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Unbalance Level Regulating Algorithm in Power Distribution Networks

Eugene Alekseevich Shutov, Tatyana Evgenievna Turukina*, Ilya Igorevich Elfimov

Tomsk Polytechnic University, Tomsk, Russia
Email: shut63@mail.ru, *tan4uk89@gmail.com, ilia_igorivich@mail.ru

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Abstract

The paper dwells on the unified power quality indexes characterizing the phenomenon of voltage unbalance in three-phase systems. Voltage unbalance is one of the commonest occurrences in the town mains of 0.38 kV voltage. The phenomenon describes as inequality of vector magnitude of phase voltage and shearing angle between them. Causes and consequences of the voltage unbalance in distribution networks have been considered. The algorithm, which allows switching one-phase load, has been developed as one of the methods of reducing the unbalance level. The algorithm is written in the function block diagram programming language. For determining the duration and magnitude of the unbalance level it is proposed to introduce the forecasting algorithm. The necessary data for forecasting are accumulated in the course of the algorithm based on the Function Block Diagram. The algorithm example is given for transforming substation of the urban electrical power supply system. The results of the economic efficiency assessment of the algorithm implementation are shown in conclusion. The use of automatic switching of the one-phase load for explored substation allows reducing energy losses (active electric energy by 7.63%; reactive energy by 8.37%). It also allows improving supply quality to a consumer. For explored substation the average zero-sequence unbalance factor has dropped from 3.59% to 2.13%, and the negative-sequence unbalance factor has dropped from 0.61% to 0.36%.

Keywords

Unbalance, Supplementary Power Losses, Load Switching Algorithm, Electric Power Quality, Distributing Networks, Function Block, Balancing System, Forecasting, Microcontroller

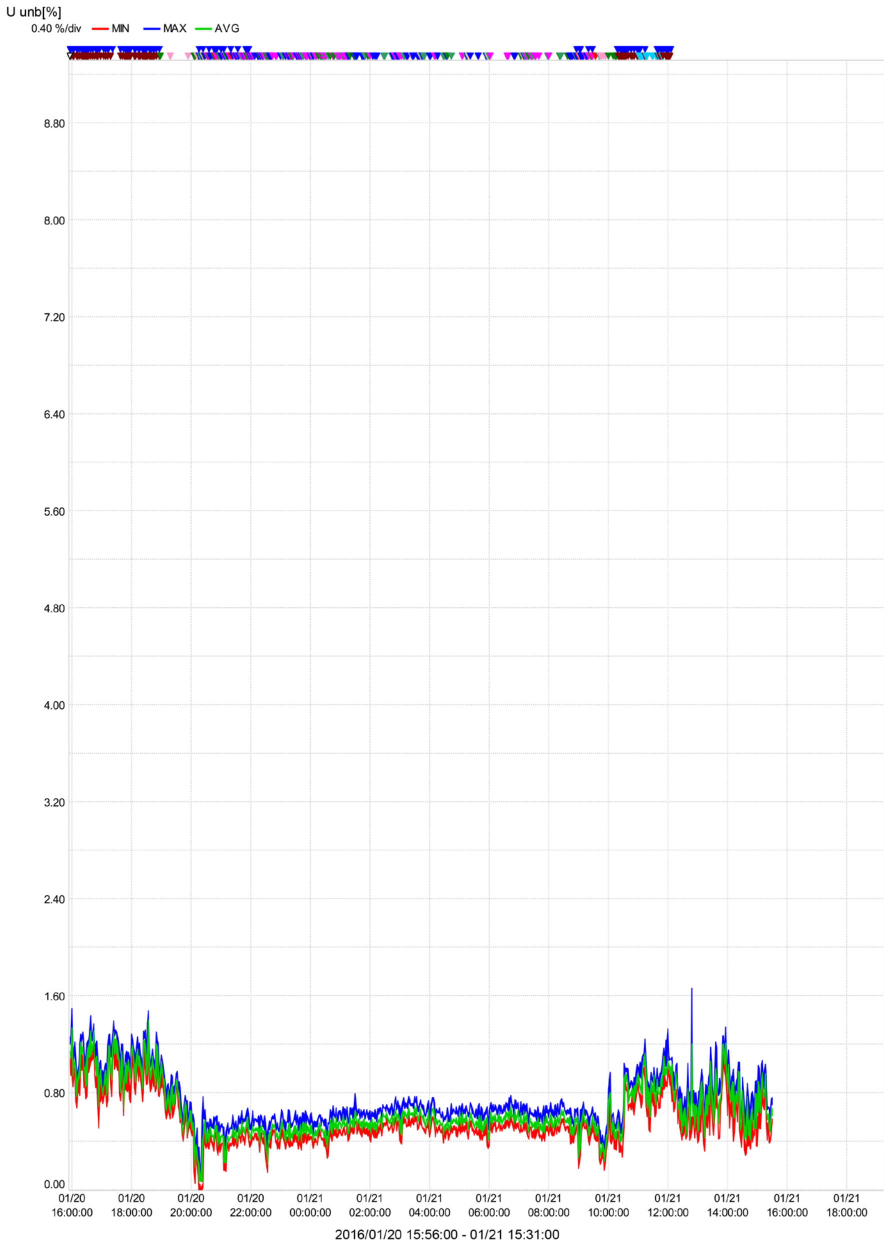
1. Introduction

New materials and fabrication method (for example, cable production) aimed at reduction of the resistance value of a wire and, as consequence, energy loss saving [1] [2]. Taking into account actual operation conditions of distribution grids will provide reduction of electric power losses by control of power quality indices (PQIs). One of the main PQIs—the value of the negative sequence component of the supply voltage by which the level of voltage unbalance present in system is specified. According to the EN 50160, in a three-electrical supply system, a voltage unbalance is a condition in which the Root Mean Square (RMS) values of the phase (or line) voltages, or the phase angles between consecutive phases voltages, are not all equal [3] [4]. Exceeding the normalized values of the said parameter leads to avalanche-type growth of electric power losses and the chance of emergency situations. Therefore, engineering operations that help to reduce the unbalance level are measures aimed at energy conservation and enhance reliability of power system operation. Town mains of 0.38 kV voltage are among the more unbalanced three-phase networks. Unbalanced conditions are principally caused by the load unbalance of power consumers and the element unbalance of electrical networks [5]. The current and voltage unbalance is shown in **Figure 1**. In **Figure 1** the voltage unbalance is shown as a plot of voltage vs. time and as a vector diagram which characterizes the phase shifts. At night with a minimum demand, the increase in current unbalance under decrease voltage unbalance is observed. At such times the load is due to the switching-on low-power single-phase consumers, generally lighting equipment. The scale of events (on/off some load) is presented in the form of the diagram elements (shown along the top of **Figure 1**). The vector diagram of phase currents and voltages is superimposed on the voltage trend for the value detailing for specified time. The values of negative, positive and zero-phase sequences of voltage and current are represented. In town mains of 0.38 kV voltage a voltage unbalance is primary.

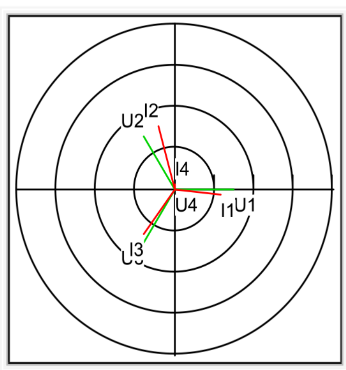
Due to the constantly growing number of the connections of low power single-phase domestic and lighting loads, total power of which in the end becomes significant in its extent. The single-phase load is determining also because of the modern trends of urbane-planning, which is linked to a transfer of the industrial enterprises to the suburbs.

Under unbalanced conditions, the voltage deviation of consumers, the deterioration of electric loads as to all network elements, the liability degradation of electric equipment operation and electrical power supply system as a whole are observed [6] [7]. The consequences of voltage unbalance are discussed in [8] on transmission lines, substation transformers. The main consequences of unbalance condition on power equipment such as power converters, induction motors, AC variable speed drive are discussed in [9] [10] [11] [12] [13]. Moreover, unbalanced condition lead to economic losses, where increasing the power losses is a constituent part.

In exit of the unbalance beyond limits set in normative documents the significant increase of supplementary losses is observed. The reduction of the voltage unbalance is appropriate even when it is within the permissible limits, because it



(a)



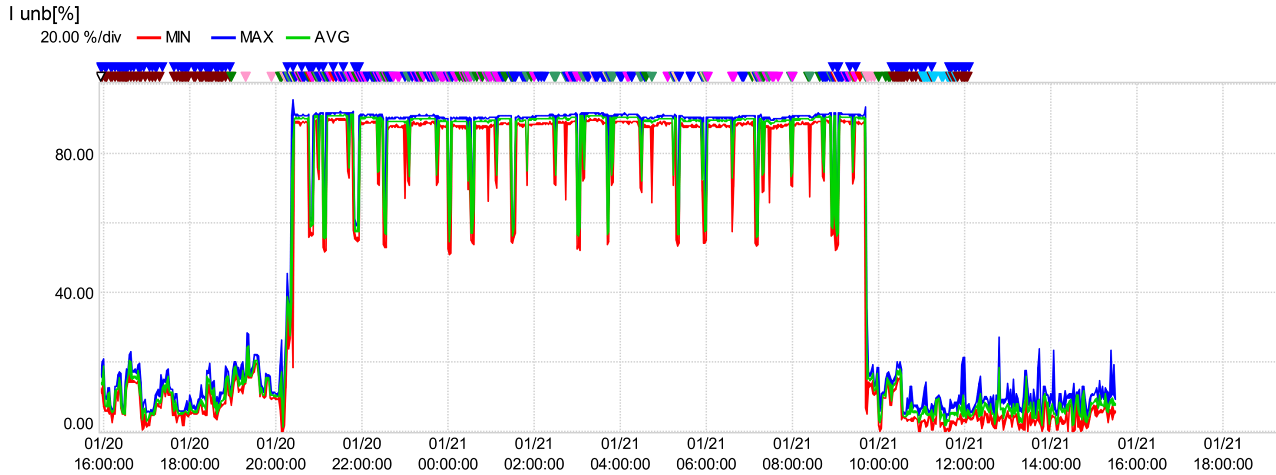
U1	222.95 V
U2	229.81 V
U3	226.49 V
U unb	0.84 %
U4	0.00 V

U:	
Positive	1.89 V
Negative	226.37 V
Zero	5.05 V

I1	29.79 A
I2	39.85 A
I3	34.12 A
I unb	11.38 %
I4	3.96 A

I:	
Positive	3.95 A
Negative	34.52 A
Zero	2.44 A

(b)



(c)

Figure 1. The typical characteristics of the current and voltage unbalance (measurements from a HIOKIPW3198).

will result in a loss reduction in electrical networks and loads. The Refs. [14] [15] [16] present approaches for reduction of energy losses in low voltage distribution network.

In this paper the balancing problem is considered not only as the means of the energy quality improvement, but also as the means of the efficiency and reliability improvement of the electrical power system as a whole. The subject of scientific research is the two-transformer substation of town electrical power supply system. The algorithm, which allows switching one-phase load, has been developed as one of a method of reducing the unbalance level. The algorithm is written in the function block diagram programming language. For determining the duration and magnitude of the unbalance level it is proposed to introduce the forecasting algorithm. The necessary data for forecasting is accumulated in the course of the algorithm based on the Function Block Diagram. The algorithm example is given for transforming substation of the urban electrical power supply system.

The outline of the paper is as follows: "Problem formulation" explores the main idea of the concept and the algorithm itself is defined in section "Algorithm description". The real data measurements and simulation results are presented in section "Results and discussions". Section "Conclusion" addresses the main benefits of the proposed concept.

2. Problem Formulation

The transformer substation of urban electrical power supply system is the subject of research. The transformer substation fragment simulated in the software complex is shown in Figure 1. There are two TM-630-10/0.4 transformers at the substation. The power supply of two nine-floor residential building is provided by this substation. An average load of these buildings is 385.66 kVA. The topology and section data of the urban network correspond to the actual operating conditions. The major part of losses in this network occur in the transformers and 0.4 kV cable lines, therefore the energy losses are considered in these elements. The substation was simulated in the software complex designed for the same tasks. The load is specified as one- and three-phase mixed load (quiescent—90%, drive—10%). Cosφ for each phase is specified as a random variable, wherein the average power factor is 80%. The load corresponds to the actual operating conditions and it is determined from the energy accounting meter of consumers. The standard daily load curve in phases for the residential building with the electrical cookers is taken to model the load. Mean power of the curve corresponds to monthly average consumed power, which is determined from the energy accounting meter. The substation load in phases as the histogram with accumulation is shown in **Figure 2**.

The motor load includes controlled induction and synchronous motors, capacitor voltage supply units, output capability of which remains constant when the voltage is changed.

The design of automated control system of unbalance in the distribution networks is one of a method of reducing the voltage unbalance. The use of such system will allow automatically remove the unbalance of three-phase system by the proportional redistribution of single-phase load in phases on the 0.4 kV substation feeder considering the forecasting data of unbalance occurrence.

3. Algorithm Description

The algorithm, which allows switching one-phase load, has been developed for the transformer substation. The single-phase transfer load sets as random variable in the range of 1% to 20% of each phase load. It is the obligatory condition—from phase to phase can be switched no more than 20% of the single-phase load. Operation algorithm and structure flow chart of the device is shown in **Figure 3** [17]. Data analysis is carried out with the microcontroller. Upon the results of the data analysis, control signal is fed to the valve keys and the load is switched to the least loaded phase. SCADA system TRACE MODE

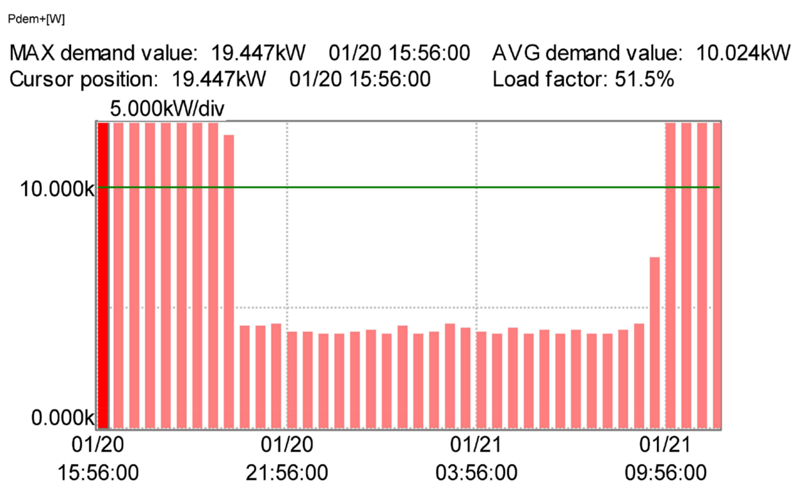


Figure 2. The load curve of the object under study.

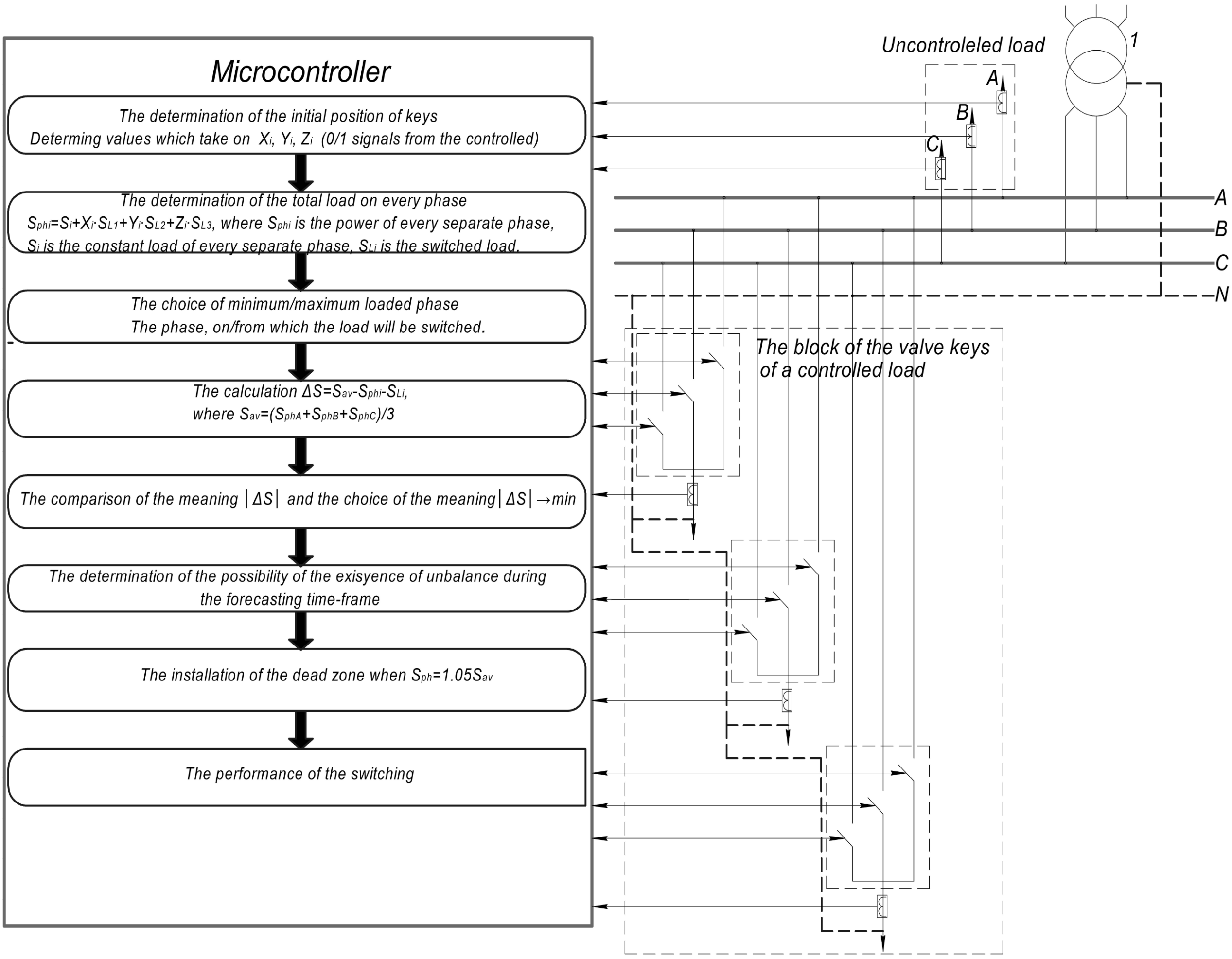


Figure 3. Operation algorithm and structure flow chart of the device.

was used to design and test algorithm. The algorithm based on the Function Block Diagram (FBD), the result is the hardware-software complex performing the function of matching device (MD). The example of algorithm part based on FBD is shown in Figure 4.

3.1. The Algorithm Based on the FBD

The first functional unit is programed to determine the initial position of keys, *i.e.* determine the meaning of X_i, Y_i, Z_i. The second unit performs a function of determining the total load on every phase, which is calculated as follows:

$$S_{phi} = S_i + X_i \cdot S_{l1} + Y_i \cdot S_{l2} + Z_i \cdot S_{l3},$$

where S_{phi} is the power of every separate phase, S_i is the constant load of every separate phase, S_{li} is the switched load. According to results, the next two units choose the maximum and minimum loaded phases to switch the load (from maximum to minimum). The functional unit of calculation of losses uses the following mathematical tools:

$$\Delta S = S_{av} - S_{phi} - S_{li},,$$

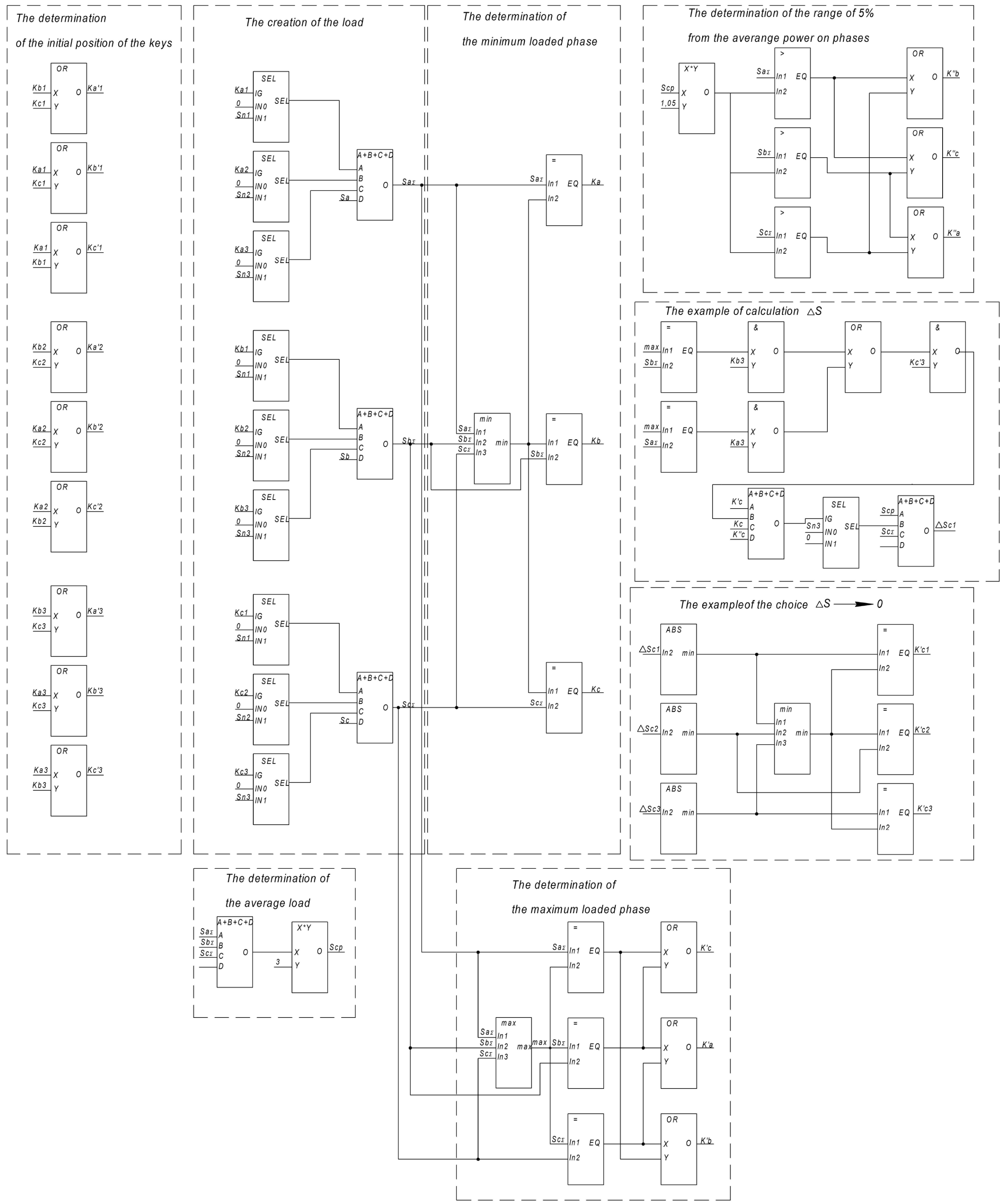


Figure 4. The example of algorithm part based on FBD.

further, the comparison unit perform the procedure and choose the minimal ($|\Delta S \to \min|$). On one of the final step of the algorithm, the functional unit is programmed to set the range ±5% from the average power on phases. The control signal won't be given on the valve keys in the range. The last step of the algorithm is the unit performing the switching. The introduction of forecast unit in the algorithm allows determining the length of time and significance of the unbalance level. The data obtained from the algorithm implementation, which is built on the FBD, is cumulative. Due to this the database to implement forecasting is formed. The forecasting time-frame is 25 minutes. The data analysis allows avoiding extra switchings, which cannot be justified from either an economic or technical point of view. The introduction of unit, which is programmed to set a turn-on delay, allows using the forecast data. The turn-on delay is equal to the forecasting time-frame.

3.2. The Forecasting Algorithm

As a forecast unit is used autoregressive moving-average model (ARMA (p,q))/Generalized autoregressive conditional heteroscedasticity (GARCH (p,q)), which is powerful tool to build accurate forecasts with a small forecasting time-frame. The ARMA-model generalizes two simpler models of time series: AR-model and MA-model. The ARMA-model is based on the fact that any series depend on past values, errors and past errors [18].

ARMA-model is described by the following equation:

$$y_t = C + \varepsilon_t + \sum_{i=1}^{p} \varphi_i \cdot y_{t-j} + \sum_{j=1}^{q} \theta_j \cdot \varepsilon_{t-j} ,$$

where p and q are integers, that determine the model order, C is constant, $\{\varepsilon_t\}$ is "white noise", the sequence of independent and identically distributed random variables (as a rule, normal) with mean zero, φ_i and θ_j are real numbers, autoregressive coefficients and coefficient of a moving average, respectively.

GARCH-process modifies the fact that current conditional variance depends on previous changes of the energy consumption and previous assessments of the conditional variance ("old news").

With the help of GARCH(p,q) model can be calculated conditional variance, the equation of which $\sigma_t^2 = E_{t-1}\left(\varepsilon_t^2\right)$ is

$$\sigma_t^2 = K + \sum_{i=1}^{p} G_i \cdot \sigma_{t-j}^2 + \sum_{j=1}^{q} A_j \cdot \varepsilon_{t-j} ,$$

with restrictions of $\sum_{i=1}^{p} G_i + \sum_{j=1}^{q} A_j < 1$, $K > 0$, $G_i \geq 0$, $A_j \geq 0$, where p is the number of previous assessments of the energy consumption, that can affect the current assessment, q is the number of the last changes of the energy consumption that can affect the current consumption, K is constant, G_i are weight coefficients determining the extent of the previous assessments of the energy consumption on current value, A_j are weight coefficients determining the extent of the previous assessments of the energy consumption on current consumption, ε is the previous changes of the energy consumption.

The forecasting model was realized using the software STATISTIKA, which allows estimating general model GARCH.

As a result, the model ARMA(1,1)/GARCH(1,1) is obtained with the following parameters (**Table 1**). The meanings of the standard errors are shown in brackets.

An analysis of the received data suggests a conclusion that all coefficients are significant as they exceed the error practically by an order of magnitude. All restrictions for the GARCH (p,q) model are implemented (K = 359,3306 > 0, G = GARCH(1) = 0.8837 > 0, A = ARCH(1) = 0.0134 > 0). Substituting these values, the following equations are obtained:

$$\sigma_t^2 = 359.3306 + 0.8837 \cdot \sigma_{t-i}^2 + 0.0134 \cdot \varepsilon_{t-j}^2$$
$$y_t = -0.6399 + \varepsilon_t + 0.4088 \cdot y_{t-i} + 0.1357 \cdot \varepsilon_{t-j}$$

Figure 5 shows the forecasting results.

4. Results and Discussions

Table 2 shows active and reactive power losses in the transformer and cable lines reduced by setting the balanced-to-unbalanced converter. Moreover, it also depends on the load, which has become more uniform and negative- and zero-sequence currents, which lowered.

An average for one day the use of balanced-to-unbalanced converter allows saving about 8% - 10% of the energy of the total consumption. In cash equivalents the saving is 30 - 40 rubles/day [19]. The pay-back times of the balanced-to-unbalanced converter is 6, 6 years considering the value of components required for the device realization. Microcontrol unit and solid state relay are the main elements of the device. Microcontrol unit has an economic life of 10 years under normal conditions [20]. The solid state relay is planned to more than 1 billion switchings [21]. Under the present operating conditions the number of switching is greater than the service life of the controller. Thus the use of single-phase switching device is the most cost-effective way for reducing current

Table 1. The coefficients of the ARMA(1,1)/GARCH(1,1) model.

Parameters	ARMA(1,1)	Parameters	GARCH(1,1)
C	0.6399 (2.081842)	K	359.3306 125.989190
AR(1)	0.4088 (0.079626)	GARCH(1)	0.8837 (0.039658)
MA(1)	0.1357 (0.083431)	ARCH(1)	0.0134 (0.003490)

Table 2. Power losses for one day if the balanced-to-unbalanced converter is installed.

	Without balanced-to-unbalanced converter		With balanced-to-unbalanced converter	
	ΔW_P, kWh	ΔW_Q, kWh	ΔW_P, kWh	ΔW_Q, kWh
Power losses in transformers	92.764	386.967	82.561	353.464
Power losses in cable lines 0.4 kV	111.313	21.694	105.931	20.998
The total power losses	204.076	408.661	188.492	374.461

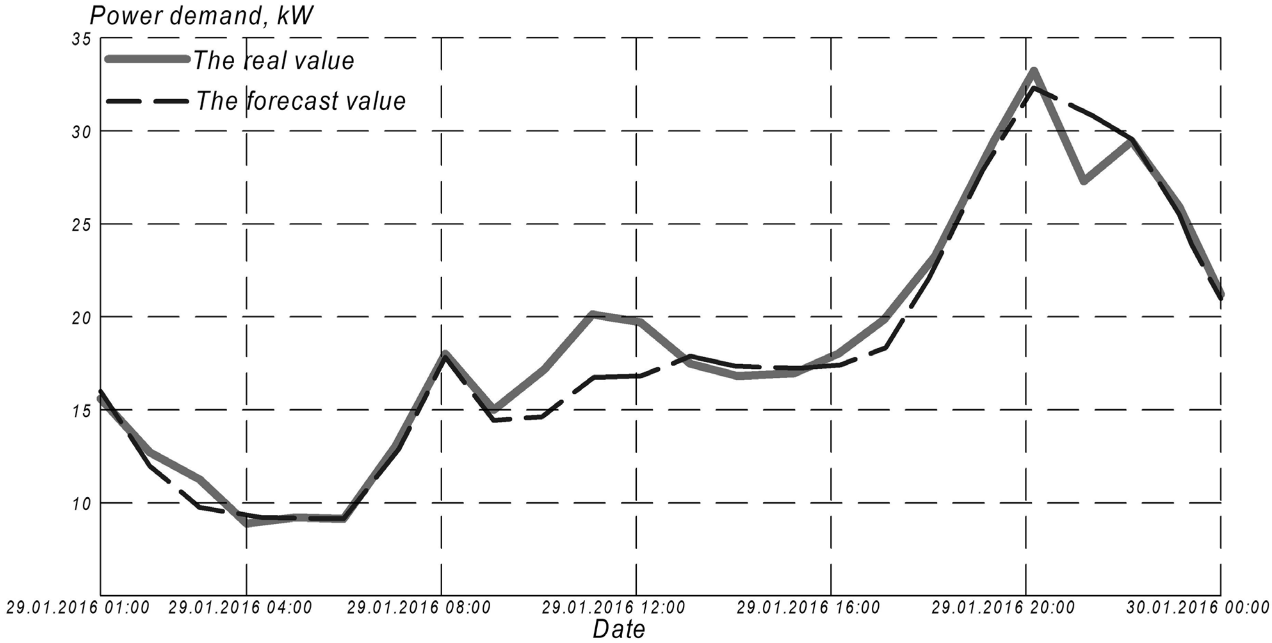


Figure 5. The forecasting results.

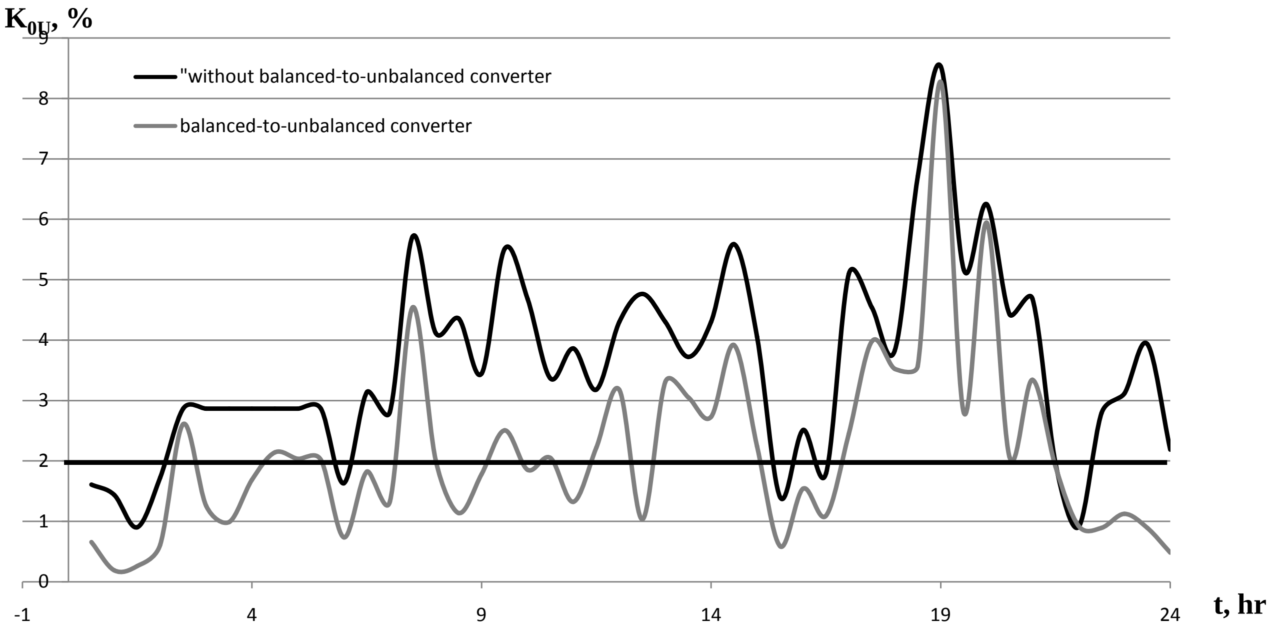


Figure 6. The graph of behavior of zero-sequence voltage unbalance ratio.

and voltage unbalance in town distribution networks. The use of automatic single-phase switching device for the substation allows to reduce energy losses (active energy losses decreased by 7.63%, reactive energy losses decreased by 8.37%). It also allows improving quality of the power supply. For the substation being studied the average zero-sequence unbalance factor reduced from 3.59% to 2.13% (**Figure 6**), and negative sequence unbalanced factor reduced from 0.61% to 0.36% (**Figure 7**).

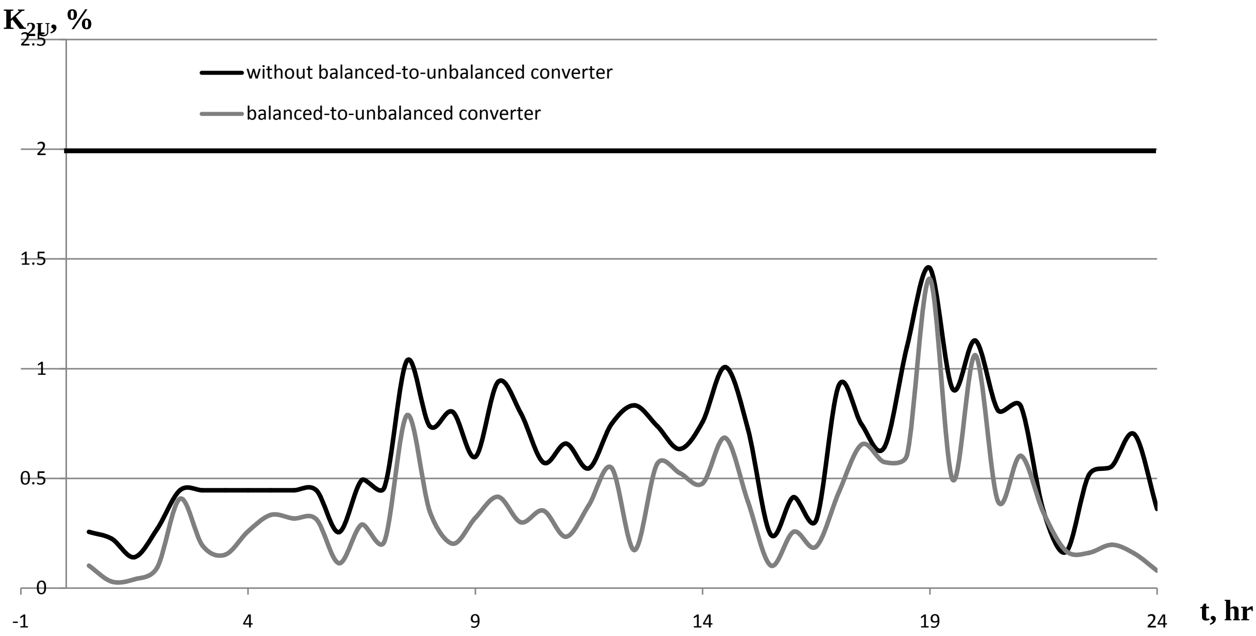


Figure 7. The graph of behavior of negative-sequence voltage unbalance ratio.

5. Conclusion

This paper investigates the method of reducing the unbalance level in town mains of 0.38 kV. In this purpose, the algorithm, which allows switching one-phase load, is presented. The algorithm includes forecast unit to avoid extra switchings. The proposed framework practically is performed on the Functional Block Diagram. The simulation of a real transformer substation of urban electrical power supply system demonstrated that the use of the proposed algorithm allows reducing consumption and losses. Finally, the use of the presented optimization method allows improving quality of the power supply.

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