

Table 1

Connection of PD to the traction transformer of substations

Scheme No.	Connection scheme of traction substations to the primary three-phase line	Phasor group of traction transformer	Terminals secondary winding of the traction transformer / Terminals primary winding of the PD			Phasor group of PD
1	2	3	4	5	6	7
1		11 and 1	*a / A*	*b / B*	*c / C*	11
2		11	*a / B*	*b / A*	*c / C*	1
		1	*a / A*	*b / C*	*c / B*	
3		11 and 1	*a / C*	*b / A*	*c / B*	11
4		11	*a / A*	*b / C*	*c / B*	1
		1	*a / C*	*b /B*	*c / A*	
5		11 and 1	*a / B*	*b / C*	*c / A*	11
6		11	*a / C*	*b /B*	*c / A*	1
		1	*a / B*	*b / A*	*c / C*	

[Owne elaboration].

of connecting the terminals secondary winding transformer and primary winding PD is chosen according to the instructions in columns 4, 5, and 6. In the cell a / A is marking connection terminal a secondary winding transformer winding and terminal A primary winding PD, b / B is connection terminals b and B; c / C is connection terminals c and C.

3. Modeling approach used for calculations

The modeling approach is based on Kirchhoff differential equations for electrical circuits, method of phase coordinates, and decomposition of a given power supply system on typical blocks to unify the subsystem. The mathematics part of the approach was presented in scientific article [6]. The general equations of the mathematical model may be described in matrix form by:

$$\mathbf{X} = \mathbf{A}^{-1}\mathbf{B} \qquad (1)$$

Where:

X – the vector of derivatives of unknown values,
A – coefficient matrix for unknown derivatives,
B – constant matrix.

Calculation of power supply scheme made by the algorithm that is implemented by performs procedures:

1. Data entering on the number and coordinates of the location of substations, consumers of electricity, power generators, etc.
2. Definition of subsystems described by standard systems of equations. Each subsystem is added to the general model.
3. The generalized model is calculated by a numerical solver.
4. Calculations of voltage and power losses

To create a mathematical model and process calculated values a library of functions was developed.

Such software packages as MathCad, Matlab, QlikView, and R programming language were used to perform the study (Fig. 4). MathCad software was used to create a model, that was calculated by numerical solver in Matlab. Data with calculated voltages were also obtained in Matlab. To output data file with current and voltage values Fourier transform was processed within R-language functions. Power Quality indices and energy losses were calculated by QlikView.

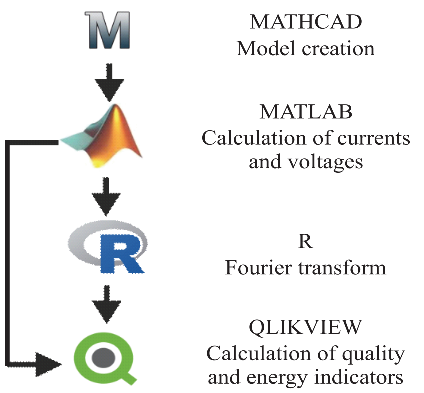


Fig. 4. Used Software Packaging with indicating the transfer direction of received results [author’ own work]

4. Determination of voltage unbalance and harmonic distortion in the 27,5 kV non-traction grid

The power supply system with 6 traction substations primary three-phase line was calculated using the mathematical model. The traction network has fed a double-track railway section with 35 electric locomotives. Electric locomotives and non-traction consumers are represented as equivalent load located as shown in Figs. 5–7.

Three ways to power supply of the non-traction consumers from the 27,5 kV network have been considered:

1. Unilateral power supply from the TWR line with alternation of substation connection to the public network (Fig. 5).
2. Bilateral power supply from the TWR line without alternating substation connection to the public network (Fig. 6).
3. Bilateral power supply from bus substation through PD (Fig. 7). The technical decision given in [14] was used to reduce the voltage unbalance and THD, namely a three-wire line was used instead of the TWR line.

The second way was investigated to determine the effect of symmetrical substation connection on power quality and power losses.

Currents and voltage frequency spectrums of the non-traction that have been obtained during the simulation are shown in Fig. 8–10.

The THD is defined the following equation [11]:

$$\mathrm{THD} = \frac{\sqrt{\sum_{i}^{n} U_i^2}}{U_1} \cdot 100\ \%, \qquad (2)$$

where:

U_i – RMS (root mean square) of voltages,
i – voltage harmonic number.

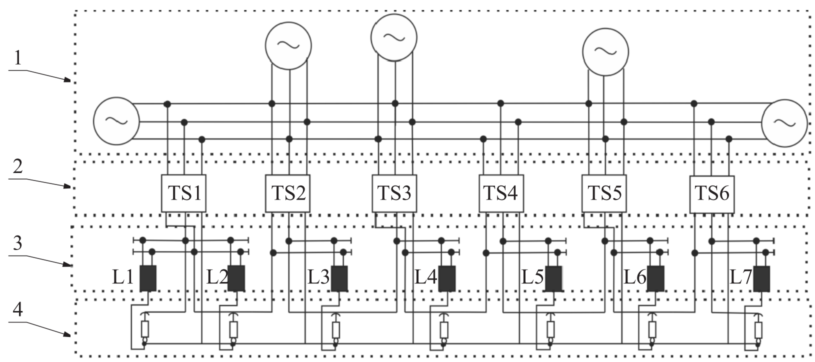


Fig. 5. Railway power supply system with alternation of substation connection to the public network: 1) public network, 2) traction substations (TS), 3) equivalent non-traction loads (L) and wires of the line “two wires-rail”, 4) equivalent traction loads and traction network [author’ own work]

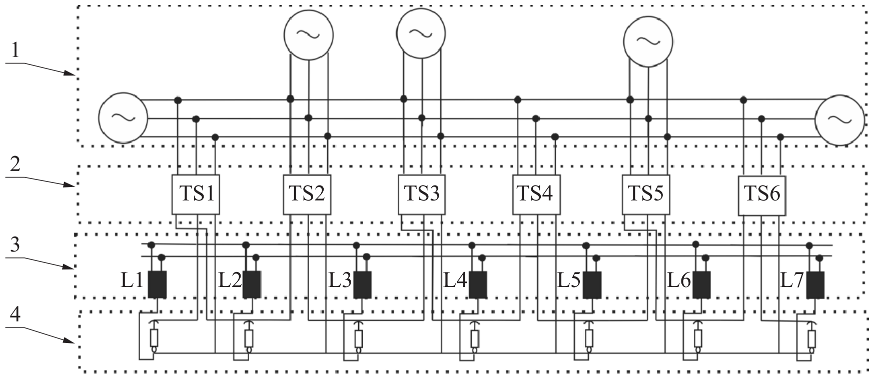


Fig. 6. Railway power supply system with alternation of substation connection to the public and bilateral power supply non-traction consumers: 1) public network, 2) traction substations (TS), 3) equivalent non-traction loads (L) and wires of the line "two wires-rail", 4) equivalent traction loads and traction network [author' own work]

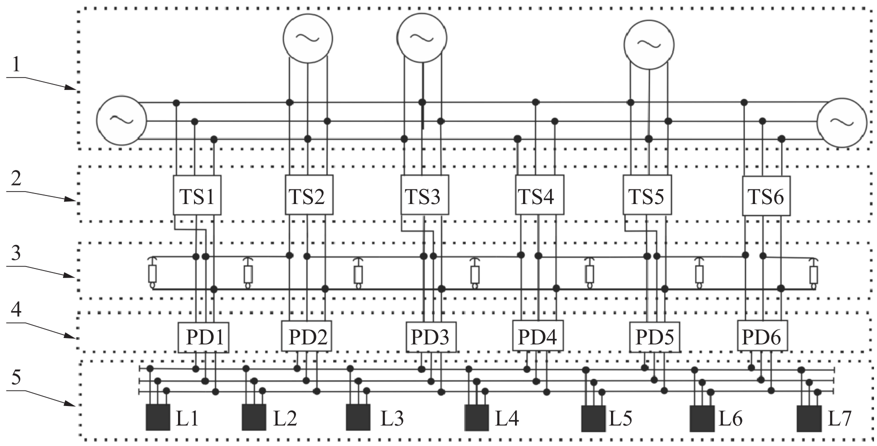


Fig. 7. Railway power supply system without alternation of substation connection to the public and bilateral power supply non-traction consumers by three-wire line: 1) public network, 2) traction substations (TS), 3) equivalent traction loads (L) and traction networ, 4) phasing device (PD), 5) equivalent non-traction loads and three-wire line [author' own work]

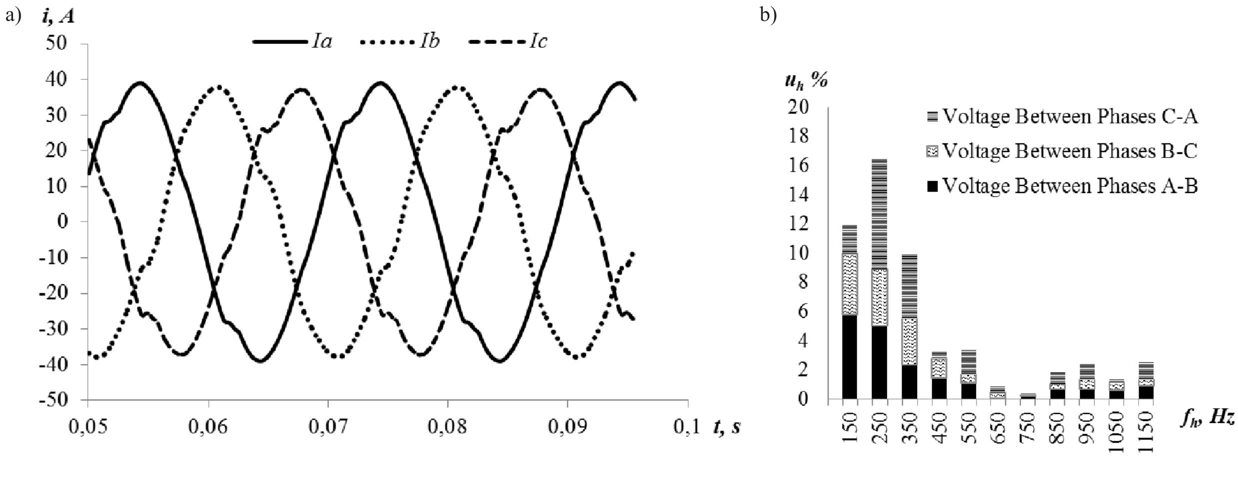


Fig. 8. Currents (a) and voltage frequency spectrums (b) of the non-traction system during unilateral power supply from the TWR line [author' own work]

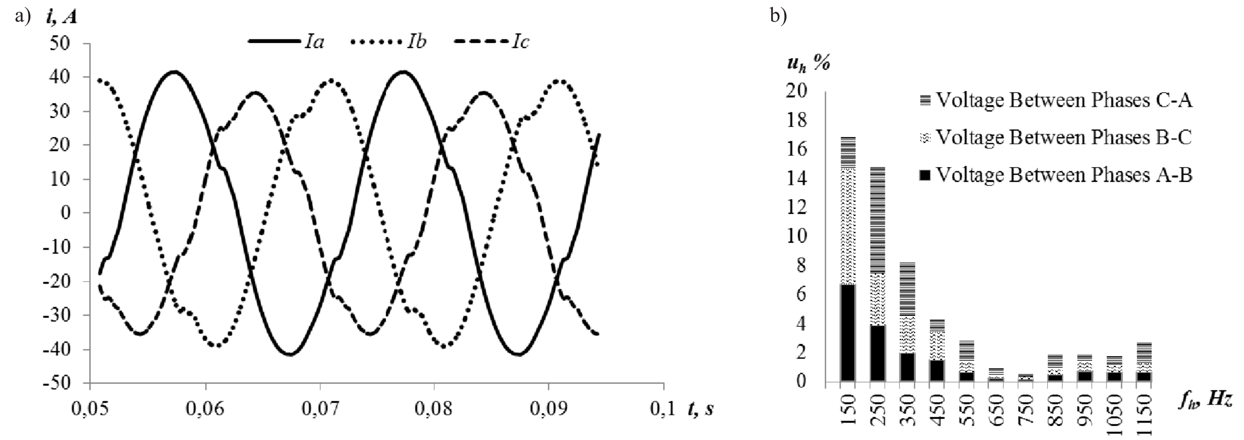


Fig. 9. Currents (a) and voltage frequency spectrums (b) of the non-traction system during bilateral power supply from the TWR line [author’ own work]

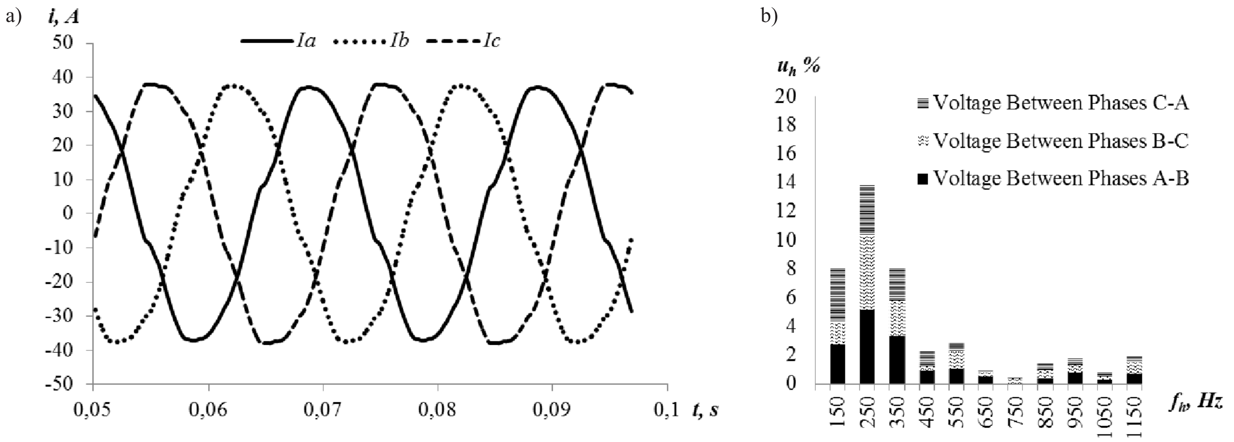


Fig. 10. Currents (a) and voltage frequency spectrums (b) of the non-traction during bilateral power supply from the three-wire line [author’ own work]

The value of the index of voltage unbalance can be calculated from the following equation [11]:

$$voltage\ unbalance = \frac{U_1^-}{U_1^+} \cdot 100\ \%, \tag{3}$$

where: U_1^+, U_1^- are RMS positive and negative sequence components of the first harmonic voltage.

The results of the power quality indices calculation are tabulated in Table 2. Indicators for unilateral power consumption are shown in the columns under the heading TWR. The ratio of quality indicators during unilateral mode to the indicator in bilateral mode power supply from the TWR or with PD are given in the column under the heading TWR2 or PD respectively.

Power losses in each part of the electricity supply system are determined with reactive power calculation by the Fryze concept [12]:

$$S^2 = P^2 + Q_F^2, \tag{4}$$

where:
S – apparent power,
P – real power,
Q_F – reactive power of Fryze.

Fryze reactive power value is determined by equation:

$$Q_F^2 = \left(\frac{\sum_{n=1}^{N} U_n^2 \sum_{n=1}^{N} I_n^2}{N} \right)^2 - \left(\frac{\sum_{n=1}^{N} (U_n I_n)}{N} \right)^2, \tag{5}$$

where: U_n, I_n are discrete voltage and current values, N is number of values.

Electricity losses in the elements of the electrical network are defined as the sum of the same ΔWP and

Table 2

Power Quality indices in the consumer network during different ways of power supply

Consumer	Voltage unbalance*	Voltage unbalance/ Voltage unbalance*		THD^*_{UAB}	THD_{UAB}/ THD^*_{UAB}		THD^*_{UBC}	THD_{UBC}/ THD^*_{UBC}		THD^*_{UCA}	THD_{UCA}/ THD^*_{UCA}	
	TWR	TWR2	PD	TWR	TWR2	PD	TWR	TWR2	PD	TWR	TWR2	PD
1	1,49	1,86	0,97	5,85	1,03	1,10	11,95	1,10	0,71	10,51	1,07	0,54
2	1,93	1,76	0,46	7,82	0,93	0,63	9,46	1,06	0,64	9,74	0,89	0,57
3	1,50	3,08	0,77	5,92	1,34	1,05	8,50	1,08	0,65	8,61	1,03	0,60
4	2,85	1,47	0,71	8,38	1,00	0,83	6,79	1,39	0,92	9,55	0,95	0,62
5	1,95	2,15	0,63	6,42	1,21	1,00	8,71	1,05	0,63	9,32	0,93	0,57
6	1,91	5,39	0,49	8,16	0,79	0,62	6,25	1,65	0,96	8,41	1,10	0,68
7	1,73	1,70	0,86	5,94	1,01	1,09	12,36	1,00	0,68	11,00	1,03	0,52
Average of ratio		1,92	0,70	–	1,04	0,90	–	1,19	0,74	–	1,04	0,59

[Author' own work].

additional ΔWQ electricity losses, which are determined by expressions:

$$\Delta W_P = \left(\frac{P}{U}\right)^2 \cdot R\tau \,, \quad (6)$$

$$\Delta W_Q = \left(\frac{Q_F}{U}\right)^2 \cdot R\tau \,, \quad (7)$$

where:

P, Q_F – real and Fryze reactive transit power,
U – input voltage of transit network,
R – resistance of transit network,
τ – duration of electricity transmission.

The monthly electrical energy transit through traction substation is 5–6 million kWh. Using the value of transit energy per month, the calculated values of generation energy and losses the total annual power losses per year were obtained. The total losses in the power supply system, the losses in the public network traction power system, and in the 27,5 kV non-traction power line are tabulated (Table 3). The losses in PD are attributed to the losses in the non-traction system.

5. Payback period of the proposed method of power supply

The payback period was determined using net present value (NPV):

$$NPV = \sum_{t=0}^{T} \frac{NCF_t}{\left(1+R\right)^t} \quad (8)$$

where:

NCF – net cash flow,
t – the time of the cash flow,
R – the discount rate,
T – the total number of periods (years).

Tablica 3

Power losses in parts of the electricity supply system per year, MWh

Power supply way	Total	Public network	Traction power system	Non-traction network
TWR	49 548	27 614	21 211	720
TWR2	51 922	30 212	21 350	362
PD	49 266	27 614	21 211	441

[Author' own work].

The increase in the cost of the tariff for the supply and distribution of electricity has been taken into account, the extrapolation results are tabulated (Table 4). Payment of electricity distribution by TWR lines is rated according to the tariff of the first voltage class (more 27,5 kV).

Table 4

Forecast of tariffs growth for electricity supply and distribution, USD / kWh

Year	Supply	Distribution (>27,5 kV)	Distribution (≤ 27,5 kV)
2020	0,069	0,002	0,011
2021	0,074	0,007	0,016
2022	0,079	0,012	0,022
2023	0,085	0,018	0,027
2024	0,090	0,023	0,032
2025	0,095	0,028	0,037
2026	0,100	0,033	0,042
2027	0,105	0,038	0,048
2028	0,111	0,044	0,053
2029	0,116	0,049	0,058
2030	0,121	0,054	0,063

[Author' own work].

Net cash flow is a profitability measurement that represents the amount of money produced or lost during a period by calculating the difference between cash inflows CF_{t+} from outflows CF_{t-}:

$$NCF_t = CF_{t+} - CF_{t-}. \quad (9)$$

Cash inflows include the cost of saved electricity, profit from electricity distribution, and accounting amortization. Saved electricity is obtained as the difference in energy losses per year between "TWR" and "PD"(Table 3). The profit from electricity distribution received for the site according to the Ukrainian railway data is 49 500 USD in 2019. Depreciation is obtained as the ratio of investment (Depreciation is obtained as the ratio of investment to 25 years of equipment use) to 25 years of equipment use.

Cash outflows include the investment (Table 5), cost of PD active and reactive energy. The additional reactive energy consumption associated with the magnetizing power of the six PD is 1500 Mvarh per year. The additional active energy is taken into account in total power losses which are presented in Table 3.

Table 5

Investments for the modernization of the TWR lines network with a length of 270 km

	Quantity	Price, USD
Project development	1	37 037
Phasing device	6	155 556
Vacuum circuit breaker	6	33 333
Disconnector	6	6 667
Protective relay and control devices	6	195 556
Wire	270 km	140 000
Insulator	16 200	120 000
Mounting	1	651 111
Total		**1 169 037**

[Author' own work].

The discount rate is the amount of domestic government bonds market rate (15 %) and annual inflation (4%). Net present value, net cash flow, and cash flow were calculated in UAH. Then the results of the calculation are given at the rate of 27 UAH per USD and presented in Table 6.

Table 6

Payback period calculation

Year	t	ΣNPV_t USD	NCF_t USD	CF_{t+}, USD	CF_{t-}, USD
2019	0	−1 169 037	−1 169 037	–	1 169 037
2020	1	−1 115 697	63 475	90 702	27 227
2021	2	−981 004	190 738	220 015	29 276
2022	3	−792 297	318 001	349 327	31 326
2023	4	−570 257	445 265	478 640	33 376
2024	5	−330 340	572 528	607 953	35 425
2025	6	−83 914	699 791	737 266	37 475
2026	7	160 826	827 054	866 579	39 525

[Author' own work].

6. Conclusions

1. The method of providing bilateral power supply to the consumers from the substation buses of 27,5 kV was proposed. Method includes changes in the scheme of phasing devices connected to the traction transformers windings, depending on the connection of the primary windings of the traction transformer to the public network.
2. The implementation of a method to increase the efficiency of electricity transmission in the of non-traction network power supply allows to reduce power

losses from 720 MWh / year to 441 MWh / year, the voltage unbalance from 1,9% to 1,3% and the total harmonic distortion from 8% to 6% respectively.
3. A full return on investment for the studied system can be expected in seven years. NPV is calculated taking into account the yield of state bonds and annual inflation, as well as taking into account the increase in tariffs for transmission and power supply.

References

1. Masoum M., Fuchs E.: *Power quality in power systems and electrical machines*, Academic Press, 2015, p. 1140.
2. Non Traction Energy Consumption, 2014, WWW http://energyefficiencydays.org/Non-Traction-Energy-Consumption [accessed on: 13 March, 2020].
3. *Study on Non-traction energy consumption and related CO2 emissions from the European railway sector – Final Report*, 2012, WWW https://uic.org/IMG/pdf/uic_non-traction_energy_study_final_report_june_2012.pdf [accessed on: 13 March, 2020].
4. Sustainable and intelligent management of energy for smarter railway systems in Europe: an integrated optimization approach, https://trimis.ec.europa.eu/sites/default/files/project/documents/20150224_151103_79650_MRLWP1DANS01306D1_1Railway_network_key_elements_and_main_subsystems_specification.pdf [accessed on: 19 September, 2020].
5. UIC-Asia Energy Conservation Project Case Study-Indian Railways, WWW https://www.ese.iitb.ac.in/~suryad/FinalReport-UICStudy-IndianRailways.pdf [accessed on: 19 September, 2020].
6. Zemskiy D.R., Sychenko V.G, Bosyi D.O.: *Simulation of the parallel operation of external and railway AC traction power supply system taking into account unbalanced conditions*, Technical Electrodynamics, Nr 2, 2020, pp. 74–85. DOI: https://doi.org/10.15407/techned2020.02.074.
7. Гриб О.Г. et.al.: *Качество электрической энергии. Том 3, Методы и средства повышения качества электрической энергии*, ПП «Граф-Ікс», Харьков 2014, с. 292.
8. Жежеленко И.В.: *Энергоэффективность систем электроснабжения. Интегральная оценка электромагнитных потерь и убытков в масштабах Украины, оптимизация качества электроэнергии в системах электроснабжения,* ГВУЗ «ПГТУ», Мариуполь 2017, с. 244.
9. Питание нетяговых потребителей от тяговой сети, Железные дороги мира, 2016, № 6, с. 67–71.
10. Система электроснабжения нетяговых потребителей на электрифицированных участках железных дорог, пат. № 47819 Россия, № RU 2005108041/22, [дата обращения 13.03.2019], WWW https://patents.google.com/patent/RU47819U1/ru.
11. Сиченко В.Г., Саєнко Ю.Л., Босий Д.О.: *Якість електричної енергії у тягових мережах електрифікованих залізниць*, Стандарт-Сервіс, Дніпропетровськ 2015, с. 340.
12. .Тонкаль В.Е., Новосельцев А.В., Денисюк С.П.: *Баланс энергий в электрических цепях*, Наук. думка, Киев 1992, с. 312.
13. Устройство для электроснабжения нетяговых потребителей на электрифицированных участках железных дорог переменного тока, пат. № 42484 Россия, № RU 2004120401/22U, [дата обращения 13.03.2019], WWW https://patents.google.com/patent/RU42484U1/ru.
14. Устройство для электроснабжения нетяговых потребителей электрифицированных железных дорог, пат. № 46979 Россия, № RU 2005109665/22, [дата звернення 11.07.2019], WWW https://patents.google.com/patent/RU46979U1/ru.
15. Финоченко Т.Э.: *Повышение качества электроэнергии в линиях „два провода-рельс" в условиях электромагнитного влияния тяговой сети переменного тока*, автореф. дисс. на соискание степени кандидата тех. наук: 05.22.07 / РГУПС, Ростов-на-Дону 2006, с. 20.