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Development of Methods to Optimize the Number and Places of Installation of Active-Adaptive Sectionalizing Elements with an Assessment of the Effectiveness of Measures in the Distribution Network

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***Abstract*—Today there is no generally accepted methodology for determining the optimal locations of division of distribution network sections, despite a wide arsenal of sectionalizing equipment. Recently, active-adaptive elements with high technical efficiency have been widely used in 6(10) kV networks: automatic reclosers and load breakers. Their use contributes both to the self-restoration of distribution network sections under unstable faults and allows automatically localize stable faults. Widespread introduction of sectionalizing equipment should consider the economic feasibility (efficiency) of its installation, depending on many factors and the allowable payback period of measures.**

This work is aimed at solving the actual problem - the development of methods and algorithms for optimal selection of installation sites, type and number of sectioning devices for feeders (trunks and extended branches) for a particular loaded network. Decision-making criteria for feeders with different degrees of distributed load are the frequency and duration of power outages, the values of the average annual shortfalls of electricity and consumer losses, losses (load and no-load) when optimizing the points of network disconnection under the condition of maintaining normal voltage levels in the points of its release.

Practical significance of the work consists in the development of methods and algorithms for optimal selection of installation locations, type and number of sectioning devices for ringed feeders with calculation of payback period of the invested funds.

Keywords*—*distribution network, power supply reliability, recloser, network modeling, statistical test method, optimization criterion.

I. INTRODUCTION

Power supply schemes (PS) distribution networks (DN) are formed of overhead and cable lines (TL) of high voltage 6 ÷ 35 kV and distribution transformer substations (TS) of different versions at 6-35/0,4 kV. Power transmission lines of the DN are connected to the power centers (CP) 6 (10) kV. Network with a radial structure of trunks and branch lines contains hundreds of pieces of equipment, which in operation is exposed to a wide range of external influences, modes of operation and maintenance, which cannot always be accurately modeled. Reliability of electrical installations is estimated by a complex of reliability indices (RI) [1]. Their assessment is based on the statistical method, including the collection and processing of operational statistics.

The tasks of optimizing the structure and improving the efficiency of DN are the most relevant at the present stage of their development and expansion [2], when connecting new energy sources with the analysis of the reliability of schemes by many modern methods [3]. Based on the processing of a large amount of information of offline and online subsystems [4], simulation of functioning of the whole complex of electrical equipment of DN [5], including additional energy sources [6], in order to maintain normative indicators of reliability and requirements of regulatory bodies [7]. When assessing the reliability of branched DN, models based on statistical testing method (Monte Carlo, MC) [8] are developed due to their advantages in describing event flows, including the use of multilevel modeling [9] and cross-entropic approaches [10]. The presence of high-tech industries and consumers in the DN also imposes increased requirements on the quality of electricity, by connecting reactive power compensation devices, in addition to diesel generator sets, in order to maintain voltage levels in the nodes of the DN [11,12].

Consideration of the reliability factor involves determining the so-called complex RIs (CRIs), including the total shortfall in electricity supply ΔW_e and the average annual probabilistic losses L_e at consumers. Other CRIs of DN feeders at time

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intervals multiple of a calendar year are also important $.T_y$., including the efficiency index K_{tu} .

Improving reliability involves not only the connection of backup sources in the DN [13,14], but also the use of automatic sectionalization of its sections, with the introduction of elements of smart grids: multi-agents and the entire DN infrastructure [15, 16].

To improve the efficiency of investment in DN it is necessary to consider many components, and the decision-making criteria should provide not only a given level of reliability [17,18], but also economically justified level of investment, leading to the reduction of damages, operating costs, including losses $\Delta P_{L,\Sigma}$ [19], while ensuring the quality of power at the points of its release.

The relevance of the article is due to the need: to develop reliability models and performance criteria of real DN with an assessment of the economic feasibility of their modernization; formation of generalized electronic databases to obtain reliable operational RI of electrical equipment DN and the values of specific damages of different categories of consumers [19].

The paper proposes a new approach to optimizing the number and locations of sectionalizing DN by the criteria of reliability and minimum losses, considering the allowable payback period of the measures taken on feeders with real and projected load.

Theoretical and methodological basis of the research consists in the use of system approach and mathematical modeling, which were determined by the set tasks and based on the theory of electric circuits, probability theory and mathematical statistics, theory of reliability of technical systems, methods of economic efficiency of investments in electric power facilities. Information base of the research includes data obtained as a result of collection and processing of a large amount of information on reliability of electrical equipment of operating DN for 2009-2014. [19].

II. MATERIALS AND METHODS

Obviously, the effect of reducing the values of ΔW_e , L_e фтв $\Delta P_{L,\Sigma}$ in the DN should in realistic terms (several years) override the investment Inv and the following annual total costs L_{Σ} [19]. The value of L_{Σ} is the sum of constant L_{const} and variable L_{var} components. In this case, such a component L_{const} as losses in the wires, can be reduced by optimizing the points of disconnection of ringed feeders in the DN, and the reduction L_{var} will occur with the installation of automated devices for locating and searching for faults, as transportation costs in the DN will be significantly reduced.

Considering the above, let us write down the expressions for multi-criteria optimization when sectioning looped feeders as follows:

$$\begin{cases} \Delta P_{L,\Sigma} \to \min,\ U_{rp,j} \ge \left(1 \pm 0{,}1\right) U_{nom}; \\ \Delta W_{e,\Sigma} \to min,\ L_{F,\Sigma} > F_{adm}\left(Inv_{a,\Sigma} + Inv_{m,\Sigma}\right); \\ L_{F,\Sigma} = \sum\limits_{j=1}^{m} q_j \cdot T_k \cdot P_{mean,j}\left(c_t + y_{0j}\right), \end{cases} \tag{1}$$

where $\Delta P_{L,\Sigma}$ - total load losses on the feeder, kW; $U_{rp,j}$ - is the voltage at the *j-th* point of EE supply, kV; $\Delta W_{e,\Sigma}$ - value of total energy shortage to consumers in the feeder, kWh/year; $L_{f,\Sigma}$ - total annual average probabilistic damage on the feeder, RUR/year; F_{adm} - acceptable value of the efficiency factor Inv at the selected financing strategy, 1/year; $Inv_{a,\Sigma}$ - amount of lump-sum investments for the measures, RUR y_{0j} - specific damage at *the j-th* consumer, rub/kWh; c_t - tariff for power transmission, rub/kWh; T_k =8760 h - calendar period; $P_{mean,j}$ - annual average feeder load at the *j-th* point of EE discharge, kW; q_j - is the probability of *j-th* consumer disconnection.

By minimizing the value $\Delta P_{L,\Sigma}$ while maintaining the normative levels of voltages $U_{rp,j}$ in the points of release of electricity, we mean the reduction of load losses by optimizing the points of disconnection of looped feeders 10 kV based on the known rule of moments for the currents or capacities [20]. At the same time, a parallel calculation of the 0,4 kV network mode, it must be confirmed the ability to maintain the required voltage levels (1) for the most remote points by means of network regulation [21]. The value of $\Delta W_{e,\Sigma}$ can be reduced within the acceptable payback period $Inv_{a,\Sigma}$ by reducing the calculated values $L_{f,\Sigma}$.

Given that the feeders consist of the lines themselves (trunk sections and branches), and a large number of TSs, the fixed and variable annual additional components after the modernization of the DN - $Inv_{m,\Sigma}$, can hardly exceed the range of 5-10% of the total cost of the sectionalizing measures [19]. $Inv_{m,\Sigma} \le 0{,}1$ $Inv_{a,\Sigma}$. Then, as a result of the measures carried out at the DN objects, we obtain the reduction of the value $L_{F,\Sigma}$ by the value of $\Delta L_a = L_{F,\Sigma} - L_a$ where the component L_a , from the measures carried out on the feeders is determined by calculation.

Then the general form of the expression for assessing the effectiveness of measures for sectionalizing the feeder DN write as

$$\Delta L_a \ge 1{,}1 F_{adm} Inv_{a,\Sigma} \tag{2}$$

In practical calculations the value of F_{adm} can be assumed to be in the range of values 0,1 ÷ 0,5 (the expected allowable payback period of 2 ÷ 10 years).

As an object of modeling, let's consider the circuit of the RC on the example of two looped feeders, each of which is powered from different CP 10 kV C1 and C2 (Fig. 1). The DN is suburban, the average loads of the TS are shown in Table 1. The diagram shows the lengths of the main sections of the feeders and branches, and the nominal capacities of the TS. Feeders are interconnected by ring disconnector KP1, and the trunk sections are sectioned by line disconnectors LR1, LR2. As noted in [14], the operational switching with consecutive switching of LR and supplying power to the undamaged sections with fault location (makes up to 60% of the total time, 40% - actual repair), leads to long interruptions. According to some estimates, the number of disconnections of 6(10) kV feeders per 100 km length is up to 30 times a year or more.

Let us propose for further consideration three network variants: the first variant B1- the original scheme, in the second variant B2 we will replace CR1 with recloser P2 (optimization of the breaking point was not carried out), and in variant B3 we will replace LR1 and LR2 with reclosers P1 and P3.

Reliability analysis will be carried out based on the MC method, for which the input data are:

- Engineering conditions of system operation and observation period T_{obs} (number of levels of facility operation S_i and their values: the number of elements taken into account and their carrying capacity, providing these levels S_i logic of operation of automation devices (protections), the duration of the considered time intervals, etc.);
- Information about the RI (type of laws of event fluxes distribution and their parameters): mean time before failure and restoration of the main elements of the DN - circuit breakers, power lines, TS, reclosers, etc.;
- Statistical series of intervals between deliberate maintenance outages, current and overhauls and their durations (integral characteristics);
- Periods of blackouts due to natural phenomena and the duration of their recovery in the DN.

When forming the computational scheme, the equipment with the simplest failures is combined into blocks of series and parallel elements, the event flows of which are not the simplest. A generalized reliability substitution diagram (GRSS) is shown in Fig. 2.

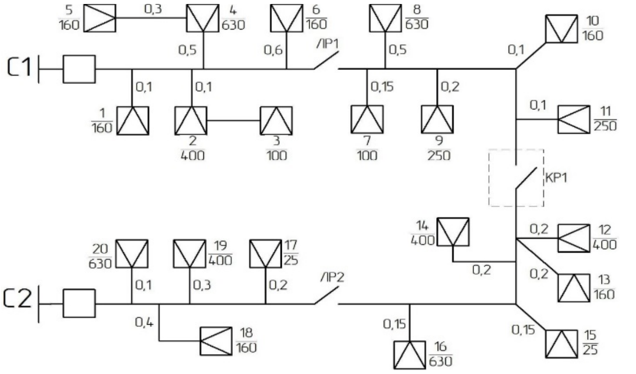


Fig. 1. Principle electric diagram of 10 kV distribution network: 1/160 - number of TS (Substation) and capacity in kVA; 0,1; 0,2; ... - length, km of feeder branches from the main to TS (Substation).

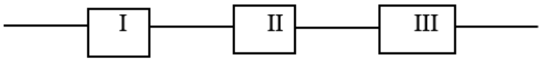


Fig. 2. Generalized reliability substitution scheme.

Considering the capabilities of the MC method, we intentionally dissected the GRSS into a block I of elements with simple failures, a block of current and overhaul repairs II and a block III, modeling external natural influences. Let's analyze them separately and give calculation formulas for CRI.

For block I, the element failure streams are simple and independent. The frequency of its failures ω and the resulting probability of failure Q are related by the relation:

$$Q = \omega \frac{T_r}{T_k}, \tag{3}$$

where T_r - average recovery time, h; T_k =8760 h.

Failures of network elements, leading to a complete failure of block I, form during the time T_k so-called coefficient of unscheduled downtime K_{upd} of consumers due to equipment failures. In the index K_{upd} it is necessary to consider the probability of failure of unit 3 - q_{ec} due to natural phenomena, i.e.

$$K_{upd} = q_1 + q_3 = Q + q_{ec} \tag{4}$$

where $q_3 = q_{ec}$ - is the probability of DN failure due to natural phenomena (external causes).

The coefficient of planned downtime of a section of the DN K_{pd} is defined as the proportion of time in the year during which deliberate shutdowns due to maintenance, current and overhaul

$$K_{pd} = \frac{T_{mt} + T_{mw} + T_{oh}}{T_k}, \tag{5}$$

where T_{mt}, T_{mw}, T_{oh} - respectively the average times of maintenance, current and overhaul for the time T_k. Then the readiness factor K_R of the section DN

$$K_R = 1 - K_{upd} - K_{pd} \tag{6}$$

In addition to the above, it is important to calculate such informative CRIs as ΔW_e and technical utilization factor K_{tu} of a network section

$$\Delta W_e = \left[\omega_{\text{o}} T_{rf} + \omega_{\text{c}} T_{rec}\right] P_{mean} \cos\varphi, \tag{7}$$

where T_{rf} - average recovery time of the DN because of equipment failures, h; T_{rec} - recovery time due to natural phenomena, h.; $\omega_o; \omega_c$ - equipment failures and natural phenomena frequencies, respectively, 1/year; P_{mean} - average annual active load power, kW with power factor $\cos\varphi$. Through the value of ΔW_e, we can determine the value of economic losses L_e for the DN by expression (1), where c_t =2,9 RUR/kWh in the network 10 kV.

The coefficient K_{tu} (technical efficiency) is determined from the ratio

$$K_{tu} = \frac{\left(K_R + K_{pd}\right) \cdot P_{mean}}{P_{mean,\,\max}}, \tag{8}$$

where $P_{mean,\,\max}$ - is the maximum declared load of the electric installations of consumers of DN, kW.

As noted above, installing reclosers will bring changes to the performance T_{rf} и T_p [14], because the line restoration time will be reduced to an average of 40% when installing reclosers instead of LR1, LR2, and KR1 (option 3) and by 20% when replacing KR1 with a recloser (option 2).

Below are the GRSS variants of the DN scheme, representing sections of feeders with corresponding levels of trunk load *Si*, and the degree of automation with the described logic of automatic reclosers.

<u>Variant 1.</u> GRSS for the original scheme of DN (LR1, LR2, KR1) (fig. 3).

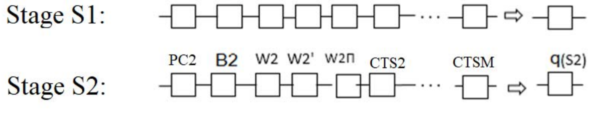


Fig. 3. Generalized Reliability Substitution Scheme for Variant 1.

Probability of total failure of levels $(S1 + S2)$:

$$Q(S1 + S2) = q(S1) \cdot q(S2).$$

In the calculations for CP1,2 we will assume that the probability of failure of each of them q_{pc} = 0,001 [19]. For switches B_i: the parameter of a stream of failures is frequency of failures at $\omega = m / n$ where n - total number of 10kV circuit-breakers installed at substations and district power grids; *m* - total number of their failures over time T_{obs}.

The probability of breaker failure is defined as

$$q_{rec} = \omega \cdot T_{rf};\ T_{rf} = \sum_i^m \frac{T_{rf,i}}{m}.$$

For the line W_i let's define: $T_f = \dfrac{\sum_i^k T_{f,i}}{k}$; $T_{rf} = \sum_i^k \dfrac{T_{rf,i}}{k}$

where *k* is the number of total failures and restorations. Per 100 km of length $\omega = \dfrac{T_k}{T_f}$ 1/year.

Then the failure probability of the line q_w, whose length is ℓ_{w1}

$$q_w = \omega^* \frac{T_{rf}}{T_k} = \frac{0{,}01 \cdot \ell_{w1} T_{rf}}{T_f} \tag{9}$$

Determine the indicators ω_i' and q_i' for the circuit element $\mathrm{W}_i' \cdot (\omega_c, \mathrm{T}_{rf_c})$ – caused by natural phenomena is not possible within the framework of this publication. Therefore, we will assume that the indicators ω_i' and q_i' are accounted for in the corresponding general indicators ω_i' and q_i'.

Indicators of intentional outages (per 100 km) for maintenance, repair and overhaul in calculations by variants of DN are as follows $\mu_p = 4{,}5$; T_r = 8h [18]. Considering the latter, the probability of line disconnection will be

$$q_w = \omega \cdot \frac{T_{rf}}{T_k} + \mu_p \cdot \frac{T_r}{T_k} = \frac{0{,}01 \cdot \ell_{w1}\left(\omega \cdot T_{rf} + \mu_p \cdot T_r\right)}{T_k}$$

<u>Variant 2.</u> NSA for DNs with LR1, LR2 and P2 Considering the ringing automatic recloser P2 included in the scheme with the ATS function, we obtain an expression for the probability of total feeder failure relative to the level $S1 + S2 : q(S1) \cdot q(S2) + qp2$. The difference from Variant 1 is in the definition of the line indicators W_i : $T_f = \sum_i^\ell \dfrac{T_{f,i}}{\ell}$;

$T_{rf} = \sum_i^\ell T_{rf_i}\left(1 - K_{re}\right) / \ell$ where K_{re} - is a coefficient taking into account the effect of recloser reclosure, after which up to 20% of faults are self-recovering. In our case $K_{re} = 0,2$; ℓ - is the number of feeder trips due to unrecovered faults. In variants 1 and 2 the coefficient of planned downtime, considering the real length of the lines will be determined as $K_{pd} = 0,01 \cdot \mu \cdot \ell_w \cdot \dfrac{T_r}{T_k}$.

Variant 3. GRSS for the DNs with P1, P2, P3. It will correspond to the following scheme of substitution with power levels of sites S_i. Considering the logic of reclosers with relay protection and recloser functions, the failures of the latter occur both in a static state (their own failure) and when they make automatic switching operations at failures in adjacent bays, characterized by the coefficient a_{auto} [19].

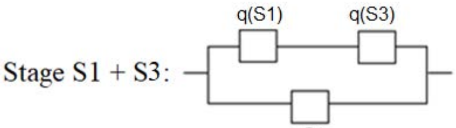


Fig. 4. Generalized Reliability Substitution Scheme for Variant 3 (Stage S1+S3).

$$Q \cdot (S1 + S3) = \left[q(S1) + q(S3) \right] \cdot q_{p1}$$

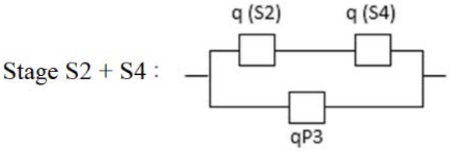


Fig. 5. Generalized Reliability Substitution Scheme for Variant 3 (Stage S2+S4).

$$(S2 + S4) = \left[q(S2) + q(S4) \right] \cdot q_{p3} Q$$

The recovery time of the lines during k of outages will be determined as

$$T_{rfw} = \sum_i^k T_{rf_i} \left(1 - K_{re}\right) \cdot \frac{\overset{=}{k}_S}{k}, \tag{10}$$

where $\overset{=}{k}_S$ - is a coefficient that considers the localization of damage by reclosers and the accelerated search for the fault location. In the usual scheme B1 without reclosers, 40% of the time from $T_{вw}$ is actually the time of line repair, therefore k_s = 0,4.

Whence the ratios $\omega_w = 0,01 \cdot \omega \cdot \ell_{w1,2}$;

$$q_w = \omega_w T_{rf} = \frac{T_k}{T_{н_w}} \cdot T_{rf_w} = \frac{0,01 \cdot \ell_{w1,2} \cdot \sum_i^k T_{rf_i} \left(1 - K_{re}\right) \cdot \overset{=}{k}_{pd}}{T_{н_w} \cdot k} \tag{11}$$

Let's define the coefficients K_{upd} и K_{pd} for circuit W1 - W3 by expressions

$$K_{upd_{w1,3}} = Q_{w1,3} = q_{pc} + q_{\text{в}1} + q_w + q_{w'}; \tag{12}$$

$$K_{pd_{w1,3}} = 0,01 \cdot \mu_p \cdot \ell_{w1,2} \cdot T_{\text{р}}; \tag{13}$$

Let's determine the electricity shortfall in option B3.

$$\Delta W_e = \left(K_{upd_{w1,3}} + K_{pd_{w1,3}} \right) \cdot T_k \cdot P_L \cos \varphi; \tag{14}$$

Similarly, circuit indicators W2 - W4 are determined.

Probability Q_n and the frequency ω_n of a complete failure of the DN can be found from the expressions

$$Q_{\text{п}} = q_{w1,3} \cdot q_{w2,4} = K_{upd1,3} \cdot K_{upd2,4};$$

$$\omega_n = \omega_{w1,3} \cdot q_{w2,4} + \omega_{w2,4} \cdot q_{w1,3} \tag{15}$$

The algorithm and methodology of calculating the CRI of the DN is given by the example of variant 3. The calculation scheme with P1 and P3 has an additional advantage in reducing the time to find the fault location, because the damaged trunk section is localized by automatic switching off: either reclosers P1 or P3 and, respectively, the main circuit breakers CP 1 or 2; or P1 or P3 and P2. As a result, its GRSS, unlike Variant 1, contains elements P1 and P3, which divide the lines W_1 and W_2 into 2 sections W_1, W_3 and W_2, W_4, respectively, and divide the load into $S_1^{'}, S_3^{'}$ and $S_2^{'}, S_4^{'}$, whereby $S_1 = S_1^{'} + S_3^{'}; S_2 = S_2^{'} + S_4^{'}$.

In contrast to the scheme of variant 2 in the scheme of variant 3 when localizing the fault, only part of the load of the lines is disconnected $S_1^{'}, S_2^{'}, S_3^{'}$ *or* $S_4^{'}$ which leads to a decrease in the under-supply to the consumers of the DN.

The computational algorithm of the model is as follows:

- At the time interval T_{obs} = 10 years for lines W1 - W3 with loads $S_1^{'}$ и $S_3^{'}$ we start the process of random variable generation $T_{f,i}$, $T_{rf,i}$, $T_{rt,i}$, $T_{r,i}$, provided that

$$\sum_i (T_{f,i} + T_{rf,i}) \le T_{obs}; \ \sum_i (T_{rt,i} + T_{r,i}) \le T_{obs}.$$

- We determine the average values T_f, T_{rf}, T_{rt}, T_r after processing the corresponding arrays by the expressions

$$T_f = \sum_i^m T_{f,i} / m; \ T_{rf} = \sum_i^m T_{rf,i} / m;$$

$$T_{rt} = \sum_{i}^{k} T_{rt,i} / k \;\; ; T_r = \sum_{i}^{k} T_{r,i} / k \, .$$

- Calculate the probability of failure states of feeders W1 - W3 with load $S_1^{'}, S_3^{'}$;

$$Q\left(S_1^{'}\right) = 0,01 \cdot \ell_{w1} \cdot T_{rf}\left(1 - k_{re}\right) \cdot k_s / T_f$$

$$Q\left(S_3^{'}\right) = 0,01 \cdot \ell_{w3} \cdot T_{rf}\left(1 - k_{re}\right) \cdot k_s / T_f$$

Similarly, to steps 1-3 perform calculations for feeders W2 - W4 with loads S_2, S_4.

- Calculate the CRI, considering the adjacent section W1 - W3

$$K_{upd}\left(S_1^{'}\right) = Q\left(S_1^{'}\right) = q_{pc1} + q_{rec1} + q_{w1} \, ;$$

$$K_{upd}\left(S_3^{'}\right) = Q\left(S_3^{'}\right) = q_{r1} + q_{w3} \, ;$$

$$K_{u\,pd}(S_1) = K_{u\,pd}(S1') + K_{u\,pd}(S3');$$

$$K_{pd}\left(S_1^{'}\right) = T_{r1} / T_{rt1} \;\; ; \;\; K_{pd}\left(S_3^{'}\right) = T_{r3} / T_{rt3}$$

Given that the adjacent sections of lines W1 - W3 are consecutive, the total value of K_{upd} и K_{pd} looks like

$$K_{upd}\left(S_1^{'}\right) + K_{upd}(S_3^{'}) = Q\left(S_1^{'}\right) + Q(S_3^{'}) =$$
$$= q_{pc} + q_{rec1} + q_{w1} + \; q_{p1} + q_{w3}$$

$$K_{pd}\left(S_1^{'}\right) + K_{pd}(S_3^{'}) = \frac{T_{r1}}{T_{rt1}} + \frac{T_{r3}}{T_{rt3}}$$

- Similarly, we calculate the efficiency factor for the section W2 - W4 and determine the values of energy shortfalls ΔW_e:

Electricity underflow on feeders ΔW_e will be defined as

$$\Delta W_{e1} = \left[K_{upd}\left(S_1^{'}\right) + K_{pd}\left(S_1^{'}\right)\right] \cdot T_k \cdot P_{L1} \cdot \cos\varphi;$$

$$\Delta W_{e3} = \left[K_{upd}\left(S_3^{'}\right) + K_{pd}\left(S_3^{'}\right)\right] \cdot T_k \cdot P_{L3} \cdot \cos\varphi.$$

The above expressions do not take into account the probability of complete repayment of all consumers of DN. Objectively, such a probability exists (overlapping of the failure of one feeder with the scheduled repair of the other, the repayment of both CPs$_1$ and CP$_2$, etc.), and is defined as

$$Q_{1,2} = K_{upd}\left(S_1\right) \cdot K_{upd}\left(S_2\right) = Q\left(S_1\right) \cdot Q\left(S_2\right)$$

Then, the total shortfall in the DN (feeders 1 and 2) ΔW_{Σ} will be determined by the expression

$$\Delta W_{\Sigma} = \Delta W_{e1} + \Delta W_{e2} =$$
$$= \left[\left[(K_{upd}\left(S_1\right) + K_{pd}\left(S_1\right)\right) \cdot P_{L1} \cdot \cos\varphi + \left(K_{upd}\left(S_2\right) + K_{pd}\left(S_2\right)\right) \cdot P_{L2} \cdot \cos\varphi\right] \times$$
$$\times T_k + \left[(K_{upd}\left(S_1\right) + K_{pd}\left(S_1\right)\right) \cdot \left(K_{upd}\left(S_2\right) + K_{pd}\left(S_2\right)\right) \cdot T_k \cdot \left(P_{L1} + P_{L2}\right) \cdot \cos\varphi]$$

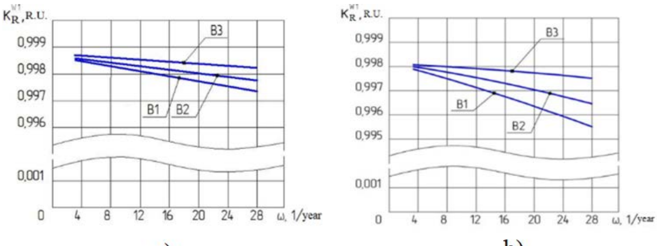
III. RESULTS

The actual feeder loads are shown in Table 1. Below is the calculation of the CRI and the analysis of the results. Graphical dependencies $K_R = f\left(\omega\right)$ for different line lengths are shown in Fig. 3.

TABLE I. TP FEEDER LOADS

NO. TP	Power, kVA	P_{mean}, kVA	NO. TP	Power, kVA	P_{mean}, kVA	NO. TP	Power, kVA	P_{mean}, kVA
1	160	60	8	630	220	15	25	5
2	400	150	9	250	80	16	630	240
3	100	20	10	160	45	17	25	6
4	630	190	11	250	110	18	160	64
5	160	40	12	400	210	19	400	140
6	160	35	13	160	45	20	630	200
7	160	29	14	400	190			

In connection with the calculated values of $\Delta L_e = (\omega)$ for different line lengths, it is appropriate to evaluate the effect on K_R of the total length (Fig. 4). As it increases, readiness rates expectedly decrease in the network variants. However, the degree of line automation has a significant influence on the dependence drop gradient, which indicates a decrease in the downtime duration after emergency and operational feeder outages due to the faster detection and elimination of damages.



a) b)

Fig. 6. Dependence $K_R = f\left(\omega\right)$ in relative units (R.U.) for feeders W1 (a) and W2 (b) for total line lengths of 10 and 20 km, respectively, by network variants.

Fig.5 shows the dependences $L_{e\Sigma} = f\left(\omega\right)$ The dependencies, based on the calculated data, show how the length of overhead lines and the degree of their load affect the reliability and performance indicators of DN variants. The dependence of the indicator $L_{e\Sigma} = f\left(K_{R\Sigma}\right)$ for B1 with a line length of 20 km at different degrees of consumer load relative to the declared $S_{L,i}$ 1 - 50%; 2 - 75%; 3 - 100% is shown in Fig. 6.

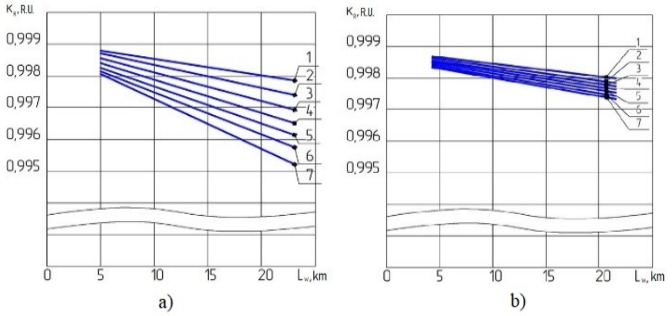


Fig. 7. Dependence $K_R = f(\ell\ \omega)$ in relative units (R.U.) for variant B1 (a) and variant B3 (b) at the frequency of outages 1/year: 1-4; 2-8; 3-12; 4-16; 5-20; 6-24; 7-28.

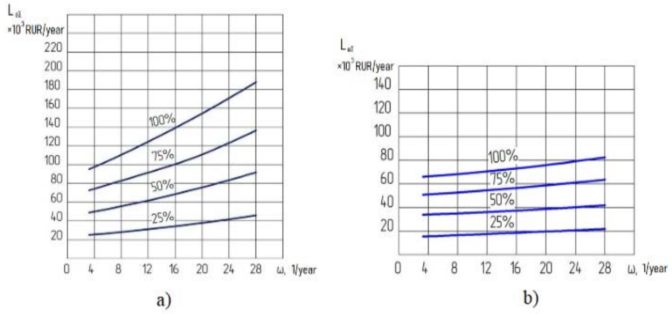


Fig. 8. Dependencies $L_{e\Sigma} = f\left(\omega\right)$ of variant 1 (a) and variant 3 (b) of the network at the degree of loading of feeders W1-W2 with the length of 20 km.

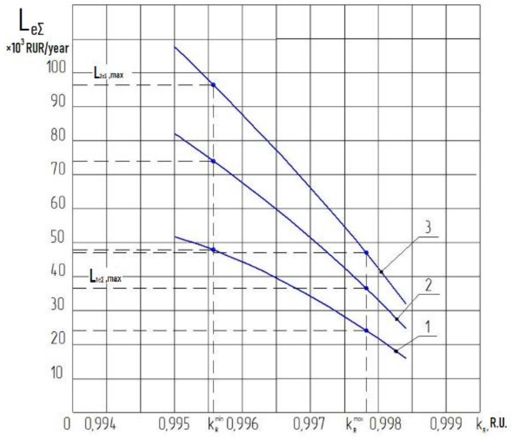


Fig. 9. Dependence of B1 $L_{e\Sigma} = f(K_{R\Sigma})$ in relative units (R.U.) with the line length W1 20 km at the degree of consumer load $S_{L,i}$: 1 - 50%; 2 - 75%; 3 - 100%.

As a result, calculating the values of CRI K_R (S_L), ΔW_e (S_L) and Y_Σ , we present in tabular form the resulting indicators ΔL_a of options B2 and B3 with respect to the initial B1, characterizing the component of internal investments, directed to modernization. From the results, given in Table 2, it follows that for one feeder with an average length of 16 km and a number of switching operations per year equal to 28 (per 100 km), it is advisable to make the following estimated investments $Inv_{a,\Sigma}$ in an amount of 780960 rubles at their payback time not more than in 10 years (F_{adm} =0,1). On the twin feeder value $Inv_{a,\Sigma}$ will make 1.56 mln. rubles. Considering that the feeder is underloaded (Tab. 1, less than 30% of nominal capacity), and the fact that in the calculations of values $L_{f,\Sigma}$ (1) no allowance was made for losses at consumers (constituent y_{0j}) and the reduction of $\Delta P_{L,\Sigma}$ in the optimization of the network division point, the results allow an optimistic view of the correlation between the values $Inv_{a,\Sigma}$ and $L_{f,\Sigma}$ when planning sectionalizing measures in the DN on feeders with high seasonal load, even taking into account the high cost of modern equipment.

TABLE II. COMPONENT OF DOMESTIC INVESTMENT FOR MODERNIZATION

No options	**ΔL_a , thousand rubles/year for B1 DN with the number of outages**						
	4	***8***	***12***	***16***	***20***	***24***	***28***
S_L = 50%							
B2	37.22	48.78	75.45	9.73	120.86	152.66	188.67
B3	62.55	107.61	153.15	196.71	258.53	309.07	390.48
S_L = 100%							
B2	74.42	97.58	150.90	199.46	240.56	305.72	377.34
B3	125.11	215.35	306.3	393.42	517.00	618.15	780.96

IV. CONCLUSION

The following results were obtained as a result of the work.

1. We propose a multi-criteria approach to cost optimization in DN when connecting active-adaptive sectionalizing elements, in order to reduce damage, losses and under-release of electricity while maintaining its quality in the points of release.

2. Calculation algorithms and feeder reliability models have been developed that allow considering both the flows of operational, emergency and repair outages in the DN, distributed according to arbitrary laws, and the logic of automation and protection devices.

3. Comparison of the calculated CRI values of variants of DN schemes, considering the influencing factors, allowing us to draw the following conclusions:

- for long overhead lines of the DN (more than 10 km long), made on bare wires with non-automatic sectionalizing equipment, there is a directly proportional dependence of their accident rate and recovery time on the total length;
- the use of modern equipment with digital protections and automation leads to a significant reduction in the recovery time of power supply to consumers and the value of ΔW_Σ . At the same time, the frequency of

shutdowns does not significantly affect the K_R - within the value of 0.01 (8.76 hours/year) in variant 3 RC.

- to a greater extent, the degree of feeder loading ΔW_Σ affects the degree of loading of feeders. It is reasonable to carry out modernization measures on well loaded feeders, when the average consumption for all TSs is more than 50% of the nominal value;
- the main factor for making decisions should be considered the load of the feeders, because the lower it is, the longer payback period of measures should be planned, or be limited to the installation of inexpensive devices that provide a quick search for the location of the damage. To date, there are no such truly effective devices in DN.

4. Calculation of "internal" investment component of modernization of DN variants according to the tariff for electric power transmission was made. It is obvious that considering the consumers' damages and reduction of load losses according to the proposed optimization criteria will increase the estimated and actual payback period of measures in the DN.

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