Software for optimal selection of places for installation of balancing devices in 0,4 kV electric power systems loaded with electric motors

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Abstract. This publication considers the issues of development of the software program for designing of 0,4 kV power supply systems with motor-actuated load under voltage unsymmetry conditions (using the example of the Trans-Baikal Territory). Voltage unsymmetry is practically constant phenomenon in the electric power networks of different voltage types. Voltage unsymmetry effects significantly the electric power consumers, including the supply mains itself. It has especially negative impact on the electrical equipment operation process and its lifetime. The urgency of the problem is confirmed by multiple research on the same topic and by significant number of damages suffered by the electric power consumers staying in service (especially in the Trans-Baikal Territory and in the Far-East regions). Voltage unsymmetry causes economic loss and reduction of the electromagnetic interference value by the voltage unsymmetry coefficient in negative-phase sequence (K_{2U}) gives inevitable economic effect accordingly. However, the payback period for the activities aimed at reduction of electromagnetic interference, will vary from some months to several years. The more accurate value of the payback period may be obtained using the developed software program. The developed software design program is implemented by means of the programming language C# in Microsoft Visual Studio environment, using the built-in cross-platform database SQLite. The software program shall allow making quick and accurate calculation of the power losses, to determine the economic feasibility of provision special measures for removal of the voltage unsymmetry, for determination of optimal application and location of the balancing devices. The software implementation in power systems loaded with electric motors will improve reliability and efficiency of asynchronous motors. The software is of interest for developers of projects on power supply systems for regions with non-linear loads.

1 Introduction

Currently, a special attention is given to the problems of electric energy quality. In modern conditions quality parameters of electric power such as voltage unbalance, unsinusoidality, become common factors which significantly reduce an efficiency of the power supply systems themselves and, accordingly, an efficiency of consumers connected to them.

A study of the main electric power quality parameters for the network equipment of 0.4, 6 and 35 kV power system in Zabaykalsky Krai showed that deviation of main quality parameters of electric power, such as voltage unbalance, voltage unsinusoidality is a common factor in Zabaikalsky power system. In some cases, unbalance level significantly (2-3 times) exceeds specified in GOST 32144 – 2013[1] value [2].

Due to unsatisfactory condition of the electric energy quality in distribution networks of Zabaikalsky power system, there is a large number of electrical failures at the consumer's facilities. Experience of electrical equipment operation shows that one of the main causes of electrical equipment failure is voltage unbalance.

A reliability and efficiency of electrical equipment depends directly on electric energy quality in distribution networks. For stable operation of electrical equipment, number of measures aimed at improving of electric energy quality, in particular, voltage unbalance elimination should be taken.

In this paper, one of possible methods for electric energy quality improvement which uses balancing devices in the electric power system both at the stage of electric network design, and in conditions of real operation is proposed.

The aim of this work is to develop an application software for optimal selection of places for installation of balancing devices in 0,4 kV electric power systems loaded with electric motors under conditions of voltage unbalance focused on engineering practice

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2 Materials and methods of research

In the research of the asynchronous motors, the problem of assessing the impact of unbalanced phase voltages on the motor operation is highly important.

To get a more complete picture of voltage unbalance impact on asynchronous motors it is necessary to define a dependence of asynchronous motors phase currents versus voltage unbalance coefficient for negative sequence K_{2U}.

The research of asynchronous motors operation modes can be efficiently carried out with by means of computer simulation using virtual model created in clear and effective simulation tool Simulink in interactive programming environment of MatLab, using a T-shaped equivalent circuit of induction motor [3-5].

The studied objects were asynchronous squirrel-cage motors of 4A series: 4A132S4Y3 with Pn = 7,5 kW and AI series: AI132M4 with Pn = 11 kW; the motors have the following rated parameters (Table 1) [6,7].

Authors developed a simulation model (Fig.1), which allows performing analysis of asynchronous motors operation modes, moreover, using this model, it was possible to study transient processes in the induction motor, measurements of operation and artificial mechanical characteristics, voltage, current and frequency in the power supply network [3].

Computer simulation of direct start of asynchronous motors was performed for motors of 4A, AI type at three-phase supply voltage 380 V with frequency 50 Hz.

Table 1. Technical data on three-phase asynchronous motors

Power of motor, P, kW	**Type of the motor**	**cos φ**	**Starting torque ratio, Kmp**	**Starting current ratio, Kp**
7,5	4A132S4Y3	0,86	2,2	7,5
11	AI132M4	0,87	2	7,5

Using the developed model, the asynchronous squirrel-cage motors were studied with regard to the following parameters:

-for different motor shaft loads (idle mode - 120%),

-for change of value of voltage unbalance coefficient for negative sequence (K_{2U}) from 0 to 5%.

The simulation scheme for study of operation modes of asynchronous squirrel cage motor created by means of simulation in Matlab Simulink is shown in (Fig.1).

In the course of process simulation, an analytical curves for the phase currents versus K_{2U} for series 4A, AI asynchronous motors were obtained.

For each phase of asynchronous motors under consideration, curves for the phase currents versus K_{2U} were obtained for different values of the motor shaft load.

The general form of the current change in the most loaded phase (phase "A") for series 4A asynchronous motors at Pn = 7,5 kW, AI series asynchronous motors at Pn=11 kW, for different K_{2U} values and different values of the motor shaft load are shown in (Fig.2,3).

Analysis of the dependences obtained in the course of study of the asynchronous motors modes showed the following:

1) when K_{2U} increases, current in one of the motor phases decreases and in the other two phases the current increase is observed,

2) it can be seen from the general view of the dependencies that: the more the motor shaft load, the more the voltage unbalance impact on the operating modes of electric motors,

3) the curves general view and directions are the same, that shows that impact of voltage unbalance on different series asynchronous motors is similar.

But currents at full load of the motor are of the greatest interest. When the load is 100%, current in phase "A" of 4A series asynchronous motors with Pn = 7,5 kW exceeds permissible overload current equal to 1,1 of rated current for K_{2U} = 1,4% [8,9]. For AI series motor with Pn = 11 kW, the permissible current overload is exceeded at K_{2U} = 2 %.

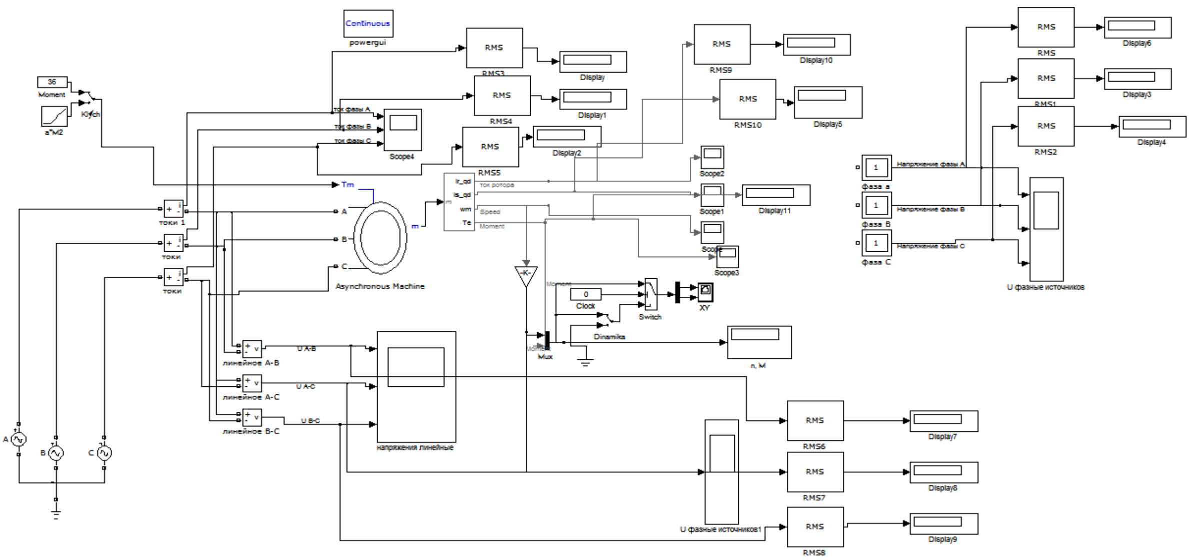

Fig.1. Simulation scheme for Matlab Simulink environment.

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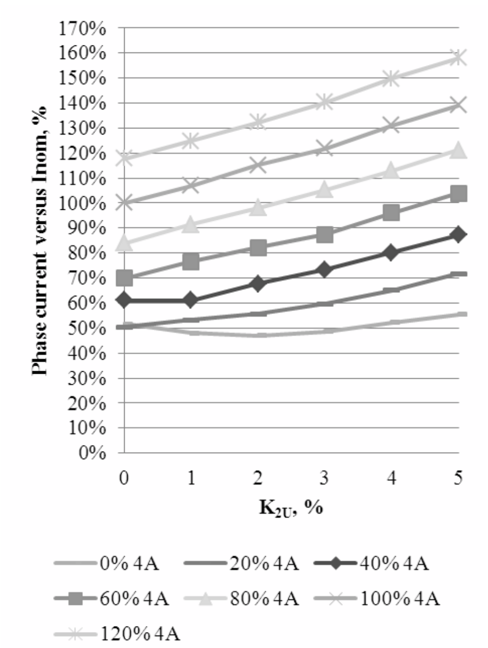

Fig.2. Curve of current for phase A for 4A series asynchronous motors with Pn = 7,5 kW versus K2U.

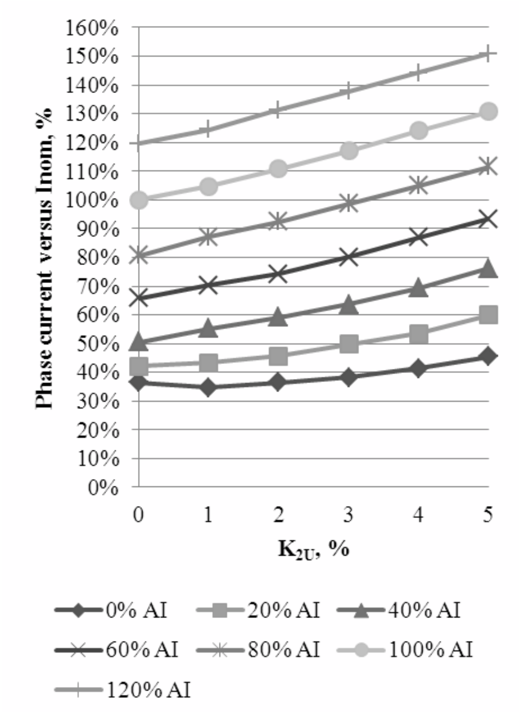

Fig.3. Curve of current for phase A for AI series asynchronous motors with Pn = 11 kW versus K_{2U}.

This shows that the motors not only have different range of acceptable values for K_{2U}, but they not always meet GOST requirements. Accordingly, if the motor is operated in areas with poor electric energy quality, it is necessary to regulate the supply voltage being guided not by GOST on power quality, but by motor operation mode.

It is obvious that the obtained values of permissible K_{2U} values for asynchronous motors will have a key role in the selection and implementation of balancing devices in the power system loaded with electric motors.

3 Formulation of the problem

The work of calculation algorithm development for power supply system taking into account balancing devices and their location, which will be a base of the software for optimal selection of places for installation of balancing devices in 0,4 kV electric power systems loaded with electric motors was performed in accordance with the intended purpose. Block diagram of the calculation algorithm for power system taking into account balancing devices and their location is shown in (Fig.4).

Based on data of the experimental study for main basic quality parameters of electric power, data on power losses in the electric power system components, and based on the allowable modes of consumers operation it is possible to select balancing devices parameters and to define optimal location of these devices in the power system.

Thus, calculation of additional power losses due to voltage unbalance will make it possible to define an economic feasibility of the special measures on unbalance elimination, and in addition to determine the optimal application and location of these devices.

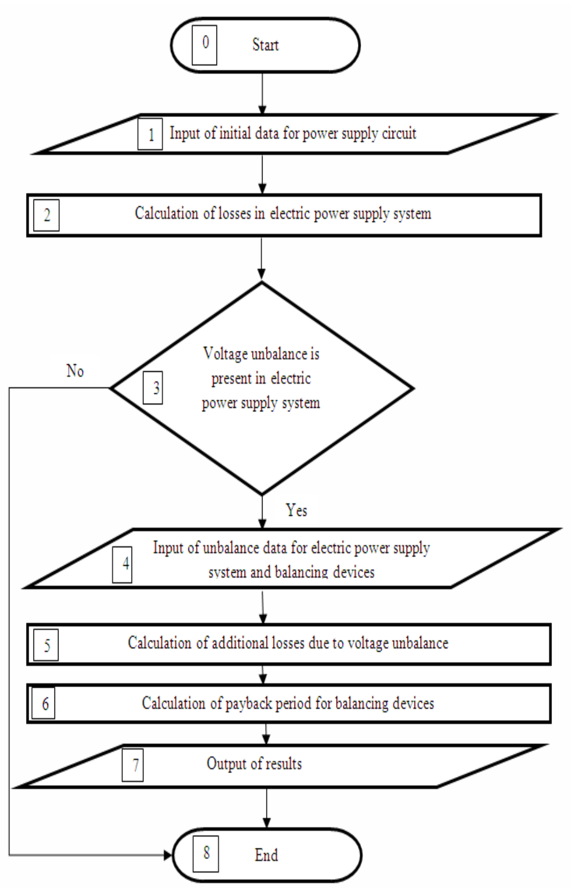

Fig. 4. Block-diagram of calculation algorithm for power supply system taking into account balancing devices and their location.

4 Calculation algorithm for power supply system taking into account balancing devices and their location

Main criterion for the software application is excess of the actual value of voltage unbalance coefficient for negative sequence (K_{2U}) in the particular electric power system over the permissible value K_{2U} specified for asynchronous motors (Table 2) installed in the same power supply system. Required K_{2U} value should be selected on the base of the permitted consumer operation mode. Permissible K_{2U} values for asynchronous motors are taken from results of the study [3].

Table 2. Table of allowable values K_{2U}.

Type of motor	The motor power, Pn, kW	Permissible value of K_{2U}, %
4A132S4Y3	7,5	1,8
AI132M4	11	1,26

The calculation algorithm for the power supply system taking into account balancing devices and their location can be implemented in the following sequence:

1) block 1 – entering of the initial data into the software.

The initial data are:

- characteristic of the circuit segment (general information about the site);
- parameters of the transmission lines (quantity of lines, lines numbers, length of lines; grade of wire and cable used in the line; the line loading);
- parameters of electric motors connected to the power line (the line number to which the motor is connected; quantity of motors in the line, the motor type);
- parameters of the transformer (quantity and type of the transformer);
- value of the voltage unbalance coefficients for negative and zero sequence in the design power supply system;
- cost of electric power.

2) block 2 – performing losses calculation for balanced operation mode in the basic elements of power supply system.

Balanced mode current (current for positive sequence) is defined from the expression:

$$I_1 = S/U, \tag{1}$$

where S – full load of the substation.

Losses in power lines are defined from the expression:

$$\Delta P_{eltl} = 3I_1^2 R_{PH} \tag{2}$$

where I_1 – balanced mode current (current for positive sequence) [10];

R_{PH} – resistance of the phase wire.

Full loading of the substation (sum of the loads due to individual lines) is defined from the expression:

$$S = \sum_{i=1}^{n} P_i , \tag{3}$$

where P_i– loading of the line.

Losses of active $\Delta P'$ and $\Delta Q'$ reactive powers for double-winding transformers are defined from the expression:

$$\Delta P' = \frac{\Delta P_k}{n}\left(\frac{S}{S_{nom}}\right)^2 \tag{4}$$

$$\Delta Q' = \frac{U_k}{100 \cdot n} \cdot \frac{S^2}{S_{nom}} \tag{5}$$

where $\Delta P_k, U_k, S_{nom}$ – passport data for particular transformer [11];

S – full load of the substation;

n – quantity of the same type transformers at the substation connected in parallel.

3) block 3 – transfer to condition: voltage unbalance is present in the power supply system.

At condition "NO" – calculation is stopped.

At condition "YES" – transfer to block 4.

4) block 4 – transfer to special measures for unbalance elimination, definition of optimal application and location of these devices. Unbalance voltage coefficients are input for negative and zero sequences for the two variants of calculation, and also selection from the database of suitable devices for the balancing.

a) variant 1 – considers installation of balancing device into common equipment of the lines comprising electric motors;

b) variant 2 – considers installation of balancing device into each line of the circuit segment comprising asynchronous electric motors.

5) block 5 – calculation of additional losses in key elements of the supply system for unbalanced operation mode.

In the course of calculation of increase in additional losses compared to the symmetric mode, presence in the network of amplitude and angular asymmetry can be accounted by using the following formula:

$$K_{unsym} = \left(1+K_{2I}^2+K_{0I}^2\right)\cdot\left(1+3\cdot\frac{R_N}{R_{PH}}\right), \tag{6}$$

where K_{2I}, K_{0I} – current unbalance coefficients for negative and zero sequences [10].

Based on the results of data processing for the main quality parameters of electric power in the equipment of 0,4 kV network located in Mogocha district, Zabaikalsky Krai, we take the following values of the coefficients: $K_{2I} = 5\%$, $K_{0I} = 4{,}6\%$, $K_{2U} = 4{,}95\%$;

R_N, R_{PH} – resistance of neutral and phase wires.

Accordingly, taking into account (6), the expression (2) can be rewritten as follows:

$$\Delta P_{suppl.eltl} = \Delta P_{eltl} K_{unsym} \tag{7}$$

Additional loss of active power in asynchronous motor is defined from the formula:

$$\Delta P_{suppl.am} = 2{,}41 K_{AM} K_{2U}^2 P_n , \tag{8}$$

where K_{AM} – coefficient which accounts for the specific parameters of the motor (rated power, copper loss of the stator, starting current ratio);

K_{2U} – voltage unbalance coefficient for negative sequence;

P_n – the motor rated active power.

For industrial loads, it is generally recommended to use coefficient with value of 1,85.

When the system is operated in power transformers in the unbalanced mode for a long time, additional power losses due to negative sequence currents appear that can be defined by the following formula

$$\Delta P_{suppl.tf} = K_{2U}^2 \quad \Delta P_{IM} + \frac{\Delta P_{SC}}{u_{SC}^2} \ , \qquad (9)$$

where K_{2U} – the voltage unsymmetry coefficient in negative-phase sequence;

ΔP_{IM} – loss during idle mode;

ΔP_{SC} – losses during short-circuit mode;

U_{SC} – short-circuit voltage.

Then total losses are calculated.

For balanced mode, losses are defined from the following formula:

$$\Delta P_{sym} = \sum_{i=1}^{n\_line} \Delta P_{eltl} + \Delta P' \qquad (10)$$

where n_line – quantity of the lines;

i – the line number.

For unbalanced mode, losses are defined from the following formula:

$$\Delta P_{unsym} = \Delta P_{sym} + \sum_{i=1}^{n_{line}} \Delta P_{suppl.eltl} + \sum_{j=1}^{n_{dv}} \Delta P_{suppl.am} + \Delta P_{suppl.tf} \qquad (11)$$

where j – motor number;

n_{dv} – quantity of the motors in the transition line.

6) block 6 – calculation of the payback period for each installation of balancing devices and the least one is taken.

Additional losses without balancing devices are defined from the expression:

$$S_{suppl\frac{w}{o}} = \Delta P_{suppl\frac{w}{o}} + \Delta Q_{suppl\frac{w}{o}} = \sum_{i=1}^{n_{line}} \Delta P_{suppl.eltl} + \sum_{i=1}^{n_{line}} \sum_{j=1}^{n_{dv}} \Delta P_{suppl.am} + \Delta P_{suppl.tf} \ , \qquad (12)$$

at the initial values of the voltage unbalance coefficients for negative and zero sequences.

If balancing device is installed additional losses can be defined from the expression:

$$S_{suppl} = \Delta P_{suppl} + \Delta Q_{suppl} = \sum_{i=1}^{n\_line} \Delta P_{suppl.eltL} + \sum_{j=1}^{n\_dv} \Delta P_{suppl.am} + \Delta P_{suppl.tf}, \qquad (13)$$

at the initial values of the voltage unbalance coefficients for negative and zero sequences.

Selection of the balancing device parameters is performed depending of conditions:

a) variant 1 – power of the balancing device should be more than or equal to the sum of loads in lines outgoing from the central equipment:

$$P_{sym} \geq S \qquad (14)$$

b) variant 2 – power of the balancing device should be more than or equal to the sum of loads in each line comprising a motor:

$$P_{sym} \geq P_i \qquad (15)$$

Calculation of the total cost of balancing devices is performed by the expression:

$$S = \sum_{k=1}^{k\_d} C\_d, \qquad (16)$$

where S – total costs of installed balancing devices;

C_d – costs of particular balancing device;

k_d – quantity of installed balancing devices;

k – balancing device number.

Calculation of payback period for installation of the balancing device is performed by the formula:

$$PP = \frac{S}{\Delta Psuppl\frac{w}{o} + \Delta Qsuppl\frac{w}{o} - \Delta Psuppl + \Delta Qsuppl \quad *C} \qquad (17)$$

where PP – payback period;

S – total costs of installed balancing devices [12,13];

$\Delta P_{suppl\frac{w}{o}} + \Delta Q_{suppl\frac{w}{o}}$ – without the balancing devices;

$\Delta P_{suppl} + \Delta Q_{suppl}$ – supplementary losses with the balancing devices;

C – cost of the electric power.

7) block 7 – output of the resulting data.

The resulting data are:

- losses for balanced operation mode;
- additional losses for unbalanced operation mode (without balancing devices; variant 1 - for case when balancing device is installed into common equipment of the lines comprising electric motors; variant 2 - for case when balancing device is installed into all lines comprising asynchronous electric motors);
- costs of balancing devices (costs of balancing device; total costs of balancing device for variant 1; total costs of balancing device for variant 2; payback period for variant 1; payback period for variant 2).

Calculation algorithm above for electric power supply system will be a base for implementation of software for optimal selection of places for installation of balancing devices in 0,4 kV electric power systems loaded with electric motors operating under conditions of voltage unbalance.

For the software implementation and testing, let us consider segment of power supply system in village Taptugary, Mogocha district, Zabaikalsky Krai.

For this work performance, following initial data were used:

1) results of data processing for main quality parameters of electric power in the equipment of the 0,4 kV network in Mogocha district, Zabaikalsky Krai,

2) configuration of the power supply system in village Taptugary, consumers characteristics.

Power supply system, which was used for the software testing is shown in (Fig.5). The site power system consists of:

1) line 1 – wired with AC-25 (steel-aluminium conductor), the line length is 350 metres, feeds 7 private residence houses with furnace heating,

2) line 2 – cabled with GRSh 3*50+1*35 (cable with flexible core, rubber cover and poly amide silk isolation), the line length is 50 metres, feeds the two-storeyed residence house, the primary school, the kindergarten, the administration building and the library,

3) line3 – cabled with AVVshv 4*50 (cable with aluminium core, PVC jacket, with protective layer in the form of pressed out hose), the line length is 70 metres, feeds the boiler house with two boilers and

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electric motors: models 4A132S4Y3 with Pn =7,5 kW in amount of 2 pieces, smoke exhaust fan Pn=3 kW, draught fan Pn=1,4 kW,
4) line 4 - wired with SIP 4*25 (self-supporting insulated conductor), the line length is 150 metres, feeds two ban mills with motors model AI132M4 Pn=11kW.

Table 3. Initial data for segment of power network in village Taptugary.

Parameter	Line 1	Line 2	Line 3	Line 4	TS
Power, kVA	30,4	49,4	20,9	25	100
Current, A	80	130	55	65	330

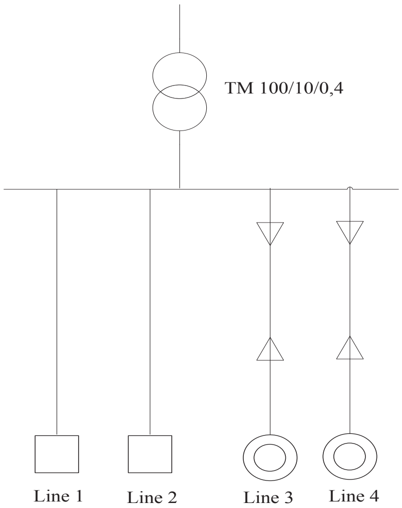

Fig.5. Diagram of segment of power supply system in village Taptugary.

5 Software implementation

The developed software is intended for reduction of voltage unbalance in segments of 0,4 kV power supply systems for the highest economic efficiency. The software can be used for calculation of economic efficiency of existing power systems modernization [14,15].

The software application will allow performing fast and accurate calculation of power losses to determine the economic feasibility of special measures for elimination of voltage unbalance, determining optimal use and location of balancing devices, with significant increase in productivity of the designer [16,17].

The developed software is implemented using C# programming language in Microsoft Visual Studio environment with the embedded cross-platform SQLite database [18-21].

The database contains tables for such areas: reference characteristics of the power system elements, table of the power supply system input data, table of output calculation data for power supply system. Each database table has its unique attributes and its purpose in the system.

The software consists of a database that stores all information necessary for calculation and design of 0,4 kV power supply systems loaded with electric motor; calculations module, which implements the algorithm of power losses calculation in the elements of power supply system; module for entering of input data and output of the calculation results for 0,4 kV power supply systems loaded with electric motor and operated under voltage unbalance conditions.

The initial data are data on the site of 0,4 kV power supply system loaded with electric motor.

The data is developed into database (DB) with its structure enabling easy manipulation of the data, and is more flexible, removing redundancy and non-conformity relations.

The database contains the tables of the following areas: reference parameters of the power supply system elements, tables of the power supply system input data, tables of the output data for calculation of the power supply system designing. Each BD Table has its unique attributes and its own designation in the system. Relationships of BD tables (logic model) are given in (Fig. 6).

The logic model represents relation between BD table.

The software interface is clear and simple (Fig. 7,8). The software interface includes means for entering of reference data for the individual elements of the power supply system, entering and display of the initial data for section of the power supply system, output of the calculation information for the power supply system, history of calculations.

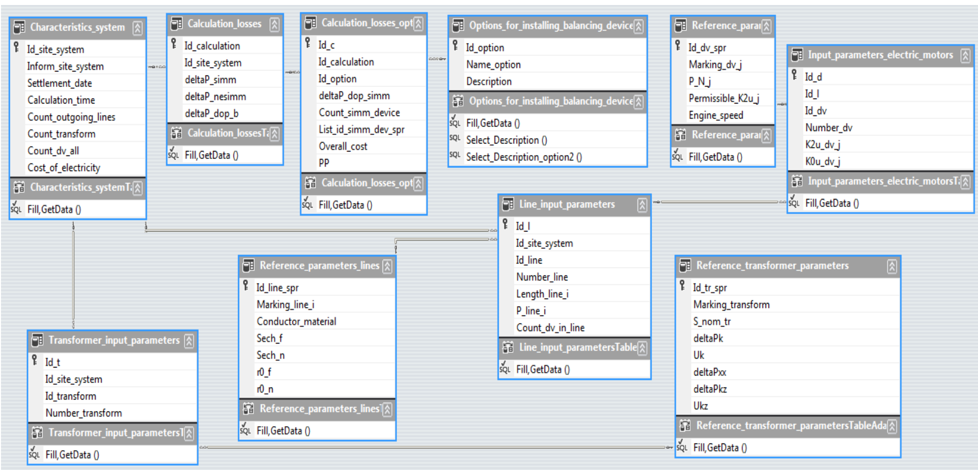

Fig.6. Dependencies of the database tables (logical model).

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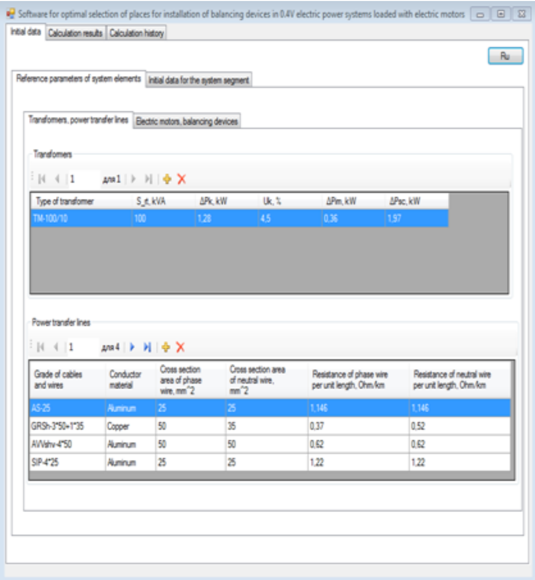

Fig.7. The software interface: input data window - reference parameters of the power supply system (transformers, power lines).

The software interface is presented in two languages (Russian and English). There is a button for language selection in the upper right corner of the software window.

Thus, using the software we defined value of power losses in main elements of power supply system for balanced operation mode, for unbalanced operation mode without installed balancing devices, for unbalanced operation mode with installed balancing devices; we defined quantity, power and installation place for the balancing device.

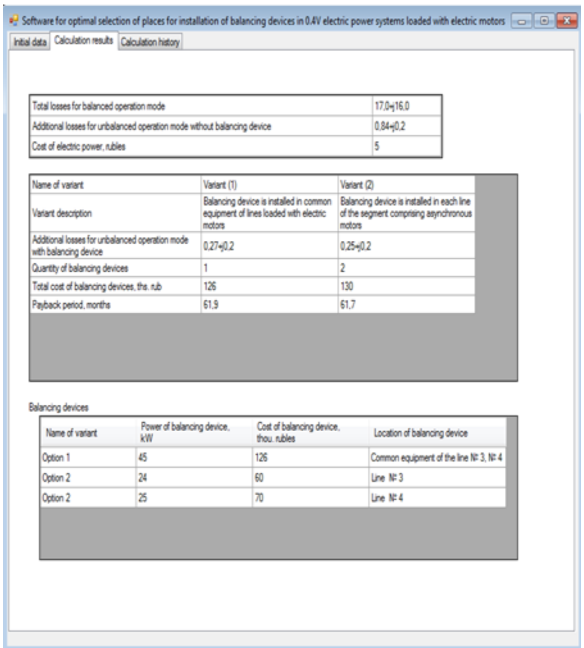

Fig.8. The software interface: window for output of calculation results.

It can be concluded from the results of the software use for the scheme under consideration (Fig.5) that it is economically advisable to install one balancing device with a capacity of 45 kW in the common equipment of the line 3,4 loaded with electric motor, but not on each motor individually.

As a result of the software implementation, necessity of use of balancing devices for industrial consumers in the considered scheme was confirmed. The most cost-effective location of the balancing device in electric power supply system, based on the payback period of measures aimed at reducing of electromagnetic interference was defined.

6 Conclusion

The software is designed for specialists involved in design of 0,4 kV power supply networks and systems operating in presence of voltage unbalance. The proposed software simplifies process of designing of power supply systems; in addition, it can be widely used by project organizations for real conditions of power supply systems operation.

Use of balancing devices reduces current and voltage unbalance in 0,4 kV distribution networks significantly improving the voltage quality at the terminals of electrical consumers, so solutions for these cases are implemented in the software. This increases the operational reliability of electric motors.

Software for optimal selection of places for installation of balancing devices in 0,4 kV electric power systems loaded with electric motors operated under voltage unbalance conditions is the first developed version. Further improvement of the software is possible by expanding the functionality so that it would make it possible to display graphic images of schemes and output a graphical image of calculation diagrams showing location of all balancing devices in electric power system, rendering of the graphs of various parameters dependencies, and also import and export of input and output data of the software.

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References

1. *GOST 32144 – 2013. Electric energy. Electromagnetic compatibility of technical equipment. Power quality limits in the public power supply systems*. – M.: STANDARTINFORM, **19** (2014).

2. V. Romanova, S. Khromov, *Ulan-Ude: Buryat Scientific Centre, Siberian Branch of the Russian Academy of Sciences*, 20 – 25 (2016).

3. V. Romanova, S. Khromov, I. Suvorov, *Up-to-date technology. Systemic analysis. Modeling. Scientific journal*. Irkutsk: Publishing house of the

DOI: 10.1051/e3sconf/20172504002

Irkutsk state University of transportation, №**1** (53), 209 – 214 (2017).

4. I. Chernykh. *Modeling of electrical devices in MATLAB, SimPowerSystems and Simulink*. (SPb.: Peter M.: DMK Press, 288, 2008).

5. S. German-Galkin, G. Karganov, *Electrical machines: Laboratory works on PC* (SPb.: Korona-print, **256,** 2003).

6. http://principact.ru/content/view/166/72/

7. http://www.elektrikii.ru/publ/6-1-0-55

8. http://www.bmrzzakharov.narod.ru/raschet/overload.html

9. V. Kogorodsky, S.Kurjenkov, L. Paperno. *Relay protection of electric motors with voltages more than 1 kV*. (M.: Energoatomizdat, 1987).

10. A.Ded, A. Parshukova, N. Khalitov, *International journal of applied and fundamental research. Scientific journal.* Moscow: Publishing house "Russian Academy of Natural History", № **10**, P. 3, 421 – 425 (2015).

11. O. Grunin, L. Sawicki, *Power systems and networks in examples and tasks*. (Chita: Publishing house ChitGU, 209, 2010).

12. http://voltmarket.ru/catalog/trekhfaznye_stabilizatory.

13. https://energo-24.ru/authors/energo-24/11017.html.

14. D. Aleksandrov, *Reliability and quality of electric power supply to enterprises*. (Ulyanovsk: UlSTU, 155, 2010).

15. N. Kuznetsov, *Reliability of electrical machines: textbook. the manual for high schools*. (M.: Publishing house of MPEI, 432, 2006).

16. V. Radkevich, *Design of power supply systems: tutorial*. (Minsk: NPOOO "PION", 288, 2001).

17. V. Mankov, *Principles of design of power supply systems* (St. Petersburg: NOU DPO "UMITTS "Electro Service", 640, 2010).

18. http://www.w3ii.com/ru/sqlite/default.html.

19. http://er.nau.edu.ua/bitstream/NAU/10100/1/SQLite.Allow.pdf.

20. R. Frost, D. Dei, C. van Slyke, *Database Design and Development*. (Moscow: Publishing house "NT Press", 570, 2007).

21. V. Medvedev *Features of object-oriented programming in C++/CLI, C# and Java*. (Kazan: Editorial and Publishing center "Shkola", 444, 2010).