Modelling of the reliability of the protection system against voltage dips

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Abstract. Oil and gas production facilities place high demands on the reliability of the power supply system. In the event of a failure of the electrical networks of such consumers, significant economic damage occurs and there is a high probability of threat to the environment. To improve the reliability of oilfield electrical networks, it is necessary to introduce automated systems to eliminate violations in power supply modes. Automatic control systems for operating modes of electrical networks must have high reliability indicators. The paper proposes to assess the reliability of the automatic control system using the event tree method. The development of an event tree makes it possible to evaluate the efficiency of the automatic control systems, to identify elements and control algorithms that do not meet the reliability requirements.

1. Introduction
A promising direction in the development of electrical networks for industrial consumers is the introduction of smart-grids. This is not possible without expanding the automation of control over the operating modes of electrical networks.

The advantages of introducing automatic control systems (ACS) of electrical network modes are obvious - reducing the likelihood of power supply failure and minimizing consumer losses [1]. But this causes an increase in the interaction of the power supply system with control systems. That is, the probability of failure of electrical networks from a failure in control systems will increase.

Consequently, an important stage in the implementation of ACS by modes of electrical networks is the assessment of their reliability.

For example, in [2], the analysis of the reliability of protection and automation systems at substations showed an increase in the probability of a power failure due to hardware and software failures of control systems.

Analysis of the reliability of control systems is an important step to ensure the safety of any technological process [3, 4]. This is confirmed by the following works.

The work [5] analyzes the reliability of an automatic level control system. The work calculates the frequency of failures and the average time between failures. The analysis carried out by the authors showed that the system has a rather low reliability due to the numerous components in its architecture. The authors identified the direction of increasing reliability in the selection of components of higher quality, or in the implementation of structural redundancy (redundancy) for less reliable elements.

In work [6] it is noted that testing the reliability of control systems for technological objects is of great importance. The authors note that the integration of hardware and software in reliability
calculations is necessary to obtain true performance. And the authors recommend building complex reliability models.

In work [7], we propose to introduce an ACS, which, in the event of a voltage dip of any duration, connects especially critical oil field consumers to an autonomous power source. Voltage dips are not a power outage and are an indicator of the quality of electrical energy. And typical systems for the protection of electrical networks do not eliminate their consequences.

The introduction of the proposed automatic system is an urgent task, since in case of voltage dips there is a possibility of stopping the technological equipment of oil and associated petroleum gas production facilities. This is due to a decrease in the torques of the induction drives of the submersible oil production units. As a result, there are losses in the production of hydrocarbons during the recovery of the technological process.

In this paper, we propose an approach to assessing the reliability of this ACS. We consider only hardware reliability indicators. In the future, we plan to carry out a comprehensive assessment of the reliability of the control system (hardware and software) and the control object (electrical network).

2. Materials and methods
ACS performs the following functions:

- identifies and recognizes a voltage dip causing, under other conditions, the shutdown of the equipment of oil production facilities;
- makes a decision on connecting the consumer to an autonomous power source;
- forms a knowledge base on the levels of voltage dips and network congestion causing shutdown of technological objects under various conditions;

For illustration, figure 1 shows a simplified scheme of the ACS.

The system has the following levels:

1. The lower level of automation of ACS is divided into sections by linear switches (S). Linear switches isolate sectors in case of damage. The local system (LS) of each sector includes sensors for monitoring voltage and load sags, actuators for switching consumers to an autonomous power source

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**Figure 1.** Simplified diagram of the automatic control system.
and other auxiliary equipment. The sensors are installed at points of the electrical network with the most important consumers, that is, having great damages in the event of a power failure. To monitor faults in the control system itself, fault detectors are installed. They are located near the voltage and power sensors. Fault detectors are activated by the fault current. The fault lies between the last activated and the first deactivated detector.

Local system elements transmit or receive data via communication units (RTUs) over communication channels (CUs) with a control center (CC).

2. The control center (CC) consists of a data processing unit in which a voltage drop is identified and a possible failure of the consumer’s electrical equipment is recognized. This unit makes a decision on connecting the consumer to an autonomous power source based on the knowledge base. The control center also processes data from the fault detectors and issues a signal to isolate the damaged section of the ACS using linear switches S.

To assess the reliability of the ACS, we use the method using the event tree. The event tree is, in fact, a model of the structure and functioning of the control system. System events are branches that lead to the result of management.

Modeling the reliability of the ACS is a complex procedure, since the control process includes many automation components and a number of sequential control actions. With this aspect in mind, we use a modular approach.

We divide the ACS into modules that can be analyzed separately. Then we combine all the modules and analyze the system using the event tree methodology.

2.1. Structural diagram of the reliability of an automatic system

We divide ACS into modules based on functional and operational characteristics. Each module is independent of the others, that is, it has no common components with other modules. The structural diagram of the ACS reliability is shown in figure 2.

![Figure 2. Block diagram of the ACS reliability.](image)

Sector local systems (LSs) contain local automation elements, fault detectors, protection relays, circuit breakers and switching devices that are connected to communication devices (RTUs).

The Control Center (CC) communicates with the LSs via Communication Channels (CUs). Communication channels must have increased reliability, as control systems for electrical networks are common.

The reliability of R modules is the probability that a module is capable of performing a required function for a given period of time under given conditions.
The reliability indicators of the modules are determined on the basis of statistical data using the theory of reliability. They have the following values: control center R (CC) = 0.99; control center communication channel R (CUc) = 0.995; breaker communication channel R (CUB) = 0.99; communication channels of local systems of sectors R (CU1) = R (CU2) = R (CU3) = R (CU4) = R (CU5) = 0.99; local breaker system R (LSB) = 0.99; local switch systems R (LS1) = R (LS2) = R (LS3) = R (LS4) = R (LS5) = 0.99; repeater R (REP) = 0.99.

2.2. Assessment of the reliability of an automatic system

We have developed a tree of events for the management procedure. The event tree gives a list of possible control results and links modules with the results of the system operation [8].

ACS assumes sequential operation of a set of components, so the event tree is convenient to use. The event tree recognizes the sequential operating logic of the system and can easily be extended to include deeper analysis of the system.

Let us consider, for example, the occurrence of a permanent failure F in section 3. The following control operations will occur: fault isolation switching, network reconfiguration, and restoration of ACS functioning.

Sequence of events and control actions:

1) Fault occurs, breaker B is tripped by protection.
2) Breaker B is automatically reclocked. Since F is permanent, B is tripped again.
3) The local LSB breaker system sends a signal to the CC control center via the CUB link to open breaker B.
4) The CC control center polls each fault detector in the local systems LS1-LS4 and determines the location of the fault.
5) The CC control center selects the switching plan depending on the location of the fault. Sends commands to local systems LS2 and LS4 to isolate damaged section 3.
6) CC sends a command to LSB to close breaker B to restore sections 1 and 2.
7) CC sends a command to LS5 to close switch TS. Sections 4 and 5 are connected to feeder 2.

In case of failures during the control process, the control center draws up an alternative switching plan and tries to re-restore as many sections as possible.

Some alternative plans are as follows:

- if LS2 fails, sections 2 and 3 are isolated, sections 1, 4 and 5 are restored;
- if LS3 fails, sections 3 and 4 are isolated, sections 1, 2 and 5 are restored;
- if LS2 B LS3 fails, sections 2, 3 and 4 are isolated, sections 1 and 5 are restored;
- if LS1 and LS2 fail, sections 1-3 are isolated by breaker B and switch S3, sections 4 and 5 are restored.

The event tree for the management process is shown in figure 3. The probabilities of events considered in the tree are the probabilities that each module will or will not successfully perform the required functions. Note that in the event tree, the success of two modules, for example CU1 and LS1, means that both CU1 and LS1 should work successfully.

The probability of each path \( P_i \) in the control process is calculated by the product of the corresponding event probabilities. Since all paths are mutually exclusive of each other, the probability of a certain control result (for example, restoration of section 1) is determined by summing the probabilities of the paths leading to this result.

For example, the probability of recovery of section 1 is calculated as follows:

\[
P(S1) = P_1 + P_2 + P_3 + P_4 + P_5 + P_7 + P_8 + P_9 + P_{10} + P_{11} + P_{20} + P_{21} + P_{22} = 0.9645.
\]

Below are the calculations of the probability of recovery of other sections:

\[
P(S2) = P_1 + P_2 + P_3 + P_4 = 0.9449.
\]
\[ P(S4) = P_1 + P_4 + P_{13} + P_{28} = 0.9452, \]
\[ P(S5) = P_1 + P_4 + P_7 + P_9 + P_{13} + P_{19} + P_{23} + P_{28} + P_{30} + P_{34} = 0.9733. \]

| CUB | CUc | Rep | CU2 | CU1 | CU3 | CU4 | CU5 | LS5 | restored section |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|------------------|
|     |     |     |     |     |     |     |     |     | 1, 2, 4, 5      |
|     |     |     |     |     |     |     |     |     | 1, 2           |
|     |     |     |     |     |     |     |     |     | 1, 2           |
|     |     |     |     |     |     |     |     |     | 1               |

\[ 9886.0)5(;9691.0)4(;9690.0)2(;9791.0)1( = SPSPSPSP = \]

- successful
- failure

Figure 3. Event tree when section 3 is damaged.

3. Results and discussion
The recovery probabilities of various ACS sections are different, although these sections are equipped with automation devices of the same reliability. Section 5 has the highest likelihood of recovery as it has more likely communication paths with the control center. Nevertheless, the results obtained are unsatisfactory for the power supply system of the oil production process.

To increase the reliability of each section of the ACS, it is possible to apply redundancy of automation equipment or supply a backup power supply, which, as a rule, is economically justified for the oil industry.

For example, when all CUs communication channels are backed up, the section recovery probabilities will be as follows:
\[ P(S1) = 0.9791; P(S2) = 0.9690; P(S4) = 0.9691; P(S5) = 0.9886. \]
4. Conclusions
A model of the ACS reliability by the operating modes of the oilfield electrical network has been developed. The event tree methodology was used. Reliability analysis was performed for some points of the ACS.

On the basis of the data obtained, recommendations were given for improving the reliability of the ACS by operating the electrical network to minimize losses from voltage dips.

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