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Substation reliability evaluation in the context of the stability prediction of power grids

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Abstract. The aim of the presented work was to examine the reliability assessment model on the example of a selected power grid object. The analyzed object was tested based on assumptions about technological breaks that were caused by overvoltage, among others. The study was conducted to check the reliability of integral elements of the power grid object and to assess the change in reliability level as a function of the frequency of inspections. The test results are to determine the optimal frequency of inspections of individual power grid objects in order to increase its reliability. In addition, the possibility of correlating optimal inspection periods resulting from the findings of this paper with periodic inspections of power network facilities was assessed.

Key words: reliability, power grid, risk analysis, substation.

1. Introduction

The expansion of the power grid in terms of power output and connection of new generation sources is one of the priority directions in development. This is to improve the reliability of electricity supply and the security of large agglomerations and minimize the risk of system failures. These activities are a consequence of, inter alia, power system failures when, due to intense rainfall, storms or other climatic phenomena, elements of the power network fail. At the same time, according to Fig. 1, this applies to networks of any rated voltage [1, 2]. Owing to the failure, a power plant or power station may stop working and, as a result, work in production plants, hospitals and other facilities will be immobilized. Due to a major accident, a total of approximately several hundred thousand inhabitants of one or several voivodships may be deprived of electricity supply.

In the substation, which is the basic element of the power grids, there are installed switchgear, and protection, alarm and measurement devices, etc. The absolute majority of emergency situations can be described as chain ones that occur in a dynamic mode during a short circuit in the network and refusal of operation of the switching devices through which short-circuit current flows, which causes activation of protections [3, 4].

One of the main causes of short-circuit currents in the power grid is atmospheric surges. As a result of these surges, overhead line insulators are most frequently damaged. However, the remaining effects apply in most station devices/elements, as shown in Fig. 2 [1].

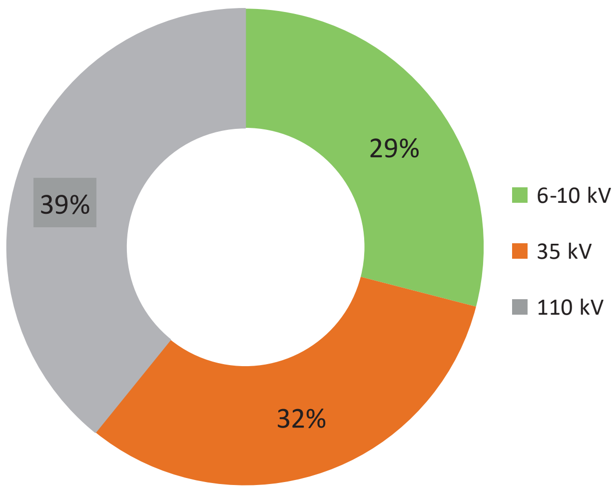

Fig. 1. Percentage share of technological breaks in the power grid of various voltages

The definition of reliability can be defined as the ability of power grid elements to supply electricity to all consumers connected to it. This energy must have standardized parameters (quantity, quality, etc.). Operators and distributors of power networks determine the reliability indicators of the power network based on the analysis of statistical data and information from consumers in the scope of planned energy consumption. The basic parameters that define the reliability of the power grid include the number of breaks, the average time to repair the network elements and the annual total time of power failure [5].

The assessment of the level of reliability of the power grid can be made by analyzing the probability of a surge wave that adversely affects the elements of the power grid [6–8]. On the

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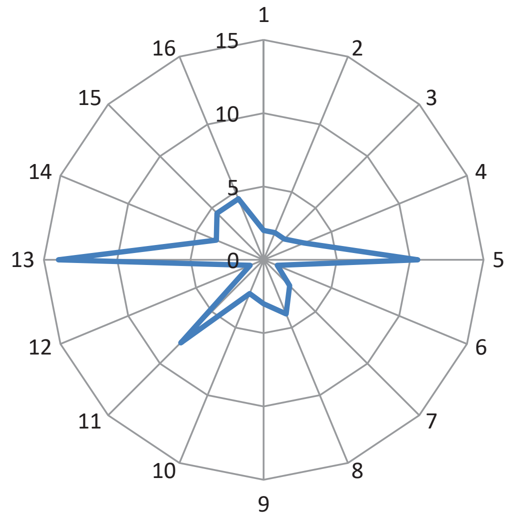

Fig. 2. Percentage share of technological breaks in the power grid as a result of atmospheric overvoltages: 1 – cable damage, 2 – current transformer damage, 3 – cable joint damage, 4 – disconnector damage, 5 – spark gap damage, 6 – fault due to the field conditions, 7 – damage to station insulators, 8 – breaker damage, 9 – damage to the overhead line spark gap, 10 – short circuit of wires, 11 – damage to poles and their structural elements, 12 – breakage of lightning conductor, 13 – breakage of wire or railing, 14 – damage to overhead line insulators, 15 – damage at the transformer station, 16 – damage to the power transformer

other hand, the number of emergency shutdowns can be eliminated or reduced by using various methods to ensure increased power grid reliability. Considering the specificity of network infrastructure management and its limited financing, a combination of maintenance options can be used that will lead to an increase in the reliability level of the entire network [9, 10]. In the case of very limited financial resources, one can focus only on the selected key elements of the network infrastructure, whose preventive maintenance can significantly translate into increased reliability [10]. At the same time, an effective but more advanced way to increase reliability is to monitor or analyze data and failure statistics [11].

In a lot of countries, operators and distributors of power grids impose stringent requirements regarding the duration of power outages. This applies to emergency situations and planned outages of network elements [12]. The planned shutdown of power grid components may be due to maintenance or repair work. In this case, part of the power grid can be supplied through non-stationary power units of the generator set type. In addition, temporary lines or bypass lines can be used in these cases. In addition, in emergency situations, renewable energy sources or energy storage systems can be used as a power source [9, 13].

In recent years, extensive research has been conducted around the world on how to monitor damage detection in power networks [14–17]. The above studies have a direct impact on maintaining high reliability of the power grid [6, 8, 14, 16, 17]. As already mentioned, due to the fact that electricity is the basis for the functioning of various types of systems necessary for humans, maintaining its parameters in acceptable limits is very important. For example, one of the key elements of the power network that affects its reliability is the power transformer. The load indicator, which defines the period of permissible peak load, is extremely important for trouble-free operation of transformers [18]. In the event of a failure on a power transformer because of peak load, the time to eliminate such a failure (repairing the transformer) can be extremely long. The above will translate into huge financial losses [19].

The reliability of electricity networks is also dependent on the network configuration. In the case of radial network configuration in which there are stations with a limited level of operational switching capabilities, the reliability of such a network is low and leads to losses of recipients [20]. An important aspect when designing a power grid is the correlation of a higher level of reliability and lower costs. The literature contains numerous ways to achieve this goal [5]. The analysis of the technical and economic aspect of reliability can be conducted in the form of a comprehensive analysis of different ways of connecting or determining the forecasted minimum income based on a mathematical model. Another way to achieve a higher level of reliability with minimal costs is through a broader network analysis that considers different levels of rated voltages.

In addition, when designing a power grid and analyzing various ways to achieve a high level of reliability, one should remember about environmental aspects and compliance with relevant ecological standards, as well as the possibility of replacing selected elements with elements with more advanced parameters. [21–23].

2. Assumptions for analyzing substation reliability

This paper analyzes network objects in the context of analyzing the reliability of a fragment of a power network, not the parameters and properties of individual electrical devices that are part of power objects, because the mechanism of assessing the degradation of electrical equipment insulation is very complicated [24]. Therefore, the model of the object in question should be simplified, which must have an understandable mathematical form and physical interpretation [25].

In this paper, attention will be focused on the element of the power grid, which is the station. The station is a connector between different voltage lines (Fig. 3). The method of assessing the reliability of such a station will be analyzed. Thanks to this analysis, a more stable electricity supply to consumers can

Fig. 3. Example view of the power grid object – substation

be ensured, which will be of great importance for the further development of the area [2].

In the event of a short-circuit current, consideration should be given to the possibility of further powering the consumers, depending on the parameters of the short-circuit current flow in the lines that depart from the station rails (flow time, reliability of operation of circuit breaker switch-off systems at power stations and the dates of their reviews (monitoring)). It is necessary to link the probability of a power outage at a given time of time of one of the station bus sections with the frequency of short circuits in the lines. If the time of failure-free operation of the station will be greater than the normalized value, we will be able to choose the time to check the circuit breaker switching off.

Below we will consider a situation in which we have a power station powered by two transformers. Not a large number of recipients is connected to the station (to reduce the number of calculations), the scheme of which is shown in Fig. 4: 5 – to the

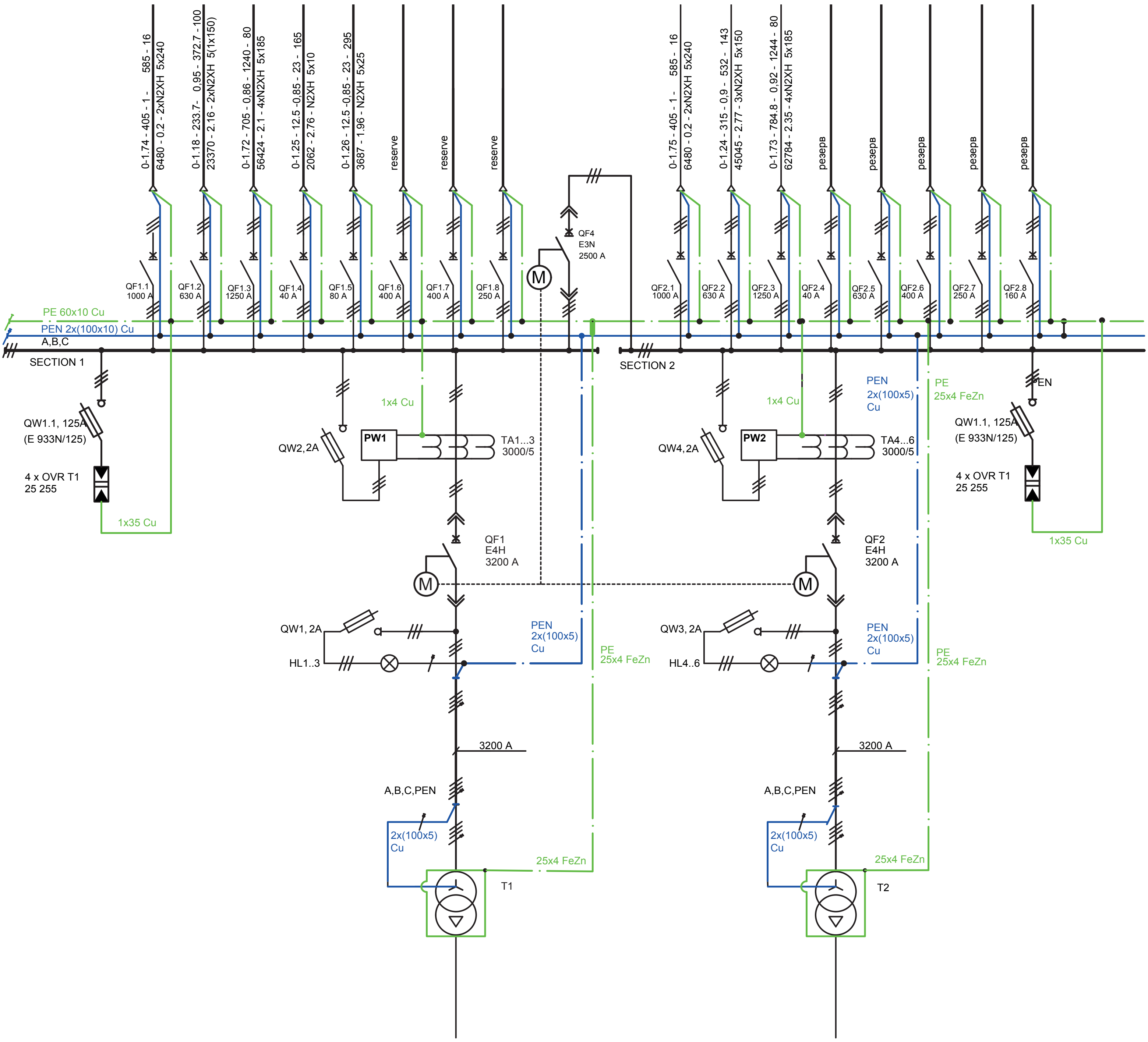

Fig. 4. Basic diagram of the substation

first section and 3 – to the second section (we do not include the reserve).

In order to define the level of reliability of a power station, one should use a quantity describing its emergency shutdown during the technological break in the overcurrent protection zone and the ego of the switching device connected to the appropriate section of the rails.

The parameter of the rail section working time can be defined as the period of operation without technological breaks, which prevents emergency shutdown of power supply to consumers.

Considering [26–28], in this paper the operating parameters of the power station presented in Fig. 1 within 10 years (T) are assumed, which are shown in Table 1. The above assumptions include conducting annual reviews (ε). Table 1 includes information about individual lines connected to the considered substation sections.

Table 1
Assumptions regarding the number of short-circuits (x) and refusals (y) at a power station

Number of line	1	2	3	4	5	6	7	8
x_j	1	0	3	6	5	2	3	4
y_i	1	7	0	6	0	3	5	4

In [22], a formula was proposed that allows to assess the reliability index of the analyzed power station:

$$F_T = \frac{1}{2^k} \cdot \prod_{j=1}^{n} \varphi_i \cdot \sum_{i=1}^{m} \Delta\tau^{2n} \cdot \varepsilon_j^2, \tag{1}$$

where: FT – the expected number of technological breaks, which is an indicator of reliability for the substation, φ_i – a short-circuit indicator in the line that is connected to the section of the busbar, which can be determined from the formula $^{x_j}/_T$, $\Delta\tau_j$ – the duration of the interval between inspections of switching devices, n – the number of switching devices through which the fault current flows, ε_j – a failure protection indicator, which can be determined by the quotient $^{y_i}/_T$, where T – a monitoring period of lines which are connected to the analyzed power station, y_i – the number of damage to the protection of individual lines connected to the power station.

Analyzing the reliability of some element of the power grid for any moment of time $0 \le T \le \infty$, one of the main evaluation criteria is the probability of damage of this element by the time T. Therefore, we can write the formula for determining the probability of failure $P_F(T)$ in analyzed time T [29, 30]:

$$P(T) = 1 - e^{F_T(T) \cdot T}. \tag{2}$$

In the case of a detailed analysis that would relate to the reliability of individual devices and assessment of its impact on the stability of the power system part considered, (1) should be modified. For the reliability analysis of a single device, the reliability indicator can be written as:

$$F_T = 0.5 \cdot \frac{x_l \cdot y_a \cdot \Delta\tau_a^2}{T^2} \tag{3}$$

where: x_l – the number of short-circuits in the line that is connected to the power station field in which the analyzed station apparatus is located, $\Delta\tau_a$ – the period between inspections of the analyzed station apparatus, y_a – the number of non-operation of the analyzed station apparatus, T – monitoring period. In a given case, it was assumed that the monitoring time of the line and the station apparatus is the same, i.e. $T = T_a = T_l$.

For example, in the case of a 110 kV switchgear field, reliability analysis can be performed for all primary circuit apparatus: bus disconnector, circuit breaker, current transformer, voltage transformer, line disconnector, transformer disconnector. In the case of assessing the impact of the reliability of individual station apparatus on the power supply stability of the recipient through the analyzed line, a reliability analysis should be performed taking into account the individual apparatus that is necessary for the functioning of the power station field (Fig. 5).

In this case, the assessment of the impact of the reliability of station equipment located in one field of the substation on the power supply to the recipient can be determined on the basis of the following formula:

$$F_T = 0.5 \cdot x_l^p \cdot \sum_{i=1}^{p} \frac{y_i \cdot \Delta\tau_i^2}{T_i}, \tag{4}$$

where: x_l – number of short circuits in the line that are connected to the power station field, p – number of primary circuit devices installed in a given switchgear field, $\Delta\tau_i$ – period between inspections of the station device located in the analyzed switchgear field, y_i – number of missing operation of the station device located in the analyzed switchgear field, – T_i monitoring period of the station device located in the analyzed switchgear field.

For example, if we analyze the linear field of a 110 kV switchgear, which consists of five primary circuit devices, the expected number of technological breaks can be determined as follows:

$$F_T = 0.5 \cdot x_l^5 \cdot \left(\frac{y_{DB} \cdot \Delta\tau_{DB}^2}{T_{DB}^2} + \frac{y_B \cdot \Delta\tau_B^2}{T_B^2} + \frac{y_{TI} \cdot \Delta\tau_{TI}^2}{T_{TI}^2} + \frac{y_{TU} \cdot \Delta\tau_{TZ}^2}{T_{TU}^2} + \frac{y_{DL} \cdot \Delta\tau_{DL}^2}{T_{DL}^2} \right) \tag{5}$$

where: $\Delta\tau_{DB}$, $\Delta\tau_B$, $\Delta\tau_{TI}$, $\Delta\tau_{TZ}$, $\Delta\tau_{DL}$ – period between inspections of the analyzed station apparatus, y_{DB}, y_B, y_{TI}, y_{TU}, y_{DL} – number of failure to operate the bus disconnector (DB), switch

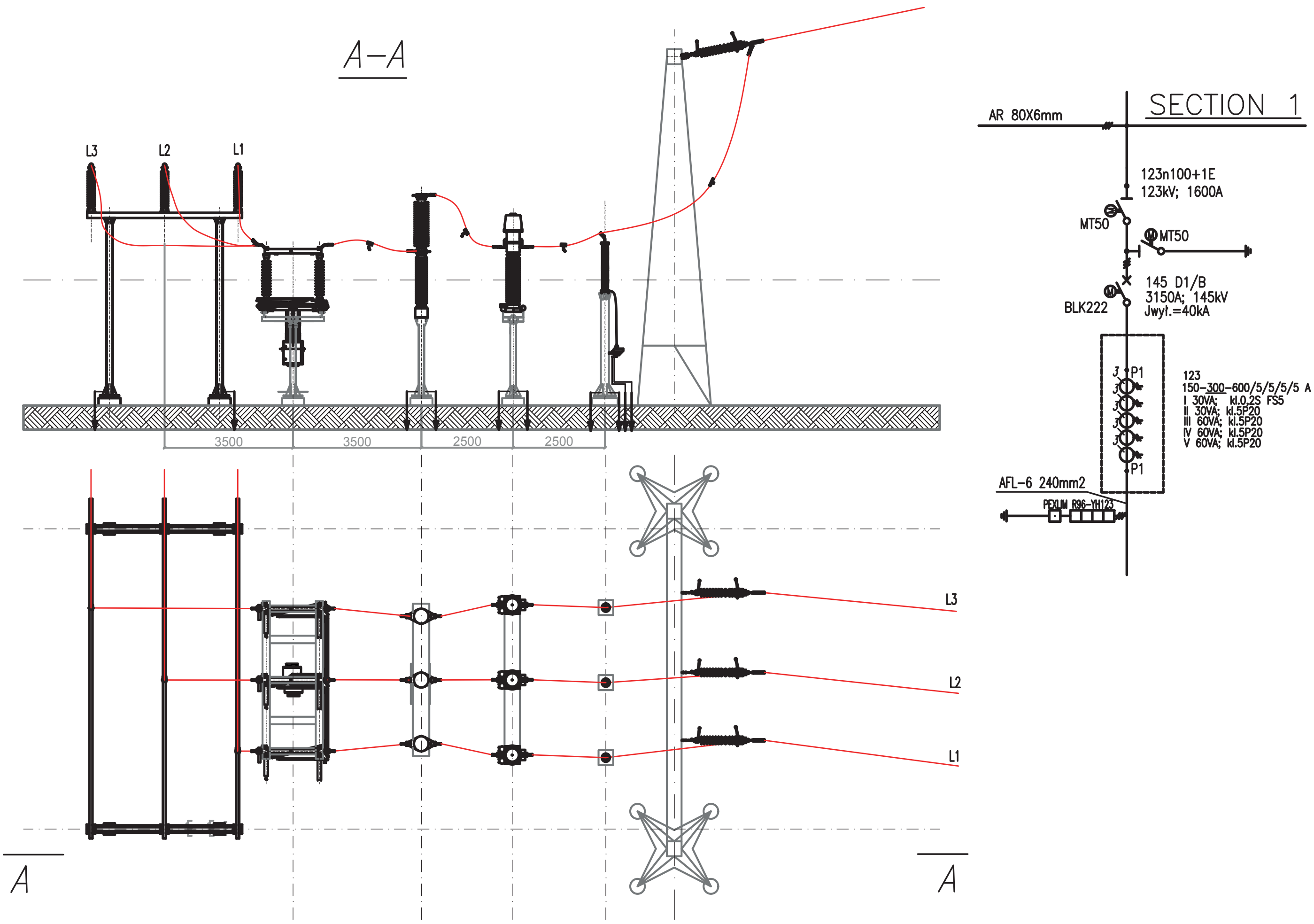

Fig.5. An example view of the 110 kV switchgear field and a basic diagram of the switchgear field

(B), current transformer (TI), voltage transformer (TU), line disconnector (DL), T_{DB}, T_B, T_{TI}, T_{TU}, T_{DL} – monitoring period of the bus disconnector (DB), circuit breaker (B), current transformer (TI), voltage transformer (TU), line disconnector (DL).

With the standard assumption, when the monitoring period T_p of all primary circuit devices installed in the analyzed switchgear field is the same (the apparatus was installed at the same time), formula (5) can be written.

$$F_T = 0.5 \cdot \frac{x_1^5}{T_p^2} \cdot \Big(y_{DB} \cdot \Delta\tau_{DB}^2 + y_B \cdot \Delta\tau_B^2 + y_{TI} \cdot \Delta\tau_{TI}^2 + y_{TU} \cdot \Delta\tau_{TZ}^2 + y_{DL} \cdot \Delta\tau_{DL}^2 \Big) \quad (6)$$

At the same time, when assessing the impact of reliability on the stability of the considered part of the power system, we deal with mutual reserving power to consumers (H system, sectioned busbar system, multi-system station systems, etc.). Therefore, in the remainder of this paper we will analyze the level of reliability of power supply to consumers connected to two sections of the busbar system.

3. The trend of changing the dependence of substation reliability

Using the above input assumptions and formulas, we can find line indicators that depart from the section and define technological breaks in these lines and substation elements. Figure 4 shows one of the standard substation systems, which includes two sections. In this paper, we consider the actual emergency situation, which occurs, for example, as a result of a short circuit (x_j) in one of the lines connected to Section 1 and the failure of the primary circuit device (y_i) to operate in the switchgear field into which the emergency line is introduced. In the event of the situation described above, in accordance with the operating principle of a given substation system, the entire section is disconnected from power supply together with all lines (recipients) that are connected to this section. Therefore, data on reliable operation of each line connected to the analyzed sections (φ_i) and elements placed in the switchgear field (ε_j) in a specified period should be analyzed. The results shown in Table 2 include one review per year.

Using formula (1) and the above results, we can determine the level of change of the power station reliability index for

Table 2
Number of failures and failures in the analyzed power grid object for specific assumptions

Number of line	1	2	3	4	5	6	7	8
ε_j, 1/rok	0.1	0	0.3	0.5	0.4	0.2	0.3	0.3
ϕ_i, 1/rok	0.1	0.6	0	0.5	0	0.3	0.4	0.3

various cases of periodic inspections. To assess the trend of change in the analyzed indicator and to determine the optimal period of periodic reviews, calculations were made that cover a time interval from 1 month to 10 years. In other words, we assume that inspections will be conducted once a month in the best case and once every 10 years in the worst case. The next points to be analyzed in this range are at equal intervals. The results of these calculations are shown in Fig. 6.

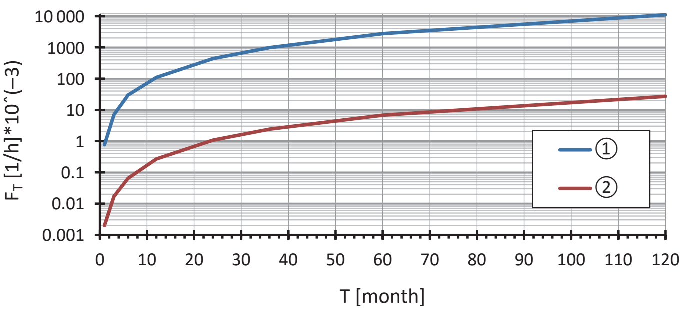

Fig. 6. Graph of the dependence of the number of technological breaks in Section 1 (1) and in Section 2 (2) on the number of inspections on a logarithmic scale

As part of the above analysis, the case of periodic reviews was reviewed monthly, once every three months, once every six months, once a year, once every two years, once every three years, once every 5 years and once every 10 years. As can be seen from Fig. 6, the reliability index of Section 2 is several hundred times lower than the indicator of Section 1. However, the change in the number of technological breaks in the analyzed facility is similar for Sections 1 and 2. From the above dependence you can see the trend that the number of periodic inspections is decisive for the number of technological breaks at the station facility. Based on the results obtained, a minimum of two characteristic time intervals can be specified:

1. From 1 to 12 months (from 1 to 12 reviews per year);
2. From 1 to 10 years (from 1 to 10 inspections in 10 years).

During the first-time interval, it is possible to specify the high steepness of the increase in the number of technological breaks (100 times greater) at the station facility during a short time interval (1 year). However, the second interval is characterized by even a greater increase in the number of technological breaks (100 times greater) over a longer period of time (9 years). Therefore, the base period of 1 year for periodic reviews was adopted. To assess the change in the number of technological breaks at the analyzed facility for individual options of periodic inspections in relation to the base period (1 year), calculations were made, and the results are presented in Fig. 7.

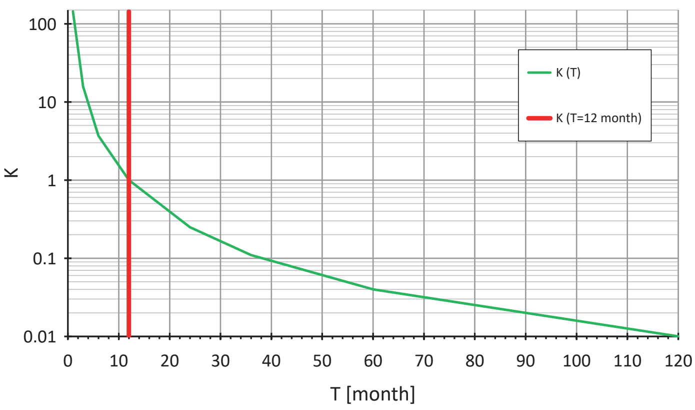

Fig. 7. Multiplicity factor of the change in the number of technological breaks depending on the number of inspections in a period of 10 years in relation to the base number of periodic inspections (1 inspection in 1 year) on a logarithmic scale

As a result of the conducted calculations, it appears that the power station reliability index with such assumptions may increase by over 100% in the case of periodic inspections conducted each month. The above statement is true if we take one review as a base point per year. An increase exceeding 100% can be observed for a lower frequency of technical inspections (up to one interim review in 10 months). As can be seen from Fig. 6, periodic inspections conducted once a year are located at an optimal point that will provide the necessary level of reliability, taking into account the capabilities of the network operator in terms of financial resources and costs. The steepness of the change rate level of the number of technological breaks is similar to what we observed in Fig. 6. This confirms the need to adopt a base period for periodic inspections at the end point of the first-time interval.

At the same time, it can be stated that minimizing the parameter leads to an increase in the trouble-free operation of the power grid object, and thus the entire power system.

At the same time, this frequency of inspections is optimal in terms of the requirements of most manufacturers of one of the most expensive station equipment – circuit breakers. According to these requirements, it is necessary to perform:

- Periodic treatments performed in two cycles:
  1. Visual inspections carried out at least once a year, including checking the number of switching operations and the value of the sum of off currents, as well as visual inspection of the technical condition of construction parts
  2. Checks over a 5-year cycle, including functional tests and checking the SF6 density monitor
- Periodic inspections of the pole and circuit-breaker drive, which should be carried out after 5000 switching opera-

tions or after reaching the permissible value of the total off current

In addition, in accordance with, inter alia, the requirements of most distributors and network operators, a quick inspection of circuit breakers should be conducted at every stay at the operational staff facility, and a complete examination should be conducted once a month by the Head of the duty team.

To assess the level of impact of the frequency of technical inspections on the reliability of Section operation for a specific station system, the probability of failure in sections was calculated based on formula 2 (Fig. 8).

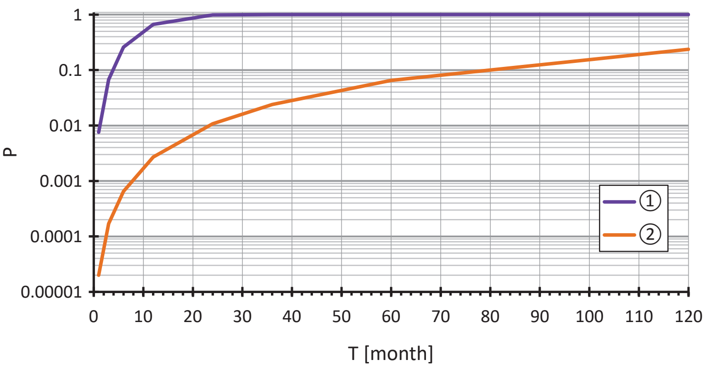

Fig. 8. Probability of failure occurrence in Section 1 (1) and Section 2 (2) in relation to the number of periodic inspections over a period of 10 years on a logarithmic scale

As can be seen in this case, Section 1 has a high steep rise in the probability of failure from 1 to 24 months. Then, minimizing the number of inspections can no longer affect the probability of failure. Therefore, conducting periodic reviews once every 12 months is the right approach. The dependence of the probability of failure in Section 2 on the number of periodic inspections has a similar course as the corresponding relationship for Section 1. However, the change in the probability of failure in Section 2 has a much wider scope of change. The above dependence is characterized by a smoother change than we could observe in Section 1. Due to the fact that the maximum value of the probability of failure in this Section is much lower than in Section 1 in the analyzed period, this will reduce the time of periodic reviews of this section.

4. Conclusions

The key and most important task of distributors and electricity operators is to ensure security of electricity supply. To implement this task successfully, an efficient and well-developed network infrastructure is required – power lines and substations. Therefore, the area related to the reliability of network infrastructure is extremely important. Thus, this article analyzes the impact of the frequency of inspection periods on the number of technological breaks in a power grid facility. By ensuring a high level of reliability of individual elements of the power grid, we also ensure stable operation of the entire power grid. The paper shows the level of impact of technical reviews and reserving power to consumers on the reliability of this power. Thanks to the results obtained in this paper, the following conclusions can be made:

1. In order to determine the most accurate assessment of the reliability indicator at the analyzed station, periodic inspections should be performed not for a group of similar elements, and specifically for each unit. This paper provides an analysis of reliability using a mathematical model that considers the station layout and mutual reserve of power supply to consumers. In addition, a mathematical model was developed for assessing the level of reliability of individual devices and devices cooperating within the field of the substation switching station. This will help you receive detailed information about the level of reliability of individual power station components at every stage of operation.
2. Monitoring of the station's electrical equipment should start from the day of their commissioning and last until disposal. As a result of the analysis, it was determined that the optimal period for periodic reviews is 1 year. This is a landmark, the deviation from which the number of technological breaks increases or decreases. In this paper, the authors provide justification for the deadlines for conducting reviews, which will avoid emergency situations. In addition, the implementation of the analysis during the power station operation based on the presented model will allow the dates and scope of required technical inspections to be changed. This will contribute to the extension of the life of the power station components, more precise planning of repair activities and the use of technical staff, reduction of the cost of purchasing spare parts and a high level of operational reliability.
3. The reliability indicator of the power grid or its element is inversely proportional to the parameter describing the number of technological breaks. At the same time, for the analyzed period (10 years), an exemplary increase in the number of periodic inspections from one to two years to one-year results in a fourfold decrease in the number of technological breaks. An analysis of the probability of failure occurrence in individual sections of the substation has been conducted, which will shorten the periodic review time for Section 2. The above approach will reduce the time of shutdowns necessary to perform such a review. This approach results from the high failure resistance of Section 2, as shown in Fig. 8.

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