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The Reliability Estimation of the Turbine Lubricating Oil System for VVER-1000 Unit

V. Kolyhanov[*], **I. Kozlov**, **K. Murenko**

Odesa Polytechnic National University, Shevchenka av. 1, Odesa, 65044, Ukraine

Abstract. The design and operating modes of the lubricating oil system for VVER-1000 unit with K-1000-60/3000 turbine are considered. Based on the reliability indicators of the system elements, the reliability of the system as a whole was estimated. The influence of the oil wedge on the lube oil temperature in the bearings was studied using the VVER-1000 block model on the full scale simulator. The critical turbine bearings are determined from the point of view of achieving the permissible lube oil temperature.

Keywords: operating modes, operational reliability, turbine lubricating oil system, lube oil temperature, oil wedge

1 Introduction

The safe and reliable operation of the NPP power unit depends not only on the reliability of the main systems, but also on the support systems. The turbine lubricating oil system belongs to such systems. The reliability of the system is determined by the reliability of the equipment that is part of it, the availability of duplication and optimal maintenance. It is also important to use effective modern technologies.

In Ukraine, since 2019, the South-Ukrainian NPP has been using a method of cleaning the circuit of the turbine lubricating oil system developed and patented by the Polish specialists of the company Ecol Sp/z.o.o [1–3]. Conventional methods of cleaning, which are provided for by the rules of technical operation, did not ensure complete cleaning of sediments or contamination from the inner surface of pipelines and equipment of the system, which led to accelerated degradation of lubricants. The latest method of the Ecol company allowed to solve the problem of cleaning the system and has already been applied in 90 power units, including the Temelin and Dukovany NPPs in the Czech Republic.

2 Turbine Lubricating Oil System

The oil supply system of the steam turbine installation ensures the operability of the turbine unit and its accident-free operation during the designated period. The main function of the lubrication systems is to ensure the reliability of the oil supply for the lubrication of the bearings of the turbine, generator, and turbocharger pump, and in some schemes, to provide lube oil for the generator shaft sealing systems and turbine control systems. Similarly, the main tasks include maintaining the tightness of systems, controlling the amount of air in the oil, regulating the ventilation of the oil path, and controlling oil oxidation and contamination.

A mandatory condition for normal operation is the use in the lubrication system of the design brand of oil that meets the technical conditions of the turbine. Turbine oil systems of Ukrainian NPPs use both petroleum turbine and flame-resistant synthetic oils.

The successful operation of fire-resistant oil with lubrication systems of a number of turbines confirmed the feasibility of its widespread use. However, at the same time, there are additional operational tasks associated with the difficulty of maintaining high purity of the oil due to greater density and solvent capacity, air release and foaming compared to petroleum oils, and this leads to greater contamination of the oil. Due to the deterioration of operational qualities over time, the lube oil becomes unusable and may require a complete oil change.

The turbine lubricating oil system [4–7] is designed for centralized lube oil supply to:

- turbine bearings, generator, generator exciters;
- bearings and reducers of two turbo-pump units;
- systems of hydrostatic lifting of rotors;
- regulation system of the turbo-feed pump;
- shaft turning device.

Turbine bearings are lubricated with flame-resistant synthetic turbine oil.

The system provides:

- maintenance of pressure oil temperature at the level of 40–45°;
- maintenance of the specified oil pressure in the grease pressure collector at the level of the turbine axis at least 1.2 kg/cm^2.

The criterion for performing the functions assigned to the turbine lubrication system is to ensure the supply of a sufficient amount of oil to lubricate the turbine support bearings and the turbo feed pump while maintaining the specified pressure and temperature.

The main equipment of the oil supply system of the turbine unit:

[*]Corresponding author e-mail: victor.kolykhan@i.ua

- main oil tank SC10B01 with a capacity of 47 m^3;
- three overflow tanks SC10B02 - 04, with a capacity of 12.5 m^3 each;
- four main oil pumps SC11 - 14 D01;
- four SC21-24W01 oil coolers;
- SC15S01 overflow tank injector.

In the nominal unit operating mode, there are three oil coolers in operation, one in reserve. The temperature of the oil after the oil coolers is kept constant ($T = 400 \circ C$) by changing the flow of cooling water. Through the outlet valves of the SC21-24S01 oil coolers, the oil through the oil line enters the reduction valve SC29S01 – for automatic maintenance of the oil pressure on the axis of the turbogenerator (TG) at the level of 1.2 kgf/cm^2. The pressure oil line to the bearings of the turbogenerator supplies oil to the bearings of the turbine (10 items), the generator (2 items), and the exciters of the generator (2 items) [9].

3 Calculation of Reliability Indicators of the Oil Supply System

On the basis of the principle diagram of the oil supply system, a simplified structural scheme (Figure 1) was built, which includes critical elements, i.e. those, the failure of which will lead to the failure of the entire system or a decrease in its characteristics.

Four parallel lines, which consist of equipment D01, S02, S04 have a success condition of two out of four, which recognizes the need for the operation of two lines for the accident operation of these elements. Four parallel lines, which consist of equipment S01, W01, S02, have a success condition of three out of four, which recognizes the need for the operation of three lines for the failure-free operation of these elements. The next group of parallel elements consists of SB11-20 turbine cylinder bearings and generator bearings and two SQ11-14 exciters. At Figure1 only the first and last bearing are marked, the other bearings are marked with a dotted line, there are 14 bearings in total.

If the elements are connected in series, they can be integrate. For example, replace three serially connected elements with one, for which the intensity of the failure flow is the sum of the constituent elements. The structural diagram after integration of the elements is presented in Figure 2. At the same time, three macro elements were formed:

- macro element 1 – consists of a tank and a reducing valve (B01 + S01)
- macro element 2 – consists of an overflow tank injector, a non-return valve, a manual valve (D01 + S02 + S04)
- macro element 3 – the composition includes a manual valve, an oil cooler, a non-return valve (S01 + W01 + S02).

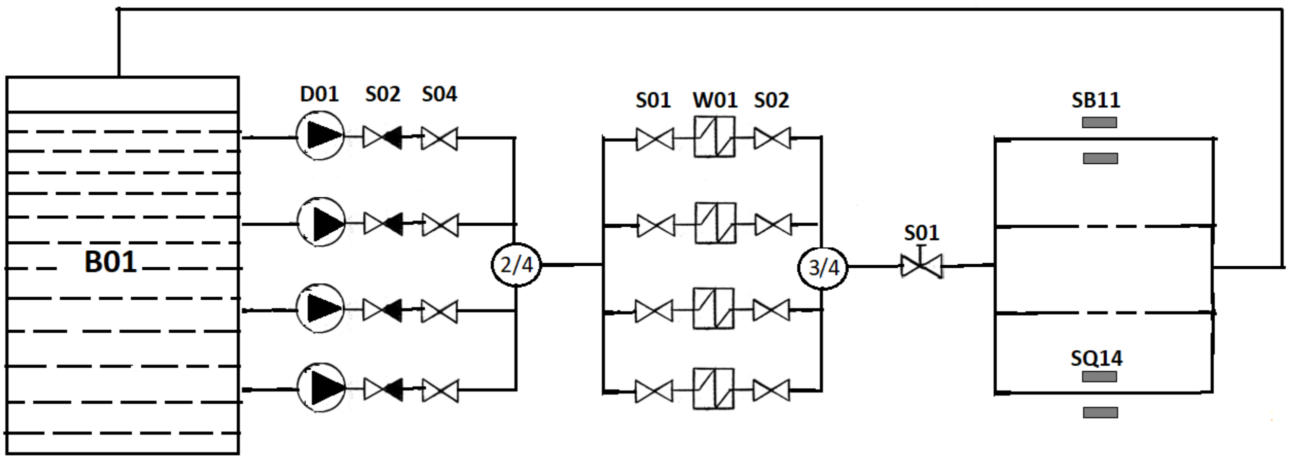

Figure 1. Structural scheme of the oil supply system: B01 – main oil tank, D01 – overflow tank injector, S02 – check valve, S04 – manual valve, S01 – manual valve, W01 – oil cooler, SB11, SQ14 – TG bearings.

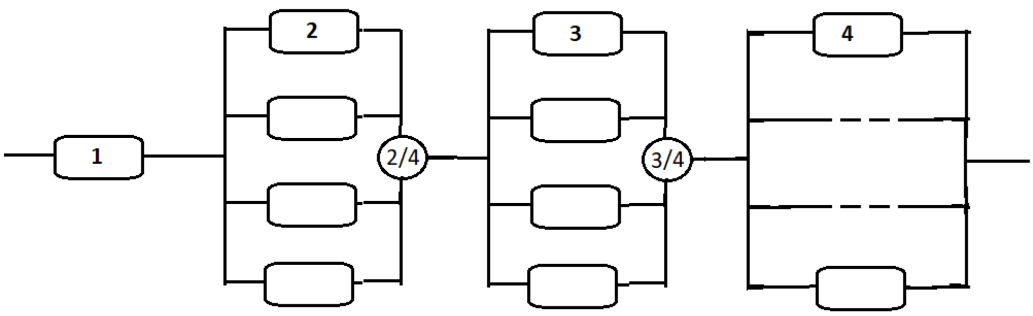

Figure 2. Structural scheme of macro elements.

The fourth element in Figure 2 is not a macro element, but represents each individual TG bearing.

The probability of failure-free operation of each element of the scheme is determined by the formula $p(t) = \exp(-\lambda t)$ and the probability of failure, respectively, as $q(t) = 1 - p(t)$. The reliability indicators of the elements and macro elements included in the scheme are given in Table 1. The reliability indicators of the elements were adopted based on data for the third unit of the South Ukrainian NPP [9, 10].

Table 1. Reliability indicators of scheme elements

Element code	Intensity of the failure flow $\lambda \times 10^{-6}$ 1/h	Macro element	
B01 S01	2.5 50	1	52.5
D01 S02 S04	50 0.1 0.5	2	50.6
S01 W01 S02	0.5 0.5 0.5	3	1.5

Well-known equations [8] were used to calculate the failure-free operation of elements that are connected in parallel and have a success criterion of m out of n. For the cases used in this calculation, namely with the success criterion 2/4 and 3/4, the equations have the form, respectively:

$$p_{2/4} = 6p^2 - 8p^3 + 3p^4 = (6 - 8p + 3p^2)p^2 , \quad (1)$$

$$p_{3/4} = 4p^3 - 3p^4 = (4 - 3p)p^3 . \quad (2)$$

The TG has 14 bearings, which are located in parallel in the structural scheme. For this forth group of parallel elements, the probability of failure-free operation is calculated by the formula:

$$p_4 = p^{14} . \quad (3)$$

The probability of failure-free operation was calculated for four macro elements and the lube oil system as a whole. Figure 3 shows how the probability of system failure-free operation changes over a period of up to 7.500 hours. This dependence is almost linear and at the end of the campaign is less than 60% (blue line Figure 3). This indicates that it is necessary to take measures to increase the reliability of the lube oil system. The probability of failure of the system and its elements is presented in Figure 4.

The main contributor to the failure of the system is element 1, which consists of a tank and a reducing valve, and at the end of the campaign, the probability of its failure is 31.4%. Thus, the most critical element from the point of view of ensuring the reliable system operation is the reduction valve. Probably this valve needs to be replaced with equipment that is more reliable. Considering this, additional calculations were carried out under the conditions that the reduction valve will be replaced by one with $\lambda = 10 \times 10^{-6}$ or $\lambda = 2 \times 10^{-6}$ 1/h. Accordingly, in Figure 3 two additional lines corresponding to the specified options are drawn. The use of a more reliable reducing valve will allow achieving higher reliability indicators of system – 79.4% and 84.4%, respectively.

To increase the reliability of the oil supply system, the pressure-reducing valve should be replaced with equipment that is more reliable.

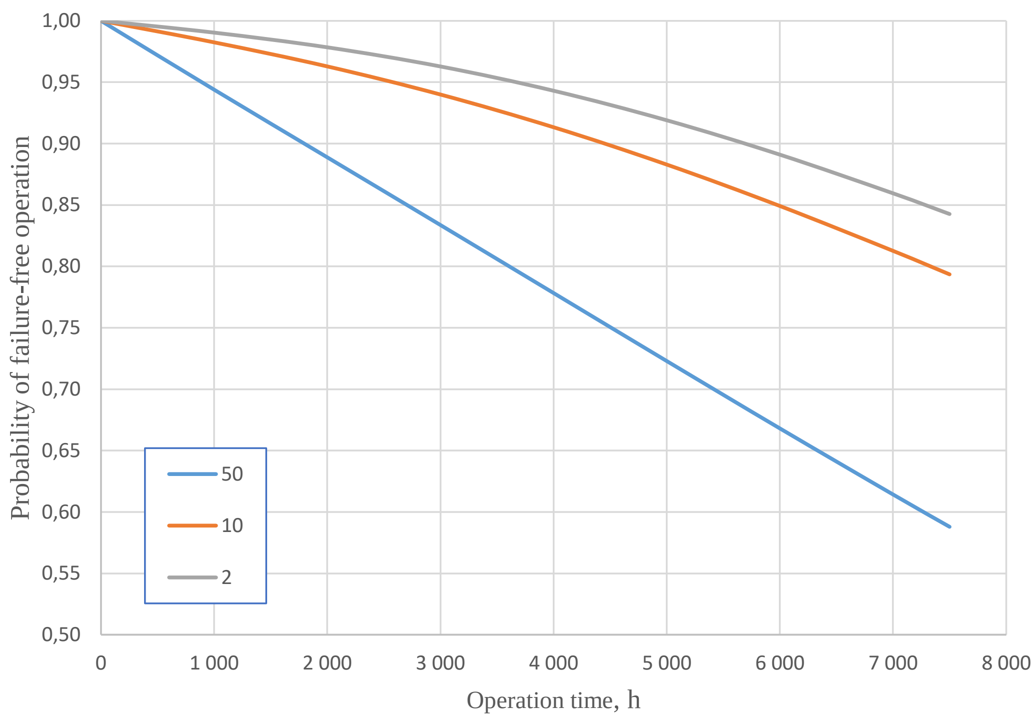

Figure 3. Probabilities of failure-free operation of the system during the campaign at different λ of the reducing valve $\lambda_{S01} = (50, 10, 2) \times 10^{-6}$ 1/h.

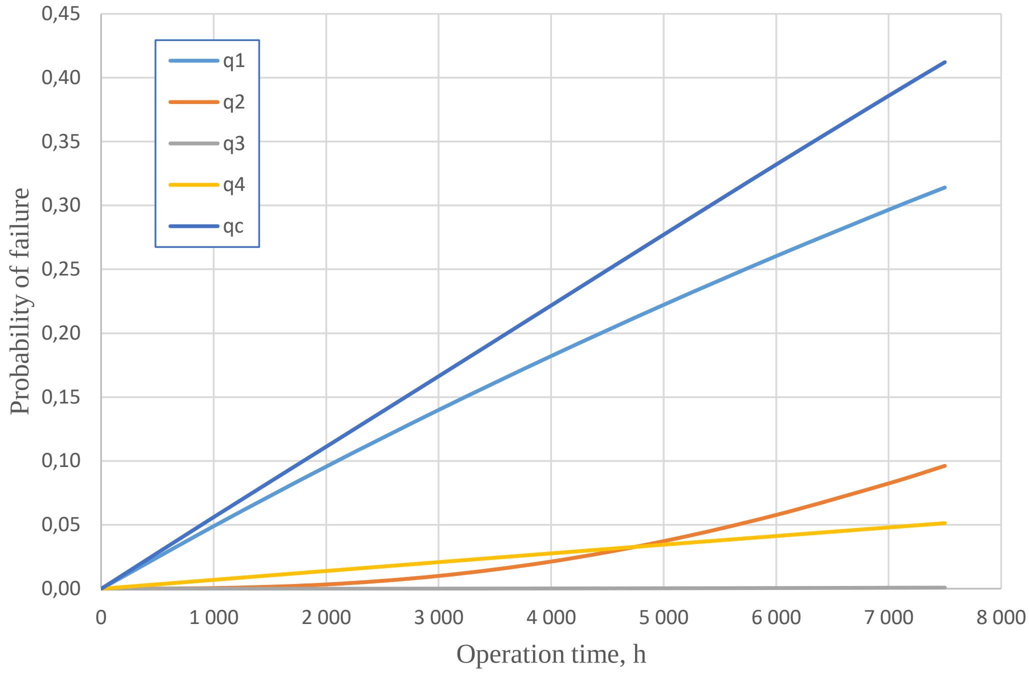

Figure 4. Probability of failure of the system and its elements during the campaign.

4 Study of the Influence of the Oil Wedge on the Temperature of TG Bearings

The operational criterion for the reliability of the bearings is the temperature of the babbitt filling. According to the current operating instructions for the turbine, the limit temperature of the babbitt filling of the liner is set at $T = 90°$. Practical tests show that the most likely limit of the temperature at which damage to the babbitt of radial bearings occurs is at the level of 130–140°. Although in rare cases the bearings worked even at higher temperatures (150–170°), the temperature of the babbitt, not collapsing. The thickness of the oil wedge is the main factor in bearing temperature changes.

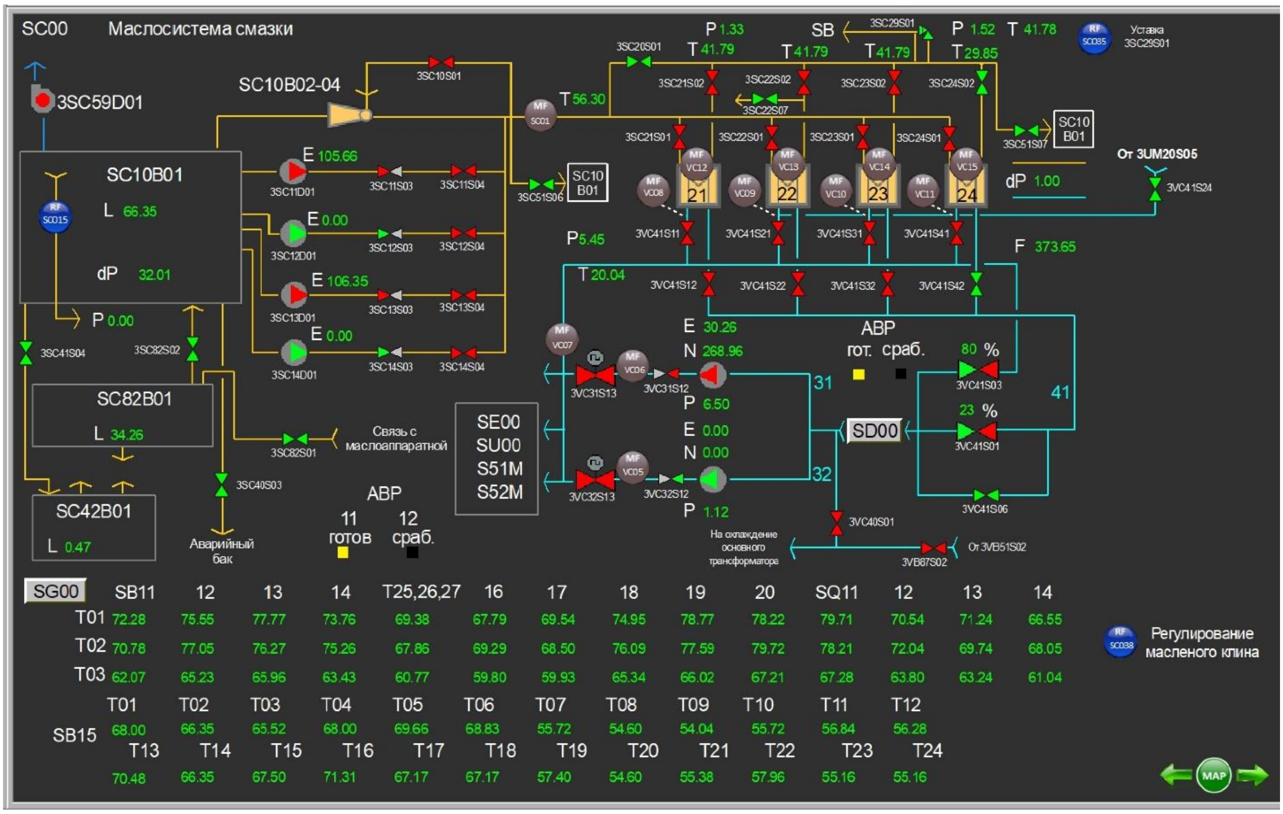

Figure 5. SC system – lubrication oil system (simulator window).

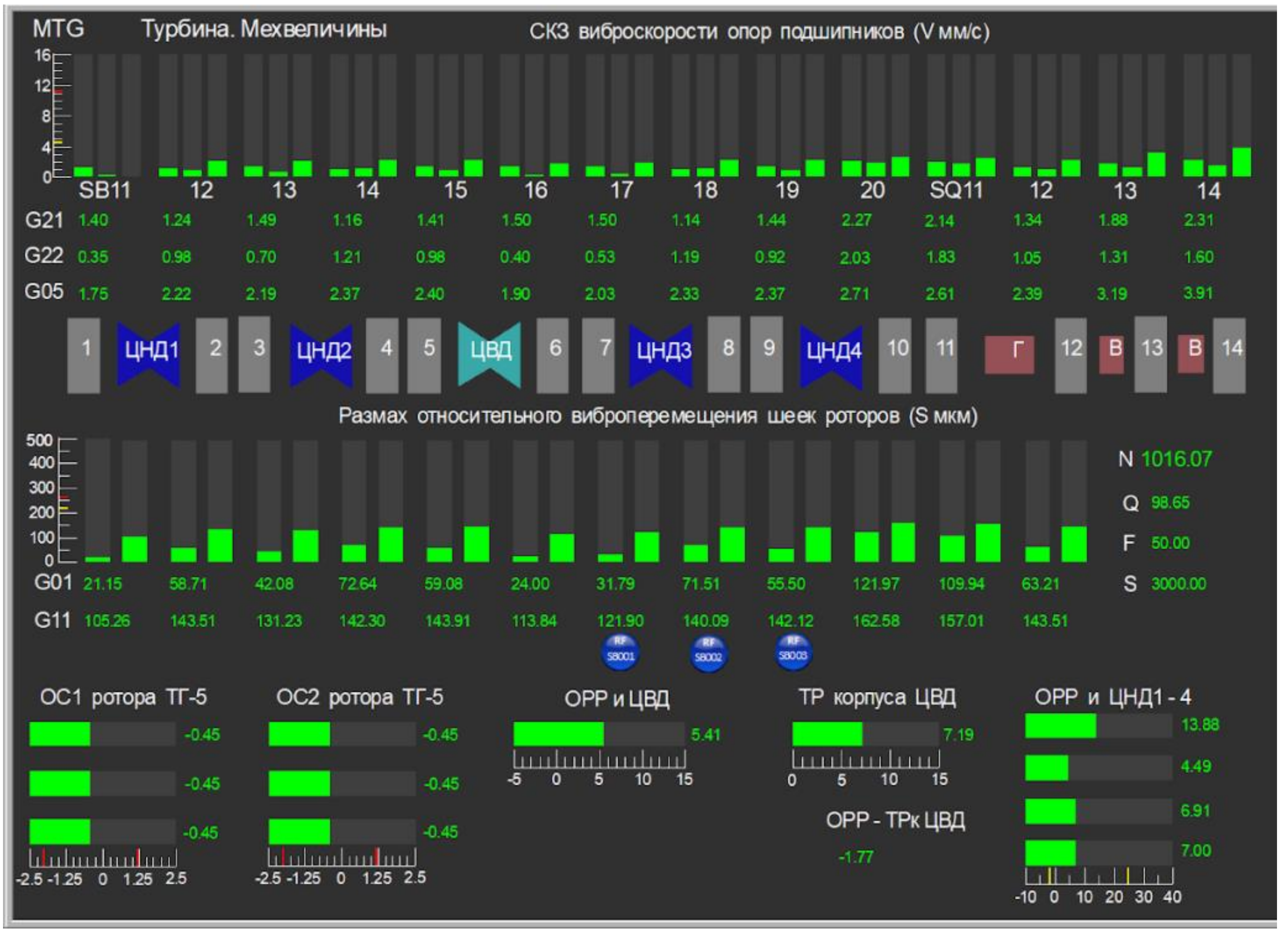

Figure 6. MTG system – turbine, mechanical quantities (simulator window).

The study of the influence of the size of the oil wedge was carried out using a full-scale simulator of the company Western Services Corporation (WSC) and a calculation model for Unit No. 3 of the Rivne NPP [11].

The oil system is presented in the simulator on the screens as the SC system – lubrication oil system and MTG – turbine mechanical quantities (see Figures 5, 6).

The screen of the SC system shows the main equipment of the oil system – HMB, pumps, oil coolers, etc. Also displayed is the temperature value of the TG bearings, the location of which is in Figure 5. The turbine consists of one high pressure turbine cylinder, four low pressure turbine cylinders, a generator and two exciters. Bearings SB11-20 belong to TG and are placed on both sides of each turbine cylinder. Bearings SQ11-14 belonging to the generator and exciters are placed one at a time between them and at the ends.

The properties of the oil affect the size of the oil wedge, and the simulator allows you to change and adjust this indicator – the blue button on the screen of the SC system (see Figure 5). The value of the oil wedge can be set in the interval from 0 to 1, by entering a certain numerical value or using the slider.

During the experiment, the initial state of the power unit was set – 100% power. In the indicated range of the oil wedge, 6 values were set with a step of 0.2. After changing the value of the oil wedge, the transition process begins for all temperatures of the 14 TG bearings. Within 10 minutes, temperatures stabilize, reaching certain stationary values. In Figure 7, you can see the general view of temperature changes of all TG bearings.

The bearing that first reached the permissible temperature value was the SQ11 bearing - the bearing is located in front of the generator. This happened because it has the highest initial temperature. The temperature of the SQ14 bearing changed most intensively – the bearing is located at the end of the turbine after the second exciter. The temperature of the bearings SB15 and SB16 changed the least intensively – these are the bearings located on both sides of the high pressure turbine cylinder.

Therefore, it can be concluded that the SQ14 bearings are the most sensitive to the temperature increase when changing the oil wedge, and the SQ15-16 bearings are the least sensitive to the change in the thickness of the oil wedge. Bearing SQ11 needs priority attention from the point of view of reaching a limit of acceptable temperature.

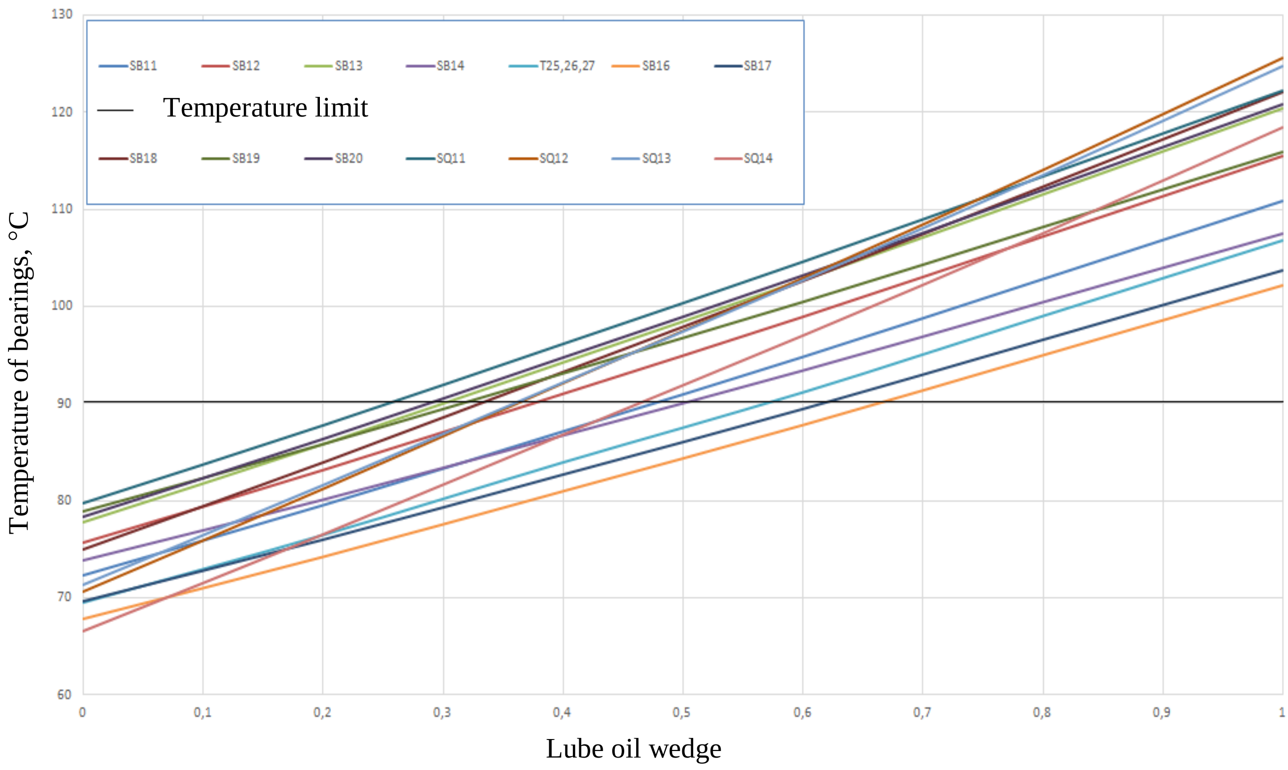

Figure 7. Dependence of the temperature of the turbine generator bearings on the oil wedge.

5 Conclusions

1. The reliability of the lube oil system of the turbo-generator was evaluated.

2. To increase the reliability of the oil supply system, it is desirable to replace the pressure reducing valve with more reliable equipment.

3. As a result of the study of the influence of the thickness of the oil wedge, the bearings whose operating conditions are most critical in terms of reaching the permissible temperature were determined.

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