Optimization of steam generators of NPP with WWER in operation with variable load

V M Parchevskii, T E Shchederkina, V V Gur’yanova

National Research University "Moscow Power Engineering Institute"
Russia, 111250 Moscow, Krasnokazarmennaya, 14

Abstract. The report addresses the issue of the optimal water level in the horizontal steam generators of NPP with WWER. On the one hand, the level needs to be kept at the lower limit of the allowable range, as gravity separation, steam will have the least humidity and the turbine will operate with higher efficiency. On the other hand, the higher the level, the greater the supply of water in the steam generator, and therefore the higher the security level of the unit, because when accidents involving loss of cooling of the reactor core, the water in the steam generators, can be used for cooling. To quantitatively compare the damage from higher level to the benefit of improving the safety was assessed of the cost of one cubic meter of water in the steam generators, the formulated objective function of optimal levels control. This was used two-dimensional separation characteristics of steam generators. It is demonstrated that the security significantly shifts the optimal values of the levels toward the higher values, and this bias is greater the lower the load unit.

1. Introduction
The steam generators (SG) are the main technological equipment of the NPP. They have the following functions:

• Split the first (radioactive) and second (non-radioactive) circuit of the NPP.
• Transfer the thermal energy generated in the reactor, a steam turbine.
• To convert the energy of high-pressure water coming from the reactor to the energy of saturated steam of low pressure.

SG must reliably produce the required amount of steam of a given quality. Indicators of quality are the vapor pressure and humidity. Efficiency of NPP turbines operating on saturated steam, is substantially reduced when the moisture of vapor at the turbine inlet is increasing, therefore, in accordance with the rules of technical operation weight moisture content should not exceed 0.2%. Currently, nuclear power plants participate in the power grids frequency regulation. Humidity of steam coming from the SG depends essentially on two parameters: load and water level. Load is controlled by power system, and the level is used to maintain the humidity at a predetermined value. In figure 1 shows typical graphs of the steam humidity ω, %, the water level h, mm, for different values of relative load d for a typical SG PGV-1000M [1]. The figure shows that the allowable range of the level at which the moisture does not exceed 0.2%, with a decrease in load increases. To select and maintain optimal operation of equipment used special features (mathematical model), we obtain the estimated or experimentally. To control SGs it is separation characteristics (SC), showing the relation of humidity and parameters on which it
depends. In the initial period of accumulation of experience in the use of nuclear energy, when NPP was in gentle basic mode at nominal load, without participating in the regulation of frequency and power, it was enough simple one-dimensional SC as a function of one argument \( \omega(h) \) obtained experimentally when operating at rated load \( d = 1 \). But the accumulation of experience in agile modes and the inclusion of the NPP one-dimensional SC can not provide quality control of steam generators.

The authors of this report proposed calculation-experimental method of development two-dimensional SC (TDSC) [1] as a function of two variables \( \omega(h, d) \). It is known that the availability of modern digital automation technology will not give the expected effect if it is not supplemented by appropriate mathematical software in the form of a set of mathematical methods, models and algorithms, the cost and complexity development of which can be ten times greater than technical, the hardware component of control systems. TDSC is a component of mathematical support, allowing to control the steam generator unit, reasonably combining economy and safety. The classical approach in the development of algorithm of optimal control of any object involves the development of control criterion - the goal function (GF).

2. The criterion of effectiveness of steam generator’s control (the goal function)

Consider the procedure for the elaboration of algorithm of optimal control of steam generators of NPP with WWER-1000. The object is a complex of 4 steam generators, the steam from which is collected in a common manifold before the turbine. In figure 2 shows four SG’s SC a single unit when operating at rated load. Despite the fact that the steam generators have same design, their SC are significantly different. In figure 2 shows the typical dispersion of characteristics. Further calculations will be performed for the unit with SC, shown in figure 2. Each of the 4 SG has its TDSC. The structure of the analytic formulas of all TDSC is the same, but separate TDSC have their own set of 19 of the constant coefficients (degrees of freedom), by which they "adjusted" under experimental or calculated data. Procedure of TDSC’s development and the structure of its analytical representation is discussed in detail in [1].

Vapor moisture in the manifold is a weighted average sum of the four summands. The calculations are performed for the six values of relative unit load: \( d = 0.7, 0.8, 0.9, 1.0, 1.05, 1.1 \). It is assumed that when the unit load is changed, all the steam generators have the same relative load. SG "sandwiched"
between the reactor and the turbine, and the only one free physical parameter determines the mode of its operation. It is the water level. From here it follows that the arguments of the goal function should be the values of the levels in 4 SG: \( h_1, h_2, h_3, h_4 \). The water level in each SG has its limits: \( \text{hmin} \leq h_i \leq \text{hmax} \) (i is the number of SG).

The lower limit of the allowable range of each \( h_i \) to all SG is the same and equal to 2350 mm, the upper limit is set to \( h_i \), at which vapor moisture is equal to the maximum allowable value of 0.2% for this workload. In the presence of TDSC, this task is not difficult. The calculation is based on approximated analytical expressions \( \text{hmax}(d) \). The result is

\[ 2350 \leq h_i \leq \text{hmax}(d). \]  (1)

The goal function \( R \) in the general case has the form:

\[ R(h_1, h_2, h_3, h_4, d_1, d_2, d_3, d_4) = L(h_1, h_2, h_3, h_4, d_1, d_2, d_3, d_4) - P(h_1, h_2, h_3, h_4, d_1, d_2, d_3, d_4), \]

where \( R \) (result) – total damage, rub/h; \( L \) (loss) – economic losses, rub/h, caused by a decrease in turbine efficiency due to the increase in steam moisture; \( P \) (profit) – profit, RUB/h caused by the increase of safety of work unit by increasing the supply of water in SG. When the accepted condition that the unit load evenly distributed between SG, i.e., \( d_1 = d_2 = d_3 = d_4 = d \), the goal function takes a more compact form, which then will be used:

\[ R(h_1, h_2, h_3, h_4, d) = L(h_1, h_2, h_3, h_4, d) - P(h_1, h_2, h_3, h_4, d). \]  (2)

The initial point of reference for all the loads is adopted \( h_i = 2350 \) mm. At this point for all SG vapor moisture is minimal and \( L = 0 \), the supply of water in the SG is minimum and \( P = 0 \). With the increase of water levels in SG vapor moisture begins to increase and the value of losses \( L \) increase the supply of water also increases, increasing the "Antiloss" \( P \). Optimal mode when the known (measured) unit load \( d \) provide water levels \( h_i^* \), where the index \( R \) is algebraic minimal.

3. The economic component of the goal function

According VNIIAM [2], the increase of saturated vapour humidity at the turbine inlet by 1% leads to a loss of power at 7 MW. These data provide the basis for the calculation of the component of the goal function \( L \). The presence TDSC of the 4 SG gives the opportunity to calculate the weighted average vapor moisture in the manifold upstream of the turbine for any mode is defined by a set of parameters \( h_1 \ldots h_4, d \) and translate it to the loss due to the lost energy, \( L \), rub/h. In the calculation was used the price of electricity 1.436 rub/(kWh), taken from the report generating Corporation "Rosenergoatom" for 2016.

4. Component of the goal function, including the security

The main difficulty in the solution of the problem represents an adequate assessment of the second component of the goal function \( P(h_1, h_2, h_3, h_4, d) \). In its meaning this component is a monetary value of the benefits of increased security of the unit while increasing the total volume of water in 4 SG in the values of water levels exceeding the "zero" value 2350 mm (see formula (1) above). You want to transfer the concept of "security" in the economic category, as measured in money. This task is divided into two subtasks: the first is to obtain a method of estimating the volume of water in the SG, with the value of the water level (the indication of level gauge \( h_i \)) and load of SG \( d \). The second is to assess the "cost" of each cubic meter of water in the SG.

4.1. Calculation of the total volume of water in steam generators

Currently there is no generally accepted, officially recommended methods for the assessment of water storage in the horizontal steam generators. This is due to the complexity and insufficient knowledge of what is happening in SG hydrodynamic processes. Most fully addresses this issue in [3]. The authors of this work used one considered in [3] approaches to the assessment of the storage of water, adding the pieces of the calculation, with the result that the method has acquired a "trademark" look of clear algorithm on which input you set the water level \( h \) and the load of SG \( d \), and the output – the volume or mass of water in SG. In figure 3 shows the results of calculations: the dependence of the volume of water in SG \( V \), \( m^3 \), on the level \( h \), mm, for loads of \( d = 0, 0.7, 0.8, 0.9, 1.0, 1.05, 1.10 \).
4.2. Cost of water storage in the steam generator

Known method of solving this problem is a method based on the use of the theory of risk. Economic risk assessment is determined by the formula [4]:

\[ \text{Risk} = U \cdot P \]  

(3)

where \( \text{Risk} \) – risk, rub/year; \( U \) – damage, rub; \( P \) – the probability of an accident, year\(^{-1}\). When using expression (3) to estimate the cost of water storage in SG you must select the type of accident from which the damage would be prevented or reduced by use of water storage in SG and know the value of the damage associated with an accident of this type. This approach is used in probabilistic safety analysis, (PSA) in the design and operation of nuclear power plants. This is carried out a thorough analysis of the components that make up the values of \( P \) and \( U \): thus, the probability of each type of disaster \( P \) is decomposed into the components caused by human factors, as components of nuclear power stations, environmental impact etc, the damage \( U \) distributes at the expense of the population, damaging of the technosphere, environment, etc.

Created and maintained a database in which are recorded the incidents of accidents and their damages. Data from these databases are intellectual property and only available to large scientific and design organizations. However, as acknowledged by the authors of the report [4] "value of \( P \) and \( U \) are in the general case of statistically uncertain, requiring for their quantitative assessment of large amounts of baseline information on the nature, patterns, sources, and scenarios of adverse events ... in fact, in domestic and international practice is as yet no generally accepted methods of analysis, calculations and simulation of accidents and disasters, and quantitative normative database to ensure survivability, risk and security”.

The authors of this report initially tried to solve the problem of valuing the storage of water in the SG by risk analysis methods, was "shovelled" a huge amount of published information to quantify the probabilities of accidents and damage, resulting have come to the conclusion that the solution of the problem must be sought in another direction.

There is an alternative, devoid of the main drawbacks of the probabilistic approach. The society spends on security as much as, on the one hand, the need to ensure its required level, and with another – how much it can afford. With the growing prosperity the boundary equilibrium is shifted in direction to the high costs, as the safety of its significance for man is second after physiological needs, without which life is impossible (the pyramid of needs by A. Maslow).

Currently, the plant is equipped with a specific set of technical and organizational means, the purpose of which is to provide required level of security. It is necessary to select those remedies, which if the accident is similar to the use of water in SG. The cost of maintaining in a mode of constant readiness of one cubic meter of water in such devices will give an estimate of the cost of 1 m\(^3\) of water in SG. The most suitable of such devices are passive emergency core cooling system (ECCS) of the reactor. Each reactor is equipped with 4 hydraulic tank with a volume of 60 m\(^3\), which under the pressure of 6 MPa, created by compressed nitrogen gas, contains 50 m\(^3\) of water solution of boric acid. Total for 1 unit - 200 m\(^3\). Contained in the hydraulic tanks water is supplied to the reactor in accidents related to the termination of cooling of the active zone, for example, complete loss of electricity supply, accounting for more than 50% of this type of accidents. When shutdown of the main...
circulation pumps (MCP) the loop pass into the mode of natural circulation, the water in the SG cools the reactor, will not evaporate yet and steam will not be released with safety valves to the atmosphere.

When assessing the cost of water in the hydraulic tank of passive ECCS, the costs were quoted to the prices 2016. Calculations were performed in accordance with [5]. Annual costs for manufacture, installation, operation, and decommissioning were evaluated according to the following formula, which is the market analogue of the above costs:

$$Z = E \cdot K + C,$$

where Z is the annual cost, rub/year; E – the refinancing rate of the Central Bank of the Russian Federation, reflecting a lower threshold of effectiveness of capital investments, E = 0.1028 – weighted mean for 2016; K – capital costs for purchase, installation and decommisioning of equipment discussed in rub, converted to prices in 2016, rub; C – annual operating cost (cost) to support the work of the CECS, rub/year. According to the designer (JSC "Atomenergoproekt", Moscow) estimated cost (2001) manufacturing K1es one set of safety injection tank (SIT) is 9964624 rub, the coefficient of inflation (2001-2016) K1i = 4.28; installation costs K2es = 201714 rub, the inflation rate K2i = 7.18. While capital costs for supply and installation of the equipment discussed on one unit are K1 = 1.706 x 10^8 rub. According to [6] in the structure of cost of construction of NPP power units in Russia equipment of long manufacturing cycle, which includes SITs of the CECS, is 24% construction and installation works – 40%, project and survey works – 9%, other equipment – 20%, other expenses – 7%. Assuming that this proportion applies to the ECCS, eliminating from consideration "other equipment" obtained the structure of capital expenditure:

$$K = K1 + K2 + K3 + K4,$$

where K2 – the cost of construction, the K3 – on feast, K4 – other expenses. K = 5.686 x 108 RUB.

Operating costs for the CECS can be interpreted as the cost of maintaining in constant readiness for use the volume of water contained in the hydraulic tanks of the CECS. Structure of annual operational costs:

$$C = C1 + C2 + C3 + C4,$$

where C1 - depreciation, C2 – cost of the ECCS equipment removal out of service, C3 is the cost of the maintenance, repair and operation (MRO), C4 – other costs. Depreciation: equipment ECCS refers to the 10-th group depreciation with a useful life Ti = 30 years, rate of depreciation Aq = 1/Ti = 0.033 year^-1, C1 = K \cdot Aq = 1.895 x 10^7 rubles a year. Under current rules, deductions for removal out of service make up 3.2% of the proceeds from the sale of plant’s products and services, but what proportion of this amount is attributable to the passive ECCS is unknown. Therefore, to evaluate the amount of annual allocations to SIT taken 25% of the depreciation. C2 = 0.25 \cdot C1 = 4.739 x 10^6 rub/year.

The cost of MRO: according to [7] for "steel tanks pressure" costs (in % of book value per year) for overhaul repairs account for 4.41%, running one is 2.28%. As book value assumed the value of the equipment K1. Then C3 = 1.175 x 10^7 rubles a year. Other costs (C4) depend on nuclear capacity and headcount and in accordance with [5] can be defined as a fraction of conditionally-constant costs. In our case C4 = 0.20 \cdot (C1 + C3) = 6.142 x 10^6 rub/year, and C = C1 + C2 + C3 + C4 = 4.159 x 10^7 rubles a year. Annual operating costs: Z = E \cdot K + C = 1.0005 x 10^8 rubles/year.

For on-line control of levels in SG uses the value (zw) of 1 m^3 of water per hour. Knowing the volume of water Vpv = 200 m^3, its cost Z and the number of calendar hours in a year h = 8760 h obtained:

$$zw = Z/(Vpv \cdot h) = 57.07 \text{ rub/(m}^3\cdot\text{h}).$$

5. The calculation of the optimal values of the levels in the steam generators

Now, having all the components of the goal function (2), they can perform calculations to determine optimal values of levels in SG for various values of load. In figure 4 shows the dependence of the goal function R and its economic L and "security" P components from the level for two of SG to rated load. For all SG considering of safety factors shifts the optimum values of the water levels in the direction of large values relative to the base (2400 mm) level. Depending on the kind of separation characteristics displacement is from 83 to 166 mm. The less load, the more allowable range of
changes in the level and displacement increases substantially. In figure 5 shows graphs dependencies of optimal values of level $h^*$ from load for all 4 SG.

6. Conclusions

The using of special mathematical models - the two-dimensional separation characteristics of SG gives to the researcher’s hands a tool to solve problems that would previously have been impossible "to approach". In particular, to give a quantitative answer to the question how to take into account the safety of the unit when controlling the level in steam generators of NPP with WWER.

The main conclusion arising from the report, is that the determination of the optimum water level in the steam generators of a nuclear power plant on complex criterion that takes into account both economics and safety, significantly shifts the optimal value of the level toward the higher values.

As you know, solving one problem inevitably creates a several others. In this case, among the generated questions are essentially two: the first is as competent to transfer the cost of water in the hydraulic tanks of passive ECCS to water in the steam generators? Apparently, it is more correct to do the transfer is not a factor of 1, as is done in the report, and others, more or fewer one, considering the specific application of both. The second question relates to whether it is necessary really to change the existing practice of regulating the level of SG? The authors of the report to the last question is no single answer. At different stages of the life cycle of nuclear power plant operation the probability of severe accidents by various, here, apparently, we need a differentiated approach.

7. References

[1] Parchevskii V M and Gur’yanova V V 2017 Thermal Engineering vol 64, No 1, pp. 20-24.
[2] Avdeev A A 2010 International forum “ATOMEXPO-2010” Optimization II circuit for NPP with WWER. Presentation. (Moscow)
[3] Trunov N B, Logvinov S A and Dragunov Yu G 2001 Hydrodynamic and teplochemical processes in steam generators of NPP with WWER (Moscow: Energoatomizdat)
[4] Makhutov N A and Gadenin M M 2009 The safety assurance of NPP with WWER A comprehensive analysis of the resource and safety of the WWER in regular and emergency situations (Podolsk: Hydropress conference, section 4)
[5] Rogalev N D, Zubkova A G, Masterova I V and other 2011 Energy Economics (Moscow, MPEI publishing house)
[6] http://www.atomex.ru.mediafiles/u/files/presentSZ/Budylin_S.V..pdf (appeal 2016. 05.04)
[7] 2003 CO 34. 20.611-2003 Cost standards for the repair of fixed assets of energy enterprises (Moscow)