Electricity supply reliability of the industrial enterprises with local power plants and the outage cost evaluation

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Abstract— **In this article, the algorithm of reliability evaluation of electricity supply systems operation is presented. It includes evaluation of the reliability of consumer's electricity supply and the reliability of power generation by the local power plants. Proposed algorithm is based on the method of sequential network reduction and allows calculating the reliability indices of the selected consumer or of the certain point of power distribution. This algorithm is implemented in the program complex (PC) KATRAN. The calculation of reliability indices allows assessing the consumer's outage cost and the interruption costs of the enterprise's power plants.**

***Keywords-** electricity supply reliability; reliability indices; power flow direction; sequential network reduction; electricity supply interruption costs.*

I. INTRODUCTION

Annual electricity shortage caused by the accidents for the large industrial enterprises in Russia is now several million kilowatt-hours. This situation calls for the development and practical application of calculation methods of the electricity supply systems reliability. The analysis of existing methods of assessing the reliability of electricity supply systems [1], [2], [3], [4], [5], had shown that the predominant methods and algorithms are focused on the simple open-loop networks and just small number of techniques designed for the backbone networks. Their application to the objects such as the electricity supply system of a large enterprise, which has, along with the multi-level-open networks of several voltage levels, the local energy sources and the closed-looped sections on the voltage of 110-220 kV, is difficult. Thus, the task of development the method of the equivalent reliability indices calculation for meshed interconnected network and creation of the software on the basis of such algorithm is important today.

II. ESTIMATION OF STRUCTURAL RELIABILITY OF A LARGE INDUSTRIAL ENTERPRISE

The algorithm for structural reliability evaluation of electricity supply system was developed at the Department of Industrial electric power supply, TU Magnitogorsk.

At the primary stage, the steady-state mode calculation, which is based on the method of sequential network reduction [6], is carried out. It is necessary for the further consideration of power flow direction when the reliability indices are calculated. This procedure makes it possible to exclude from the calculation the part of scheme which is not involved to the electricity transmission to any particular consumer.

The recursive bypass of the scheme, which starts with the selected element, is organized in the PC KATRAN [7]. The integrated power flow is defined for each connection with the adjacent elements. If the power flow direction is positive, the flag is set for the element, and then this element will be involved in the equivalent reliability indices calculation. The full bypass of the scheme is carried out, if there is identified an element for which the power flow direction is negative, such element is excluded from the scheme for the structural reliability calculation.

As an example, simple scheme of power supply of the consumers L1 and L2, receiving power from 3 sources G1, G2, G3 (Fig. 1) is considered. The power flow direction is determined for evaluation of reliability relatively to the consumer L2. The result is that element "B" is excluded from the scheme for reliability calculation.

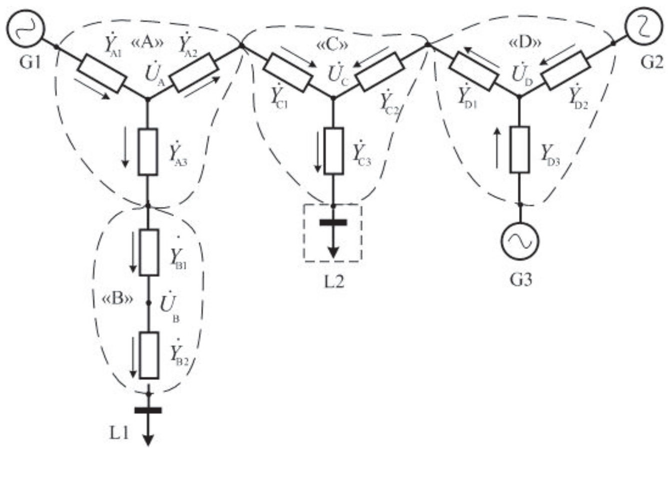

Figure 1. Nodalization diagram.

The analytical method was chosen to calculate the reliability indices. This method is used when the reliability of complex system, consisting of the large number of elements with known information about the reliability indices, structure and interaction between this elements, is analyzed. The block diagram scheme is formed for the reliability evaluation. This scheme is an analog of connections of the real circuit elements-transformers, generators, circuit breakers, power lines, buses.

The combination of the sequential network reduction method and the Newton's method [8], [9] is proposed for the reliability indices calculation for the meshed interconnected systems. According to the sequential network reduction method each element of the block diagram scheme is represented as a multi-beam star (Fig. 2), the form of which is determined by the number of element's connections at the scheme.

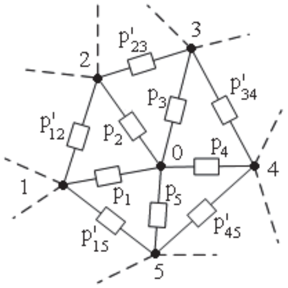

Figure 2. The segment of scheme before the excluding of node "0".

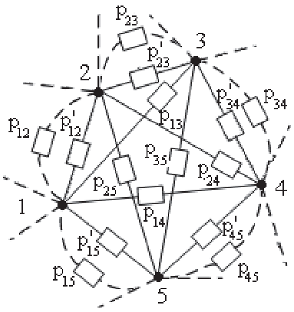

Figure 3. The segment of scheme after the excluding of node "0".

The procedure of replacement of the n-beam star by the n-gon with diagonals (Fig. 3) is the basis for transformation. It allows to reduce the number of elements at the each stage of transformation by one. For the excluded element the system of equations, which establish the connection between the probability of no-failure of the star (p_1, p_2, p_3, p_4, p_5 at Fig. 2) and of the polygon sides and diagonals (p_{12}, p_{13}, p_{14}, p_{15}, p_{23}, p_{24}, p_{25}, p_{34}, p_{35}, p_{45} at Fig. 3), has the following form:

$$\begin{cases} p_1p_2 - p_{12} - p_{14}p_{24} - p_{13}p_{23} - p_{25}p_{24} = 0 \\ p_1p_3 - p_{13} - p_{12}p_{23} - p_{14}p_{34} - p_{15}p_{35} = 0 \\ p_1p_4 - p_{14} - p_{13}p_{34} - p_{12}p_{24} - p_{15}p_{45} = 0 \\ p_1p_5 - p_{15} - p_{12}p_{24} - p_{13}p_{35} - p_{14}p_{45} = 0 \\ p_2p_3 - p_{23} - p_{12}p_{13} - p_{24}p_{34} - p_{25}p_{35} = 0 \\ p_2p_4 - p_{24} - p_{12}p_{14} - p_{23}p_{34} - p_{25}p_{45} = 0 \\ p_2p_5 - p_{25} - p_{12}p_{15} - p_{23}p_{35} - p_{24}p_{45} = 0 \\ p_3p_4 - p_{34} - p_{24}p_{23} - p_{13}p_{14} - p_{35}p_{45} = 0 \\ p_3p_5 - p_{35} - p_{13}p_{15} - p_{23}p_{25} - p_{34}p_{45} = 0 \\ p_4p_5 - p_{45} - p_{14}p_{15} - p_{24}p_{25} - p_{34}p_{35} = 0 \end{cases} \quad (1)$$

The Newton's method was chosen to solve (1) as the most efficient iterative numerical method for finding the roots of nonlinear equations. The obtained values of the probability of no-failure combined with existing ones in the scheme.

To determine the value of the system's failure intensity λ_{ekv} [10] the system of equations are compiled (2):

$$\begin{cases} \Lambda_{12} = \lambda_{12} + \lambda_{13}Q_{12} + \lambda_{14}Q_{12} + \lambda_{23}Q_{12} + \lambda_{24}Q_{12} + \lambda_{34}Q_{12} + \lambda_{45}\cdot 0 \\ \Lambda_{13} = \lambda_{12}Q_{13} + \lambda_{13} + \lambda_{14}Q_{13} + \lambda_{23}Q_{13} + \lambda_{24}Q_{13} + \lambda_{34}\cdot 0 + \lambda_{45}Q_{13} \\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \\ \Lambda_{45} = \lambda_{12}\cdot 0 + \lambda_{13}Q_{45} + \lambda_{14}Q_{45} + \lambda_{23}Q_{45} + \lambda_{24}Q_{45} + \lambda_{34}Q_{45} + \lambda_{45} \end{cases} \quad (2)$$

Or $\Lambda_{ij}=Q_{ij}\lambda_{ij}$, where $\Lambda_{ij}=\lambda_i+\lambda_j$, $Q_{ij}=1-\lambda_{ij}$.

From (2): $\lambda_{ij}=Q_{ij}^{-1}\Lambda_{ij}$.

On the basis of the equivalent values of the probability of no-failure p_{ekv} and the failure intensity λ_{ekv} the equivalent recovery time (3) is determined:

$$T_r = \frac{1-p_{ekv}}{\lambda_{ekv}} \quad (3)$$

More detailed description of the calculation algorithm is in [6], [11].

With the approbation purpose the algorithm was applied to the fragment of electricity supply system of the large industrial enterprise (Fig. 4). Assessment of the reliability of power generation by the local power plant with total capacity of 191 MW to the buses of the Substation 1 was carried out. The elements of part "A" (Fig. 4) were unaccounted for reliability indices calculation procedure as they don't participate to the electricity transmission to the buses of the Substation 1. The results of reliability indices calculation by using the PC KATRAN are shown in Table 1.

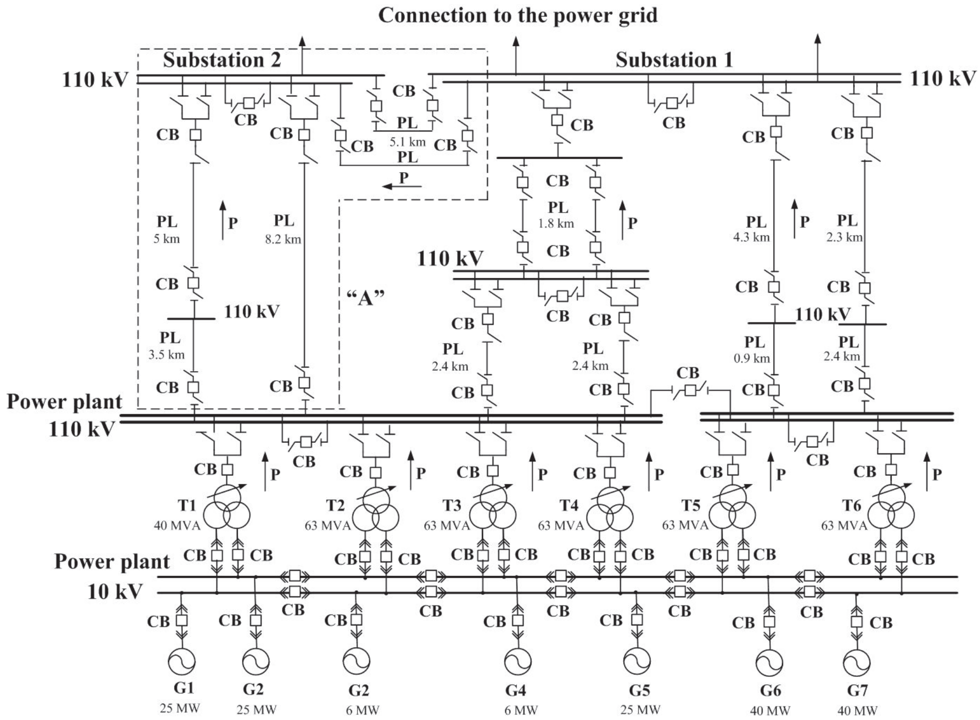

Figure 4. The fragment of the scheme of electricity supply system of the Iron and Steel Works: G - generator, T – transformer, CB – circuit breaker, PL – power line

TABLE I. THE RESULTS OF RELIABILITY INDICES CALCULATION

Operating mode	Probability of no-failure, p_{ekv}	Failure intensity, λ_{ekv} (1/h)	Restoration time, T_r (h)
Normal operating mode	0.9986	0.005987	0.2338
Planned maintenance of 1 CB, failure of 1 PL	0.9912	0.006043	1.4562

III. DAMAGE ASSESSMENT

Characteristic feature of the large industrial enterprise is the existence of local power plants. In general, the electricity supply interruption costs of such enterprise consist of the system's damage, the consumer's outage cost and the interruption costs of the enterprise's power plants.

1. The system's damage consists of the damage from frequency reducing in electricity supply system, the damage of consumers which was disconnected by the under-frequency load shedding (UFLS), the costs of creating the repair capacity reserve in system in case of the long lock-generating capacity of the power plant in repair modes.

2. The consumer's outage cost D_c (4) is caused by sudden interruption in the electricity supply, the consequence of which is the spoilage costs and the violation of technological process:

$$D_c = d_0 \cdot \Delta P \cdot T_r \tag{4}$$

where d_0 – the average damage, depending on the type of production, (RUB/kW·h) [12]; ΔP – reducing of the power plant load during T_r, (kW), T_r – system's recovery time, (h).

3. The electricity supply reliability of consumers with local power plant is mostly determined by the reliability of generating equipment. The interruption costs of the enterprise's power plant D_{st} (8) include the following components:

a) The damage from electric power underproduction D_u (5), which is caused by interruption of the power plant equipment operation. In this situation consumers would have to buy additional amount of electric power at a higher price:

$$D_u = (C_g - C_p) \cdot \Delta P_{st} \cdot T_r \tag{5}$$

where $(C_g - C_p)$ – the difference between the cost of electricity generated C_g by enterprise's power plants and purchased electricity C_p, (RUB/kW·h); ΔP_{st} – underproduction of power by local power plant during T_r, (kW).

b) The damage associated with additional fuel consumption D_f (7), which can appear in case of necessity of starting generating equipment operation, if it was stopped because of electricity interruption. The value of this damage depends on the time of liquidation of emergency mode (6):

$$T = T_r + T_{start} \tag{6}$$

where T_{start} – time necessary for starting equipment operation, (h); for example, the time to set generator load from hot position is about 0.5 hours and from cold position – from 3 to 8 hours.

$$D_f = k_{st} \cdot d_0 \cdot \Delta P_{st} \cdot T \qquad (7)$$

where k_{st} - coefficient depending on the time of liquidation of emergency mode T: $k_{st} = 2$, if $T > 1$h; $k_{st} = 1$, if $T < 1$ h.

$$D_{st} = D_u + D_f \qquad (8)$$

System's damage for the considered above example insignificant, because there are no consumers which can be disconnected by the UFLS and effect of system's frequency reducing for this scheme will be small in any operating mode. Main components of the total damage D (9) for large industrial enterprise with local power plants are the consumer's outage cost D_c and the interruption costs of the enterprise's power plant D_{st}:

$$D = D_c + D_{st} \qquad (9)$$

For the scheme (Fig. 4) on the basis of the reliability indices calculation the damage was assessed: D_c = 427 854 (RUB), D_{st} = 449 384 (RUB), D = 877 238 (RUB).

For the calculation the following values were taken: $C_g = 1.1$ (RUB/kW·h), $C_p = 2.39$ (RUB/kW·h), $d_0 = 18.3$ (RUB/ kW·h), $T_{start} = 0.1$ (h), $\Delta P = 100$ (MW), $\Delta P_{st} = 50$ (MW).

Thus, the probability of no-failure in normal operating mode p_{ekv}=0,9986 shows that electricity supply system of the Iron and Steel Works is reliable, but damage from the unreliability (D = 877 238 RUB) is high. To reduce its value some recommendations were given to increase reliability of the enterprise. For example, we can change the system structure by adding more protective devices or by updating of equipment.

Conclusion

The proposed algorithm makes it possible to calculate the basic reliability indices – probability of no-failure, failure intensity and recovery time. This algorithm can be applied for the schemes of any complexity, regardless of what elements predominate – connected in series or parallel, because the same procedure is used for the node elimination. Consideration of the power flow direction allows to carry out the on-line analysis of planning operating modes with account of scheme configuration. The comparison of different variants of normal and repair maintenance schemes of network, in the task of regime planning and reconstruction, is possible on the basis of reliability and damage indices assessment. The developed algorithm within the PC KATRAN is implemented in the exploitation at OJSC MMK (Joint Stock Company Magnitogorsk Iron and Steel Works, Russia). Thus, the algorithm presented in this paper can be used to evaluate the reliability of an existing distribution system and to provide useful planning information regarding improvements to existing systems and the design of new distribution systems.

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