Analysis of reliability of Boguchany Dam circuit of power output while taking into account the perspective of Siberian United Energy Systems development

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Abstract. Calculation and analysis of reliability of power output circuits of Boguchany Dam has been performed, which allows to identify types of accidents, to determine the frequency of their occurrence and the terms of liquidation for them. With the help of the obtained values of frequencies and duration of accidents, it is possible to determine the relative undersupply of energy to consumers and reduction of electric power generation by the station, which makes it possible to estimate the value of mathematical expectation of economic damage.

1. Introduction
The development of network infrastructure and generating capacities, the ensuring of reliable functioning in the long term are the current tasks of the Siberian United Energy Systems.

In 2017 the consumption volume of electric energy on United Energy Systems of Siberia was 205.876 billion kWh which is 0.62% below the level that was in the previous year. By 2024 the demand level for electric energy in United Energy Systems of Siberia is predicted at the level of 229.872 billion kWh (average annual rate of gain for the period is 1.59%). The dynamics of demand for electric energy in the United Energy Systems of Siberia is characterized by relatively high growth during the period of 2019 – 2020, with a slowdown during the period of 2021 – 2024 (Scheme and program for the development of the Unified Energy System of Russia for 2018 – 2024).

The growth rate of demand for electric energy on the power system of Krasnoyarsk Krai is higher than the average, which is connected to the planned growth of aluminium production due to the construction of an aluminium smelter in Boguchany district, the electricity supply of which is provided by Boguchany Dam.

The total capacity of Boguchany Dam is taken as a part of nine power units with a unit capacity of 333 MW (2997 MW).

The circuit of power output of Boguchany Dam and its connection to 500-220 kV network of United Energy Systems of Siberia is rigidly bound with the circuit of external power supply of Boguchany Aluminium Smelter with capacity of 1210 MW and with power supply of developing territories of Lower Angara region.

Versions of the Dam power output circuit are formed in connection with the development of the region and circuit-mode analysis of the Siberian United Energy System variants. Correction of Boguchany Dam power output circuit is the result of technical approvals of Boguchan aluminium plant.
power set schedules and HPP units input, change of the United Energy System mode situation, but without the quantitative assessment of reliability.

Assessment of reliability indicators is based on calculation of specific values of failure-free operation probabilities of the circuit according to information on averaged values of parameter of failure flow for a unit of equipment and average time of its recovery over a certain period. Further, according to the probability of failure-free operation (failure probability) of a particular network element (transformer, generator, line, connection), similar indicators for the circuit as a whole are determined.

Methods to analyze improvement in the reliability of a distribution system to reduce outage frequencies and duration have been proposed [1, 2]. Presents the reliability improvement of the electrical distribution system of the substation, by simulation analysis using the DIgSILENT Power Factory program [3].

2. Reliability analysis of the circuit of power output

Analysis of reliability of Boguchany Dam power output circuit was performed using table logical method of reliability calculation [4]. When developing the fault tree, the diagrams shown in figures 1 and 2 were taken into account.

Figure 1. Power output diagram Var. 1.

Figure 2. Power output diagram Var. 2.
The calculation of reliability of the main connection circuits of the power plant is made with the help of TOPAS [5] software complex, which allows to analyze reliability of the main connection circuits, including switchgear of any voltage class, generator connections, high-voltage power lines (HV), connection of auxiliary power standby transformers, coupling transformers between switchgear.

Calculation of logical indicators of reliability of the main circuit is carried out on the basis of determining the number of combinations of events (conjunctions) leading to failure of the k functioning [4, 5, 6]:

\[ C(k) = \sum \sum \sum L(i, j, s, k); \]

where \( L(i, j, s, k) \) – the logical function that takes a value of 0 or 1.

Calculation of k-th form \( \lambda(k) \) operation failure frequencies and duration of disaster recovery \( T(k) \) is generally carried out by the expressions [4, 6]:

\[ \lambda(k) = \sum I \sum j q(j) \lambda(i) Q(s/i) L(k) \]

\[ T(k) = \frac{1}{\lambda(k)} \sum I \sum j q(j) \lambda(i) \min \left( \frac{t(j)}{2}; t(i); t_{o.s.} \right) Q(s/i) L(k) \]

where \( q(j) \) – relative duration of j repair mode, per unit.; \( \lambda(i) \) – damage frequency of i circuit element, 1/year; \( t(j) \) – Duration of j repair mode of the circuit, h; \( t(i) \) – same post-accident recovery of the i circuit element, h; \( t_{o.s.} \) – time of operational switching, h; \( Q(s/i) \) – failure probability in operation of relay protection or switching device.

The value of the emergency decline in annual output (undersupply) of power is determined by the formula [5]:

\[ \Delta W = 8760 \left( \sum k \lambda_{v.r.}(k) \Delta N(k) T(k) + \sum k \lambda_{o.p.}(k) \Delta N(k) \tau_{o.p.}(k) \right) \]

where \( k \) – type of accident; \( \lambda_{v.r.}(k) \) – shutdown frequency for events not related to the circuit structure, 1/year; \( \Delta N(k) \) – emergency power decline at, MW; \( \lambda_{o.p.}(k) \) – shutdown frequency for the events that depend on circuit structure; \( \tau_{v.r.}(k) \) – average time of operational switching after the k accident, hour.

Prior data on the reliability of elements of switchgear with a voltage of 330 kV are summarized in table 1 [7, 8].

| Circuit element               | Specific frequency of failure 1/year per 100 km | Emergency recovery time T, h | Scheduled repairs frequency \( \lambda_{rep} \), 1/year | Scheduled repairs term \( T_{rep} \), h |
|------------------------------|-----------------------------------------------|-------------------------------|---------------------------------|-----------------|
| Power generating unit        | 0,1                                           | 175                           | 1                               | 175              |
| Power line 220 kV            | 0,057                                         | 15                            | 5,4                             | 61,3             |
| Power line 500 kV            | 0,04                                          | 16                            | 3,5                             | 105,1            |
| Coupling autotransformers    | 0,15                                          | 350                           | 2                               | 80               |
| Collecting bars 220 kV       | 0,039                                         | 4                             | 0,498                           | 9                |
| Collecting bars 500 kV       | 0,03                                          | 5                             | 0,498                           | 15               |
| Switching units 220 kV       | 0,003                                         | 40                            | 0,2                             | 40               |
| Switching units 500 kV       | 0,01                                          | 120                           | 0,2                             | 120              |
The operational switching time in the calculations - 0.5 h - is regulated by the instruction. As a result of the calculation, for the variants of the main circuit of electrical connections shown in Figs. 1 and 2, the frequencies (1/year) and the duration of emergency shut downs (hours) (in the integrated emergency codes) for events that are not related to the structure of the circuit and for events that depend on the structure of the circuit (at the time of restoration and repair, at the time of operational switching) were determined. Besides, the total frequency of shut downs and the average recovery time (hour) was determined. In addition, the value of the annual undersupply of electricity was obtained.

3. Conclusion
Frequency of failures of outgoing power transmission lines is less for option 2 than for option 1 on Angara by 3.8%, on Kodinsk by 96.7%
Power transmission lines outage for Boguchany Aluminium Smelter in the circuit of Var. 1 - 1.071/year, which is more than outage of 500 kV autotransformers in the circuit of Var. 2 - 0.241 1/year in all combinations of simultaneous failure of circuit elements.

Thus, Var. 1 turns out to be a less reliable power distribution circuit in normal mode compared to Var. 2, which is explained by the large number of connections within the circuit.

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