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Analysis of the Power Supply Restoration Time after Failures in Power Transmission Lines

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Abstract: This paper presents the analysis of power supply restoration time after failures occurring in power lines. It found that the power supply restoration time depends on several constituents, such as the time for obtaining information on failures, the time for information recognition, the time to repair failures, and the time for connection harmonization. All these constituents have been considered more specifically. The main constituents' results values of the power supply restoration time were analyzed for the electrical networks of regional power supply company "Oreolenergo", a branch of Interregional Distribution Grid Company (IDGC) of Center. The Delphi method was used for determining the time for obtaining information on failures as well as the time for information recognition. The method of mathematical statistics was used to determine the repair time. The determined power supply restoration time (5.28 h) is similar to statistical values of the examined power supply company (the deviation was equal to 9.9%). The technical means of electrical network automation capable of the reduction of the power supply restoration time have also been found. These means were classified according to the time intervals they shorten.

Keywords: power supply restoration; power supply outages; failures; time intervals; obtaining information; information recognition; connection harmonization

1. Introduction

Improving power supply efficiency from private homes to large industrial enterprises is an urgent and difficult task for power supply (PS) enterprises. This is because power supply companies often encounter problems such as the remoteness of energy consumers from power distribution points, insufficient capacity margin, depreciation of power supply equipment, and the lack of specialists involved in servicing this equipment. As a result, it leads to the increase in the number of equipment failures and the increase in PS interruptions. In turn, this translates into losses for power supply companies due to the elimination of the failure's consequences and for consumers due to a disruption of the technological process caused by the power supply outages.

This article deals with the analysis of power supply restoration after power line failures. Thus, the organization of the article is as follows. Section 2 is a literature review of the state of the art with the motivation and contribution of this paper. Section 3 introduces the problem of power supply reliability. It indicates the elements that have an impact on the total time of restoration. In Section 4, the calculation of each element is performed based on real data obtained from a Russian power supply company. Section 5 contains a discussion of the results and propositions for the technical means of automation of electrical networks to reduce the power supply restoration time. Section 6 is the conclusion part.

2. State-of-the-Art Power Supply Restoration Issues

The present research described in the literature concerns the problem of power supply reliability in different areas. The aim of this research is a power supply restoration analysis [1]. Thus, current research trends in the literature are analyzed with regards to restoration issues. The presented literature review is divided into two areas:

- research based on simulations for both transmission and distribution systems,
- analysis for real objects obtained from historical data.

2.1. Research Based on Simulations

The present literature is generally based on simulations. The analysis of power supply reliability in point of restoration issues was divided into two parts—distributed and transmission systems.

Distributed grid:

- The article [2] presents the networked microgrids aided approach to service restoration in a power distribution network. This paper proposes to use a mixed-integer linear approach. The main contribution of the article is to leverage networked microgrids to simplify service restoration. The proposed model was verified using the modified IEEE 123 node distribution test system.
- The article [3] deals with service restoration for a distribution network. The element under consideration is the uncertainty of restoration time. In the article, a two-stage adaptive algorithm for service restoration was proposed. This algorithm uses the Wasserstein distance metric. It is applied to calculate two restoration times with different probabilities. Then the higher probability is used as the restoration time.
- The paper [4] describes a multi-stage restoration method. It is applied to an medium voltage (MV) distribution system with distributed generation. The proposed service restoration approach concerns intentionally connection islanding of distributed generators (DGs) with network reconfiguration to maximize restoration of switched-off loads. It is realized by matching islanding schemes. Then the restoration of network connectivity and DGs is realized. Finally, the network reconfiguration as well as load shedding optimization are proposed. This research is based on a Pacific Gas & Electric (PG&E) sixty-nine bus system.
- The article [5] proposes a heuristic method for distribution network restoration. The proposed algorithm was implemented and tested on the IEEE 33-bus standard network.
- The article [6] concerns optimal network restoration after faults in a distribution network with distributed generation. The selected method is a meta-heuristic Artificial Bee Colony algorithm. The restoration algorithm and the load flow analysis were simulated using MATPOWER in MATLAB software. That research aimed to minimize out-of-service loads and power losses and improve the voltage profile. The article presents two examples of two single-fault and multi-fault cases. For each example, five different scenarios were studied. The results showed the significant power loss reduction and improvement in minimum voltage.
- Other papers that concern simulations to increase reliability are based on restoration issues for distributed grids, e.g., static island power supply restoration strategy [7], power restoration method using a genetic algorithm [8], the state-of-the-art fault localization and service restoration [9], robust power supply restoration for self-healing active distribution networks [10], intelligent power supply restoration [11], power restoration strategy [12], and a fast power service restoration method [13].

Transmission grid:

- The article [14] concerns power system restoration planning. The strategy presented in the paper uses an optimal energizing time needed to sectionalize islands. The method contains the identification of transmission lines that are not adequate to connect to the islands. The article methods consist of a combination of optimization methods: heuristic and discrete. The heuristic one is used to indicate an initial solution which is close to the optimal solution. Then it is input to the discreet method, which is the discrete Artificial Bee Colony approach.
- The paper [15] is based on a resilience analysis of transmission line restoration. It indicated that transmission line capacitance is based on resilience factors. The proposed ideas were verified in two IEEE tests.
- The article [16] presents a parallel automated resilience-based approach to restoration. The appliance aims to minimize the influence of the emergency power outages in a power system. The article proposes that during the power restoration process, a black start element is allocated to a little region on an as-needed demand. Then a mixed-integer nonlinear programming approach is indicated. The bi-level programming was used in the proposed solution to such a large-scale optimization model. The application was realized using both 6 and 118 bus IEEE test systems.
- The article [17] presents a possibility to solve the problem of expansion planning. The article contains the proposition of using multistage stochastic programming to solve this issue. The indicated mixed-integer linear programming proposes the placement of the construction and reinforcement of new transmission lines to assure the high reliability and quick restoration. The presented results are based on the IEEE 30-bus system with assuring to minimalize cost.
- The article [18] proposes the post-disaster restoration planning model that enables finding an optimal repair and activation schedule for damaged system components. In this model, an aim is to maximize load accommodation capability, as well as to minimalize the make-span of the restoration process. The obtained results increased maintenance efficiency. The IEEE 118 and 30 bus test systems were tested in the study. Moreover, the advantages of using the sequence-dependent repairing period are discussed.
- Other papers that concern simulation results in transmission systems and reliability are: using interline dynamic voltage restoration [19], a method for the optimization of a power system restoration path [20], a transmission line restoration using an emergency restoration system structure [21], an indication of the maintenance schedule of transmission lines [22], a definition of a restoration strategy in a transmission system during windstorm [23].

2.2. Research Based on Historical Data and Real Objects

The previous subsection includes literature resources from the last three to five years. However, all of them are based on simulations and different models (e.g., IEEE models). The authors indicate that there is a lack of present research of restoration issues based on real data, even if it is only input to further algorithms. This article is devoted to transmission lines restoration time; thus, this part is narrowed down only to transmission grids. Some interesting papers that concerns real object analysis using historical data can be found in the "SCOPUS" data base for key words "restoration" & "transmission lines" from the last three to five years:

- The article [24] presents a black start case study. However, the article contains simulations which are based on real data from Benghazi North Power Plant. The data were used to validate a black start plan for steady-state and transient operating conditions. The article indicates that the optimum size selection of the black start is defined by the capacity of the biggest motor, transmission line capacitive charging reactance, transformers size, and vector group.
- The article [25] presents a fault location system. The system is based on synchro phasors measurements. It is used for 345 kV and 161 kV transmission networks at Taiwan Power Company. Additionally, the article presents an evaluation based on historical cases.

- The paper [26] presents an issue that was connected with noticeable transmission lines failures in India under natural disasters. Data used in the article consisted of historical measurements when real disasters happened. The article discusses emergency restoration system applications. This system uses structure and foundation information, weather-related failure information, weather conditions, structural loading, and damage sizes.
- The paper [27] is related to the economic impact of climatic events in the USA. It additionally discusses why emergency restoration plans are needed. The second part of the article presents a case study from Oman. It presents emergency restoration procedures to downed transmission lines. Key aspects of emergency restoration procedures are discussed. The article indicates that with the development of materials and techniques, emergency restoration procedures must be periodically reviewed using actual technologies.
- Other papers that concern using real data in a transmission system and reliability are: an analysis of the empirical probability distribution of transmission line restoration time over 14 years [28], a case study of black starts of transmission lines in Australia [29], the development of a sequential restoration strategy and its empirical verification in a Korean power system [30].

2.3. Motivation and Contribution of the Paper

The number of articles, indicated in previous subsections, that concern simulation in recent years is huge. However, there is a lack of recent analyses realized for real cases although such real case analyses were common in the previous century. However, they are still necessary because the development of the materials and technics has totally changed in different areas. Thus, this article is a case study for the Russian power supply company "Oreolenergo" that concerns the analysis of restoration time in power lines based on analyzing historical data and a survey. In the analyzed regional power supply company "Oreolenergo", there are no monitoring systems for outages in the considered electrical networks. There is practically no automation equipment, and power lines are made radial. The structuring of the power supply restoration time given in the study makes it possible to consider in more detail all the constituents of the power supply restoration time and to establish the factors affecting it.

It is difficult to assess the real time of power supply restoration, since there is no real data on the time of the power supply outage beginning. The countdown of the power supply restoration time in most cases starts from the moment when the information on a failure is received by the dispatcher of a power supply company. As a result, restoration time is underestimated. Consequently, the damage from the undersupply of electricity is also inaccurate. Therefore, the constituent "time for obtaining information" was introduced into the structure of the power supply restoration time. The value of this constituent was determined by the Delphi method. This method was also used for the determination of the time for recognizing information. The choice of this method is due to the impossibility of evaluating the data on power supply restoration time constituents by other means. The questionnaires used for Delphi were designed specifically for this purpose and were sent to specialists who work in the power supply company "Oreolenergo" and who have at least five years of work experience. The choice of experts was justified by the fact that the dispatchers of the power supply companies receive information from consumers about power supply outages, register the moment of this information receipt, send a repair brigade to search for places of damage and to eliminate the identified damage, and register the corresponding time intervals for repairs and switching on. In most cases of power supply outages, especially in the 0.4 kV electrical network, dispatchers receive information about outages from consumers, since there are no monitoring systems for power supply outages. Nevertheless, they have cases of receiving information about the time of obtaining information, for example, during planned power supply interruptions made by the personnel of power supply companies. In these cases, they can register the time of disconnection and the moment of receipt of the information on the power supply outage from the consumer. Thus, there is the opportunity to analyze the time interval for obtaining information on power supply outages and the experts were competent in estimating time intervals for obtaining and recognizing information. A total of 20 experts responded to the questionnaires. In turn, the repair time was determined by using the method of mathematical statistics, while the time for connection harmonization was determined by using the analysis of literature sources. To summarize the method's end elements indicated for the restoration time indication, Figure 1 was prepared. Additionally, in the article, the technical means of electrical network automation to reduce the power supply restoration time were also found.

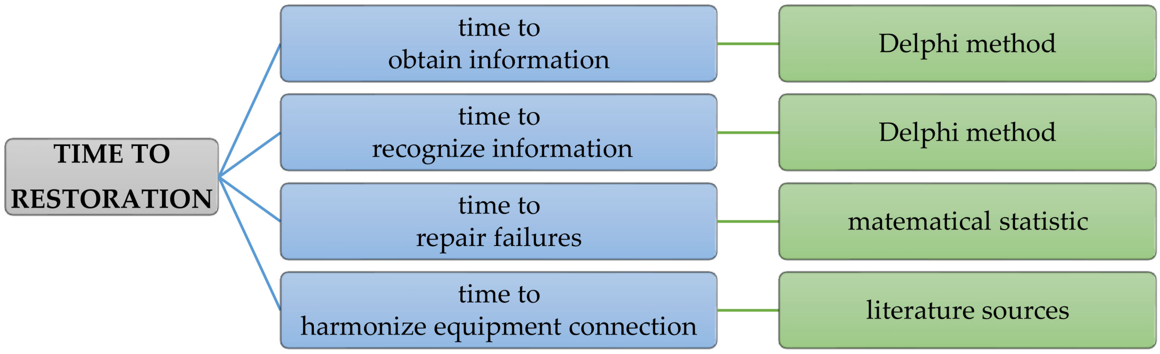

Figure 1. The proposed methodology to obtain restoration time for a selected power supply company.

3. Power Supply Reliability

One of the main criteria for power supply efficiency is power supply reliability, which implies the continuous supply of electricity to consumers in accordance with an electricity consumption schedule [31]. In turn, a main indicator of the PS reliability is power supply restoration time [32]. It can include the following constituents: time for obtaining information, time for information recognition, time to repair failures, and time for connection harmonization [33]. That is, the PS restoration time can be determined by Equation (1):

$$t_{\text{restor.}} = t_{\text{obt.infor.}} + t_{\text{rec.infor.}} + t_{\text{repair}} + t_{\text{harmonize}} \tag{1}$$

where

- $t_{\text{obt.infor.}}$ —time to obtain information;
- $t_{\text{rec.infor.}}$—time to recognize information;
- t_{repair}—time to repair failures;
- $t_{\text{harmonize}}$—time to harmonize equipment connection.

Each component of this equation can be further analyzed and contains several more time intervals, each of which ultimately has an impact on the overall power supply restoration time.

A time for obtaining information is denoted as an interval from the beginning of a failure until obtaining information on it by a dispatching service of a PS company [33]. This time includes the following intervals:

$$t_{\text{obt.infor.}} = t_{\text{infor1}} + t_{\text{infor2}} + t_{\text{infor3}} \tag{2}$$

where

- t_{infor1}—time for obtaining information on failures by means of primary information links. This link can be electrical equipment receiving power energy from an electrical network and disconnecting in case of a power failure, a sensing device of an automation system, or network status monitoring (for example, a voltage sensor);
- t_{infor2}—time for obtaining information on failures by means of secondary information links. It can be the compared element of an automation system as well as a monitored network status. The specified time interval can be significantly reduced in the case of the use of automation, since a person (consumer) noticing disconnected equipment has to make sure that this disconnection occurred due to failures;

- t_{infor3}—time for obtaining information on failures by means of third information links. This link can be a dispatcher that receives a network failure signal or an element of a network status monitoring or another automation system making a decision based on received information (for example, a data processing unit, a microprocessor, etc.). This time interval largely depends on the data transmission channel. Thus, a person (consumer) can report a failure by phone, e-mail, or in person to the dispatcher, etc. t_{infor3} will be different in each of these cases.

  The information recognition time may be described using this equation: [33]

$$t_{\text{rec.infor.}} = t_{\text{read.infor}} + t_{\text{dec}} + t_{\text{search}} + t_{\text{report}} \tag{3}$$

where

- $t_{\text{read.infor}}$—time required for information message recognition, that concerns failures in an electrical network. This time also depends on the data transmission channel through which the message arrived, the method of data transfer, and the speed of data recognition (who decrypts the message: a person or automatic equipment);
- t_{dec}—time spent on a decision by a dispatching office. It includes a time to decode information on failure, and it lasts until a place and a failure type are determined by a brigade;
- t_{search}—time required for a brigade to search the failure (depends on transport type, the remoteness of the failure place, the terrain type, the failure type, and brigade equipment for the search);
- t_{report}—time required to send information on a location and a failure type by a brigade (depends on the type of data transfer).

The repair time is an interval starting from the preparation of equipment to eliminate a failure up to the harmonization of the repair equipment [33]. This time can be represented as the following equation:

$$t_{\text{repair}} = t_{\text{repair.prepar}} + t_{\text{repair.reach}} + t_{\text{repair.switch}} + t_{\text{repair.permit}} + t_{\text{repair.work}} + t_{\text{repair.complet}} \tag{4}$$

where

- $t_{\text{repair.prepar}}$—time required for a repair brigade to depart including the preparation of work permit, equipment, devices, and loading on transport;
- $t_{\text{repair.reach}}$—time required for a repair brigade to reach a failure location. It depends on the distance to the failure place, the transport type, the landscape, road condition, the season, and the time of day;
- $t_{\text{repair.switch}}$—time required to switch necessary equipment;
- $t_{\text{repair.permit}}$—time required to obtain a permit for the work of a repair brigade. It depends on the work complexity as it impacts the preparation time of the workplace, that is, the implementation of technical measures to perform safe work;
- $t_{\text{repair.work}}$—time required to carry out direct repair work. It depends on brigade staff (quantitative and qualitative ones) and equipment with the appropriate tools and devices, along with the complexity of work;
- $t_{\text{repair.complet}}$—time required for the completion of work, the cleaning of a workplace, the exit of a repair brigade from a workplace, documenting the completion of work.

  The time of the connection harmonization $t_{\text{harmonize}}$ can be described using this equation [33]:

$$t_{\text{harmonize}} = t_{\text{inf.transfer}} + t_{\text{pre.connect}} + t_{\text{connect}} + t_{\text{ensure}} \tag{5}$$

where

- $t_{\text{inf.transfer}}$—time required for information transfer time to a dispatching office the need to connect repaired equipment;

- $t_{pre.connect}$—time required to prepare the equipment connection and to document this;
- $t_{connect}$—time of equipment connection. It depends on the network diagram, the type of devices used for switching on, the distance from the personnel carrying out the switching up to the switching devices;
- t_{ensure}—time required to ensure that the equipment was successfully connected.

The literature positions indicate that data on the above time intervals are incomplete or often missed. However, the analysis of these time intervals reveals the potential to realize a reduction of the power supply restoration time that results in the power outages to consumers and the associated failures. Since the diagnostic methods and technical means for obtaining information about failures may be different [34], there are many factors that make it difficult to accurately determine the power supply restoration time and each of its constituents.

4. Results

4.1. Obtaining Information Time

The most correct method of determinization of obtaining information time of failures in electrical networks ($t_{obt.infor}$) is the Delphi method. This method was successfully applied in different researches, e.g., [35,36].

The questionnaire was prepared specifically for this research. It was given to twenty experts working in PS companies (dispatchers). The experts had at least five years employment experience.

This research proposes obtaining information time in 12 intervals. The specialists had to give a score from one to ten for each time interval. The most probable time interval got ten points from experts while the least probable got zero points. In the case that the expert indicates the same time interval probability, they could estimate the time intervals by points. The harmonization degree of the participant of the questionnaire was calculated. For this, a concordance coefficient (Equation (6)) proposed by Kendall was used:

$$W = \frac{12 \times S}{m^2 \times (n^3 - n)}, \quad W = \frac{12 \times 35.9 \times 10^3}{20^2 \times (12^3 - 12)} = 0.62 \tag{6}$$

where

- S—the sum of squared differences between the sum of the estimates given by all experts to the i-th time interval ($\sum_{i=1}^{m} N_{ij}$) and the arithmetic mean of all the estimates $\overline{N}$;
- m—the number of experts surveyed; n is the number of time intervals in the questionnaire;
- N_{ij}—the score given by the j-th expert to the i-th time interval.

$$W = \frac{12 \times 35.9 \times 10^3}{20^2 \times (12^3 - 12)} = 0.62 \tag{7}$$

The arithmetic mean of all estimates was determined in accordance with the well-known Equation (8):

$$\overline{N} = \frac{\sum_{i=1}^{n} \sum_{j=1}^{m} N_{ij}}{n}, \quad N = \frac{172 + 180 + 164 + 135 + 117 + 97 + 71 + 61 + 57 + 41 + 31 + 19}{12} = 95.4 \tag{8}$$

The sum of the squares of differences was determined according to Equation (9):

$$S = \sum_{i=1}^{n} \left(\sum_{j=1}^{m} N_{ij} - \overline{N}\right)^2, \quad S = (5.8 + 7.1 + 4.7 + 1.5 + 0.5 + 0.00256 + 0.6 + 1.2 + 1.5 + 3 + 4.2 + 5.8) \times 10^3 = 35.9 \times 10^3 \tag{9}$$

Since the time intervals were indicated in the questionnaires, fixed points were chosen for calculating the expectation at each interval. These points corresponded to the middle of the intervals. The mathematical expectation was determined by the following equation:

$$M(t) = \frac{\sum_{i=1}^{n}(t_{ci} \cdot \sum_{j=1}^{m} N_{ij})}{\sum_{i=1}^{n}\sum_{j=1}^{m} N_{ij}}$$
$$M(t) = \frac{21.5+67.5+102.5+111.3+131.6+133.3+115.3+114.3+121.1+97.3+81.0+54.0}{1145} = 1.01 \quad (10)$$

where

- $M(t)$—the mathematical expectation of the time for obtaining information;
- t_{ci}—the time value of the middle of the i-th interval.

The calculation results are indicated in Table 1.

For clarity, the distribution of expert estimates given to the corresponding time interval is presented in Figure 2.

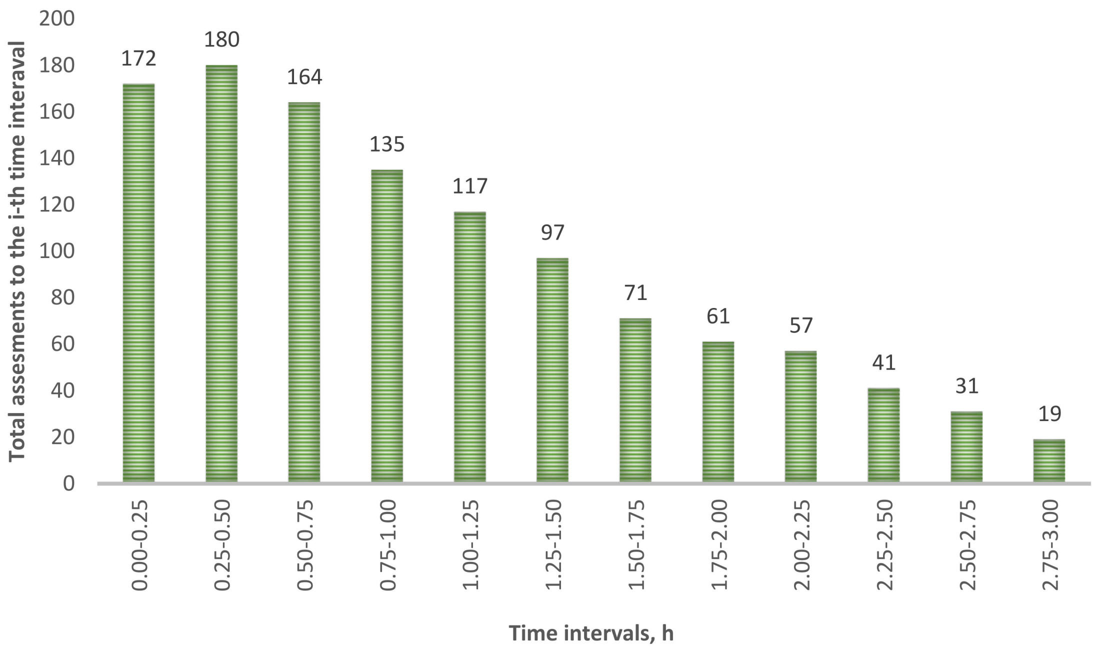

Figure 2. The histogram that represents the assessment of experts concerning a distribution of the time for obtaining information on failures.

The mathematical expectation of obtaining information time on failures was 1.01 h with the concordance coefficient of 0.627. In the questionnaires, it was considered that there were no monitoring systems of electric network, i.e., a PS company dispatcher obtained information on failures from the consumers.

This is quite a long time, which can and should be reduced by various means. A proposition to reduce the time may be, e.g., an automatic detection of failures facts and places in electrical networks and unmanned aerial vehicles allowing to monitor the power line state and detect failure places.

Table 1. The results of the expert survey to determine the time for obtaining information on failures.

Experts	Expert Estimates Given to the *i*-th Time Interval											
	Time Intervals, Hours											
	0.00–0.25	0.25–0.50	0.50–0.75	0.75–1.00	1.00–1.25	1.25–1.50	1.50–1.75	1.75–2.00	2.00–2.25	2.25–2.50	2.50–2.75	2.75–3.00
	1	2	3	4	5	6	7	8	9	10	11	12
1	9	8	8	7	8	4	3	3	2	3	5	2
2	8	10	9	6	5	5	2	3	3	2	1	3
3	10	9	7	8	6	4	3	4	3	1	2	1
4	7	9	8	7	6	5	4	2	3	3	2	1
5	9	10	7	8	4	3	5	3	2	1	2	2
6	8	8	9	6	7	5	3	4	2	2	1	1
7	10	10	7	5	6	4	3	3	3	2	2	0
8	8	10	9	6	5	5	2	3	2	2	1	0
9	10	9	7	8	6	4	4	3	2	3	2	1
10	7	8	9	6	5	4	2	3	3	2	2	0
11	8	9	9	7	5	6	3	2	1	3	0	0
12	9	9	8	6	7	5	5	3	4	2	1	1
13	8	7	6	7	5	4	2	3	4	2	1	1
14	9	8	10	7	6	5	4	2	3	1	1	0
15	9	10	7	8	8	6	4	3	3	2	1	1
16	8	8	10	6	7	6	5	5	4	2	2	2
17	7	10	9	8	6	6	5	4	3	3	1	0
18	10	9	7	7	5	6	4	3	4	2	2	1
19	8	9	10	6	5	5	4	2	3	2	1	1
20	10	10	8	6	5	5	4	3	3	1	1	1
$\sum_{i=1}^{m} N_{ij}$	172	180	164	135	117	97	71	61	57	41	31	19
t_{ci}	0.125	0.375	0.625	0.825	1.125	1.375	1.625	1.875	2.125	2.375	2.625	2.875
$t_{ci} \cdot \sum_{i=1}^{m} N_{ij}$	21.5	67.5	102.5	111.3	131.6	133.3	115.3	114.3	121.1	97.3	81.0	54.0
$\sum_{i=1}^{m} N_{ij} - \overline{N}$	76.6	84.6	68.6	39.6	21.6	1.6	−24.4	−34.4	−38.4	−54.4	−64.4	−76.4
$(\sum_{i=1}^{m} N_{ij} - \overline{N})^2$	5.8×10^3	7.1×10^3	4.7×10^3	1.5×10^3	0.5×10^3	2.6×10^3	0.6×10^3	1.2×10^3	1.5×10^3	3.0×10^3	4.2×10^3	5.8×10^3
W = 0.627 $M(t)$ = 1.01												

4.2. Recognizing Information Time

The present data indicated in the literature that concerns time of recognizing information on failures $t_{rec.infor}$ is not fully explored. However, it is worth noting that this time interval may take 75% of the time of the PS restoration. The Delphi method was also used to determine this time, and there were also 20 experts.

The results of the calculations are summarized in Table 2, the distribution of expert assessments given to this time interval is shown in Figure 3.

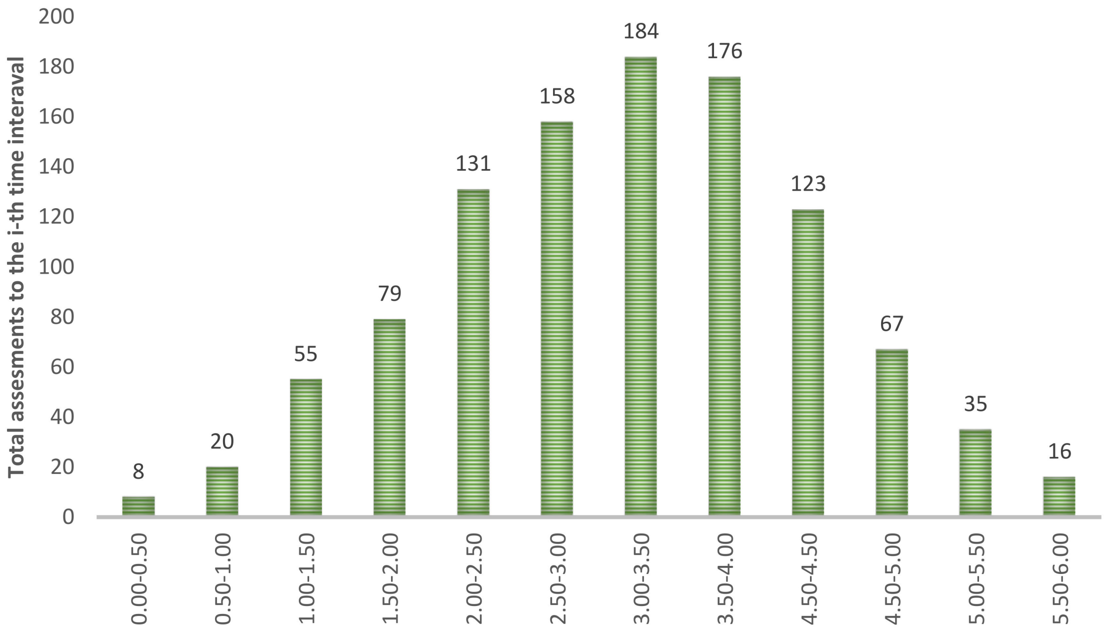

Figure 3. The histogram that represents the assessment of experts concerning the distribution of the recognizing information time.

The mathematical expectation of a time of recognizing information on failures was indicated as 2.94 h (a concordance coefficient is 0.79).

Table 2. The results of the survey of experts to determine the time for recognizing information on failures.

Experts	**Expert Estimates Given to the *i*-th Time Interval**											
	Time Intervals, Hours											
	0.00–0.50	**0.50–1.00**	**1.00–1.50**	**1.50–2.00**	**2.00–2.50**	**2.50–3.00**	**3.00–3.50**	**3.50–4.00**	**4.00–4.50**	**4.50–5.00**	**5.00–5.50**	**5.50–6.00**
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
1	0	0	1	3	6	8	10	9	5	2	1	0
2	1	1	3	2	5	7	9	8	4	3	2	1
3	0	1	2	4	7	7	9	9	6	2	3	2
4	1	1	2	3	6	8	8	8	7	4	1	1
5	0	0	1	2	6	7	9	10	4	2	2	0
6	1	2	3	4	5	7	8	9	7	5	3	0
7	0	1	4	6	6	8	9	8	6	3	2	0
8	0	0	2	4	7	9	9	10	8	5	1	1
9	1	1	5	5	6	9	10	8	7	4	2	2
10	0	2	3	3	5	8	10	8	6	3	1	0
11	0	1	4	4	8	9	10	9	7	4	1	1
12	0	0	2	3	7	9	8	8	6	3	1	0
13	1	1	4	6	8	8	10	9	8	3	2	1
14	1	1	3	5	9	9	9	8	6	2	2	2
15	0	0	2	3	7	7	8	10	7	4	0	0
16	1	3	3	5	6	6	10	9	5	5	3	0
17	0	2	3	5	5	7	9	8	4	4	2	1
18	1	1	2	4	7	9	10	10	7	3	2	1
19	0	1	4	4	8	9	10	9	7	4	1	1
20	0	1	2	4	7	7	9	9	6	2	3	2
$\sum_{i=1}^{m} N_{ij}$	8	20	55	79	131	158	184	176	123	67	35	16
t_{ci}	0.25	0.75	1.25	1.75	2.25	2.75	3.25	3.75	4.25	4.75	5.25	5.75
$t_{ci} \cdot \sum_{i=1}^{m} N_{ij}$	2	15	68.75	138.25	294.75	434.5	598	660	522.75	183.75	81	92
$\sum_{i=1}^{m} N_{ij} - \overline{N}$	−79.8	−67.8	−32.8	−8.8	43.2	70.2	96.2	88.2	35.2	−20.8	−52.8	−71.8
$(\sum_{i=1}^{m} N_{ij} - \overline{N})^2$	6.4×10^3	4.6×10^3	1×10^3	0.0774×10^3	1.9×10^3	4.9×10^3	9.2×10^3	7.8×10^3	1.2×10^3	0.4×10^3	2.8×10^3	5.1×10^3
W = 0.79 $M(t)$ = 2.94												

4.3. Repair Time

This work uses the statistical data of time to repair failures t_{repair} obtained by using the year statistics of a power supply company ("Oreolenergo") [37]. The used data that concern failures and repair time are summarized in Table 3 and shown in Figure 4.

Table 3. Number of failures for specific repair time.

Repair time, *h*.	0.00–0.50	0.50–1.00	1.00–1.50	1.50–2.00	2.00–2.50	2.50–3.00	3.00–3.50	3.50–4.00
Number of failures, pcs.	75	50	29	38	12	3	2	3

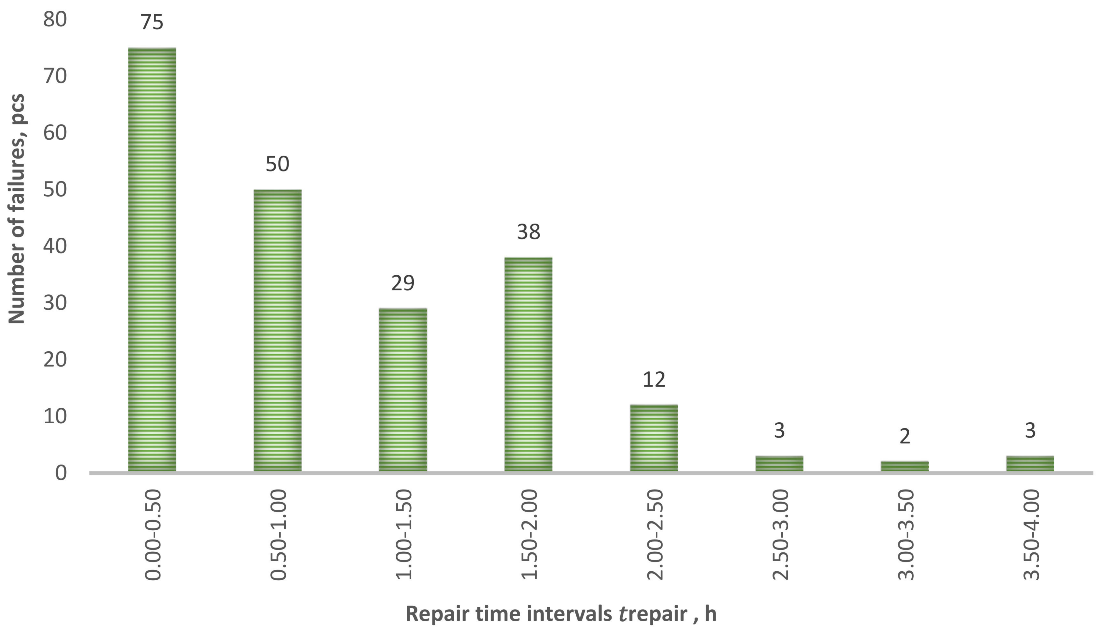

Figure 4. Number of failures for specific repair time.

The values of the mathematical expectation and dispersion of the repair time were determined from this data [5,10,18]. To do this, the sampling mean X_B was found out by Equation (11):

$$X_B = \frac{1}{n} \times \sum_{1}^{N_i} (X_i \times N_i)$$
$$X_B = \frac{0.25 \times 75 + 0.75 \times 50 + 1.25 \times 29 + 1.75 \times 38 + 2.25 \times 12 + 2.75 \times 3 + 3.25 \times 2 + 3.75 \times 3}{212} = 1 \quad (11)$$

where

- n—number of failures, $n = 212$;
- X_i—i-th repair time for which the calculation is made;
- N_i—frequency of the i-th time value.

Next, the conditional values U_i were determined by Equation (12):

$$U_i = \frac{X_i - C}{h}$$
$$U_1 = \frac{0.25 - 0.25}{0.5} = 0 \quad (12)$$

where

- C—constant (the repair time with the highest frequency of occurrence), C = 0.25 is for the first time interval;
- h—scale (the time step h = 0.5 h).

Similarly, other indicators were calculated, and the results are summarized in Table 4.

Table 4. Conditional values of the repair time.

No interval	1	2	3	4	5	6	7	8
$\boldsymbol{U_i}$	0	1	2	3	4	5	6	7

The conditional sample value U_B was determined by Equation (13):

$$\begin{gathered} U_B = \frac{1}{n} \times \sum_{1}^{N_i} (U_i \times N_i) \\ U_B = \frac{0\times75+1\times50+2\times29+3\times38+4\times12+5\times3+6\times2+7\times3}{212} = 1.5 \end{gathered} \tag{13}$$

The sample value X_B through the conditional sample value U_B was found by Equation (14):

$$\begin{gathered} X_B = U_B \times h + \mathrm{C} \\ X_B = 1.5 \times 0.5 + 0.25 = 1 \end{gathered} \tag{14}$$

The value of sample dispersion D_B was determined by Equation (15):

$$\begin{gathered} D_B = \frac{1}{n} \times \sum_{1}^{N_i} [(X_i - X_B)^2 \times N_i] \\ D_B = \frac{1}{212} \times [\,(0.25-1)^2 \times 75 + (0.75-1)^2 \times 50 + (1.25-1)^2 \times 29 + (1.75-1)^2 \times 38 + \\ (2.25-1)^2 \times 12 + (2.75-1)^2 \times 3 + (3.25-1)^2 \times 2 + (3.75-1)^2 \times 3\Big] = 0.61 \end{gathered} \tag{15}$$

Root-mean-square deviation:

$$\begin{gathered} \delta_B = \sqrt{D_B} \\ \delta_B = \sqrt{0.61} = 0.781 \end{gathered} \tag{16}$$

The corrected root-mean-square deviation S was found out to obtain a more accurate value of the deviation:

$$\begin{gathered} S = \sqrt{\frac{n}{n-1}} \times \delta_B \\ S = \sqrt{\frac{212}{212-1}} \times 0.781 = 0.782 \end{gathered} \tag{17}$$

The probability of determining the repair time interval was taken to be $\gamma = 0.95$. Therefore, the value for determining the interval is $t = 1.96$.

The accuracy of the assessment:

$$\begin{gathered} 2F = \gamma = 0.95 \\ F = 0.475 \end{gathered} \tag{18}$$

The estimation deviation:

$$\frac{t \times S}{\sqrt{n}} = \frac{1.96 \times 0.782}{\sqrt{212}} = 0.105 \tag{19}$$

The boundaries of the confidence interval:

$$\begin{gathered} X_B - \frac{t \times S}{\sqrt{n}} = 1 - \frac{1.96 \times 0.782}{\sqrt{212}} = 0.895 \text{ is the lower interval} \\ X_B + \frac{t \times S}{\sqrt{n}} = 1 + \frac{1.96 \times 0.782}{\sqrt{212}} = 1.105 \text{ is the upper interval} \end{gathered} \tag{20}$$

Thus, the time to repair failures was in the interval 1 ± 0.105 h with 95% probability.

4.4. Connection Harmonization Time

The time for the harmonization of the equipment connection $t_{\text{harmonize}}$ depends on the applied communication tools, the time for preparing the equipment to be connected and its documentation, the time for equipment connection, and the time needed to ensure that the connection was successful.

The dispatcher must check the possibility of switching on a power line [38]:

- on records in the operational log and applications;
- by the telephone book "About the delivery and acceptance of lines";
- by the absence of posters on the drives of disconnectors;
- by interviewing operating personnel of substations and power plants about the absence of working people on the power line equipment which should be switched on.

After that, the command to turn on the equipment is given. In total, the time of connection harmonization can take up to 20 min.

4.5. Analysis Results

Considering the values of time intervals, the PS restoration time was calculated using Equation (1):

$$t_{\text{restor.}} = 1.01 + 2.94 + 1.00 + 0.33 = 5.28 \text{ h}$$

The indicated time of power supply restoration based on our analysis is equal to 5.28 h. This duration is significant and can cause considerable material damage to consumers supplied from the electric grid where blackout has occurred especially for those sensitive to process shutdown.

5. Discussion

Annually, the investigated regional power supply company "Oreolenergo", a branch of IDGC of Center, has an average of 344 power supply outages with a total of 98,495.835 kWh of unsupplied electric power [17]. The total number of power outages includes consumer outages, outages due to damage of overhead lines, cable lines, transformers, equipment of transformer substations, and distribution points. The average power supply restoration time is 5.86 h, which is close to the time obtained based on the performed studies (5.28 h). The deviation is 9.9%. It should be noted that these data on the power supply restoration time are related to failures in power transmission lines, which are the most unreliable element of the power supply systems.

A power supply restoration time of more than 5 h causes significant damage both to consumers and to power supply companies. Opportunities should be sought to shorten this time as much as possible. In most cases, it is difficult, since a noticeable number of power lines especially in rural areas have surpassed their resources and require replacement [39,40]. According to the statistical data of "Oreolenergo" [17], the causes of damage to power lines are shortcomings in maintenance (45%), the influence of natural and weather conditions (33%), the influence of unauthorized persons (15%), other reasons (e.g., birds, animals, etc.) (7%). At the same time, it is indicated that shortcomings in maintenance includes fallen trees and short circuits because of trees touching power line wires caused by untimely cleaning of power line routes, breaks of wires, fallen utility poles, and other causes associated with power line aging and late monitoring of their condition.

The PS restoration time may be reduced by different methods, especially the electrical network automation means. Almost all automation means can reduce the time to perform a particular operation and increase the accuracy of its execution. For example, the time to obtain information and recognize it can be significantly reduced by using a power supply reliability monitoring system or by using means for monitoring the technical condition of an electric network equipment, such as using unmanned aerial vehicles (UAVs) as in the articles [41–44] or the thesis [45]. Calculations realized in [45] indicated the implementation of the developed power supply reliability monitoring system in the Mtsensky electric grid of the Orel Region, Russian Federation. They showed that the time to obtain information was reduced from 1.01 h to 0.09 h, and the time to recognize information was reduced from 2.30 h to 0.25 h. In [46], UAV tests were described based on the Orelenergo branch of the IDGC of Center, PJSC. They showed that it was possible to achieve a reduction in the time of a PTL round check (the time for recognizing information) from 3.5 h/km to 5 . . . 15 min/km, that is, more than 30-fold.

It should be noted that if there are means of sectionalizing and redundancy of power lines such as automatic circuit reclosers (ACR), the time of power supply outages can also be significantly reduced [47,48]. However, in this case, the power supply restoration will be carried out by redundancy means, and the time for this restoration $t_{\text{restor.redund.}}$ is determined by the equation

$$t_{\text{restor.redund.}} = t_{\text{damaged section isol.}} + t_{\text{backup power act.}} \tag{21}$$

where $t_{\text{damaged section isol.}}$ is the time spent on the isolation of the damaged section from intact ones, h; $t_{\text{backup power act.}}$ is the time spent on backup power actuation, h.

All means of electrical network automation can be classified according to the time intervals that they shorten. This classification is shown in Table 5. Thus, the existing and promising methods and technical means of electrical network automation aim at reducing the specific constituents of the power supply restoration time.

Table 5. Methods and technical means of electrical network automation for reducing the power supply (PS) restoration time.

Time Interval	Methods and Technical Means of Electrical Network Automation
$t_{\text{obt.infor.}}$	• Monitoring of the technical condition of electric network equipment; • Monitoring of power supply reliability; • Telecontrol.
$t_{\text{rec.infor.}}$	• Monitoring of the technical condition of an electric network equipment; • Monitoring of power supply reliability; • Monitoring of electric network operation modes; • Telecontrol; • Means for determining the failure location.
t_{repair}	• Automation tools (processes digitalization of work authorization of brigades, registration of the beginning and end of work, etc., for example, the "Digital Electrician complex" [15]); • Repair work automation.
$t_{\text{harmonize}}$	• Means for remote communication of the brigade members with the dispatcher and with each other; • Monitoring the technical condition of electric network equipment; • Monitoring of electric network operation modes; • Telecontrol.
$t_{\text{damaged section isol.}}$	• Automatic sectionalizing of power lines; • Monitoring the technical condition of electric network equipment; • Monitoring of power supply reliability; • Telecontrol.
$t_{\text{backup power act.}}$	• Automatic redundancy of power lines and consumers; • Monitoring the technical condition of electric network equipment; • Monitoring of power supply reliability; • Telecontrol.

6. Conclusions

The power supply restoration time analysis of power transmission lines shows that it depends on several constituents. The constituents of time restoration analyzed in this study are:

- time for obtaining information,
- time for information recognition,
- time to repair failures,
- time for connection harmonization.

In this article, the methods of obtaining each of them were proposed and described. The case study calculations were realized for the Russian power supply company "Oreolenergo". The obtained restoration time was theoretically equal to 5.28 h. This value is equal to the statistical data obtained from the selected power supply company. The result deviation was less than 10%. Additionally, after obtaining the value of PS restoration time, it was proposed how it may be decreased. The proposition of the technical means of electrical network automation was indicated. These means were proposed and ordered in accordance to the time intervals they shorten.

Future research directions will be aimed at numerically estimating the impact of methods and technical means of electrical network automation on the constituents of the power supply restoration time. This will allow evaluating the effectiveness of their introduction by comparing the received values of the power supply restoration time constituents with initial ones and determining the reduction in damage from a lack of electricity supply.

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