ASSESSMENT OF THE EFFECT OF LARGE - CAPACITY UNITS ON RELIABILITY OF RUSSIA'S UNIFIED POWER SYSTEM

G.F. Kovalev, L.M. Lebedeva
●
Energy Systems Institute, Siberian of the Russian Academy of Sciences,
Irkutsk, 130, Lermontov Street, 664033, Russia
e-mail: kovalev@isem.sei.irk.ru

ABSTRACT

Methodical approaches to study on the problem of using large-capacity units are substantiated. Based on the multi-variant calculations of adequacy of Russia's Unified power system (UPS), that were carried out by the software package "YANTAR", the conclusions were drawn that the use of large-capacity units is feasible in terms of capacity increase and admissible in terms of system reliability.

Problem characteristics

The major factor that fosters the use of generation units of increasingly larger capacity in electric power systems is cost effectiveness which implies a decrease of specific construction and operation costs due to the improvement of efficiency at electricity generation, reduction of specific consumption of primary energy resource and decrease in the number of personnel per unit of installed capacity [1–3]. However, objectively there are factors that reduce to a certain extent the economic benefits of large-capacity units. These are:

- the increase of negative consequences due to security-related failures, since the units of large and super large capacity contain much greater potential energy reserves that can be released and do harm during emergencies. Neutralizing the negative impacts naturally requires additional efforts and expenses;

- the statistical data on operation of units of various capacities shows that the capacity growth raises the probability of emergency downtime q:

$$q = \frac{\tau_r}{T_o + \tau_r},$$

largely due to increase of time for unit restoration after failures τ_r; T_o – operating time between failures. Figure 1 presents graphically the dependence $q = f(P_{unit})$, where P_{unit} is capacity of a unit (based on [1]);

- the rise in capacity of generation units is also accompanied by decrease in their availability factor K_a:

$$K_a = \frac{T_{cal} - \tau_r - \tau_{pl}}{T_{cal}}$$

due to increase of both duration of restoration time τ_r, and duration of downtime in the planned maintenances τ_{pl} over the considered calendar period T_{cal} (normally a year). For example, K_a for 100–150 MW units makes up 0.85–0.9, and for 1000 MW units – 0.7–0.75;

– the capacity increase of every generation unit causes rise in the required generation capacity reserves [1].

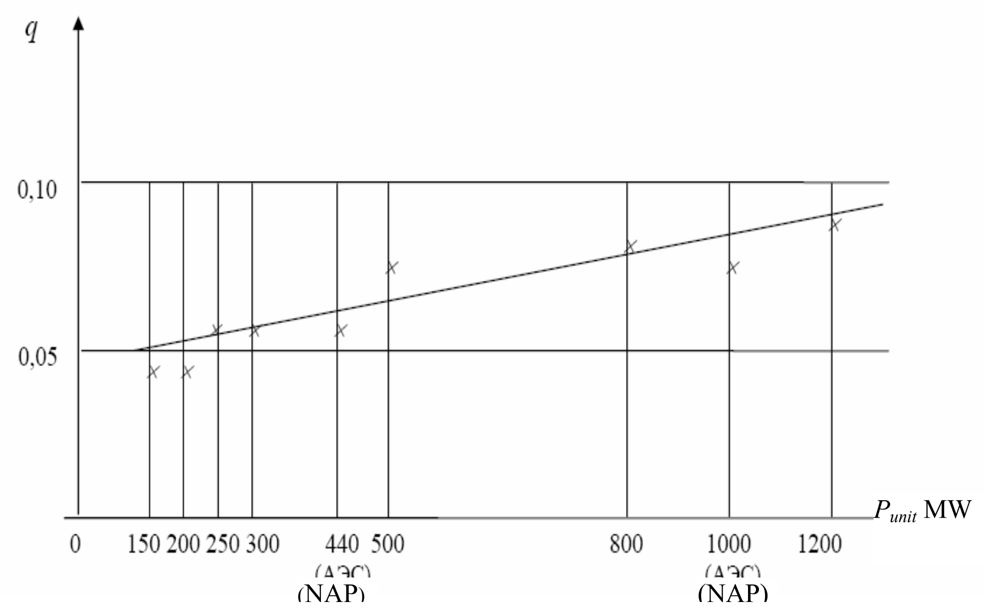

Fig. 1. Emergency rate indices for units of various capacities

Technical and economic conditions for reliable operation of electric power systems are such that the question of appropriate capacity of every generation unit directly depends on capacity of the entire system. It is known that the larger the generation unit capacity the greater the reserve capacity is necessary to provide the required reliability of power supply. This can be shown by a simple example.

Assume that the power required to cover the load is 100 MW. The reliability level is standardized by the deficit-free operation probability equal to 0.999. There is a possibility to install 10, 25, 50 and 100 MW units. The calculated values of the required installed capacity for these conditions and available capacities of every generation unit are summarized in Table 1. It is assumed that the emergency rate of units q=0.1 and no less than one unit should be periodically removed from service for maintenance (current or capital) [4].

As seen from Table 1 rise in the unit capacity from 10 to 100 MW calls for increase in reserve capacity by 300–70 = 230 MW in order to maintain the required level of reliable system operation.

The reliability analysis also shows that an increase in power system capacity leads to rise in the rational capacity of every generation unit. However, it should be understood that this analysis is much more complicated than that demonstrated above by the elementary example. It requires employment of the entire set of negative and positive, technical and economic factors related to the capacity growth of every generation unit in a system.

Table 1. Calculated values of the required number of units at load P_l=100 MW, reliability level **P**≥0.999 and various capacities of units

CAPACITY OF GENERATION UNITS P_{UNIT}, MW	REQUIRED NUMBER OF UNITS N, PCS.	INSTALLED CAPACITY P_{INS}, MW	DESIGN RELIABILITY INDEX P*	VALUE OF RESERVE $P_{res} = P_{ins}^g - P_{\max}^l$, MW
10	17	170	0.99950	70
25	9	225	0.99962	125
50	6	300	0.99954	200
100	4	400	0.99900	300

*Deviations from **P**=0.999 are related to the integer nature of the problem solved.

In the past two decades in power systems of Russia and other countries along with a tendency towards increase in the capacity of generation units an opposite tendency has emerged towards construction of the so called distributed generation in large power systems, i.e. small-capacity generation which is placed at load nodes. The dialectical combination of the two tendencies makes it possible to maintain alone with economical efficiency a high level of power supply reliability and thus, to a great extent, mitigates the negative impacts of using large-capacity generation units. However, based on the expert estimates [6] the total capacity of distributed generation will not exceed 7–8 % of the total capacity in the system, i.e. the larger part of system capacity will consist of generators of medium, large and extra-large (above 1000–1500 MW) capacity.

The level of system reliability that depends, as was already mentioned, on the generation and network reserves of power systems, in many countries is standardized as a reliability index , i.e. the probability of deficit-free power system operation. In the former USSR this value was equal to 0.996 which corresponded to 35 hours of power system operation a year with power deficit $(P^l > P_{ay}^g)$. In developed Western countries this value is assumed to be 0.9996 (3.5 *h*/year). In Russia, in the context of unfolding the "Concept…" [5] there are suggestions to use this value in the UPS of Russia at the level of 0.9991 (7.9 *h*/year).

The results of reliability calculations for Russia's UPS with large-capacity generation units

Initial calculated variant of Russia's UPS expansion, 2020.

The basic variant for 2020 [6] was assumed to be the initial variant. The considered scheme consists of 7 interconnected power systems (IPSs) and 9 tie lines connecting them, Fig.2. The reliability calculations were made by the software package "YANTAR" [7]. The software package "YANTAR" allows a more detailed representation and consideration of power system but at this stage of work we will confine ourselves to the level of interconnected power system.

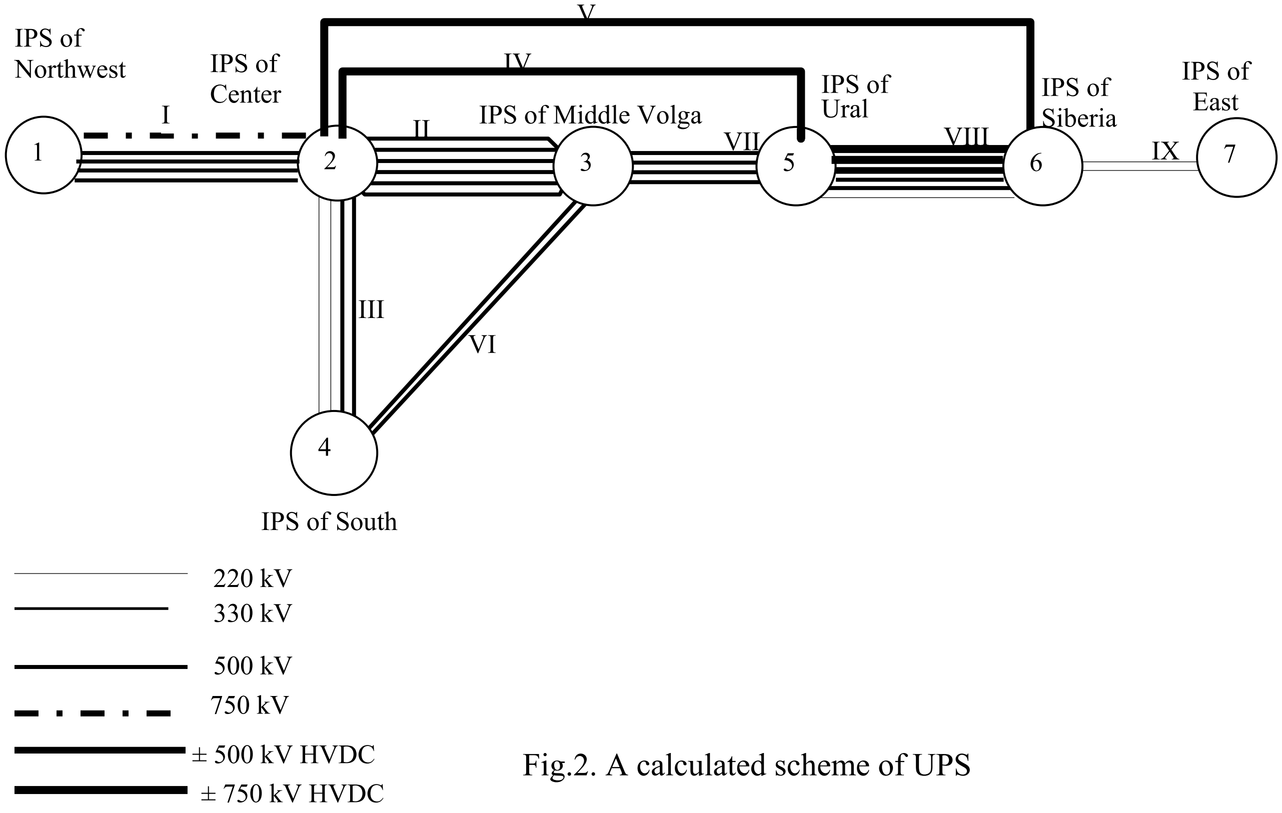

Fig.2. A calculated scheme of UPS

The major parameters of IPSs are presented in Table 2.

The transfer capabilities of tie lines connecting the interconnected power systems are presented in Table 3.

The load of nodes includes auxiliaries, export and trans-boundary power exchanges. The installed generation capacity of nodes differs from the available one by the value of underused power plant capacities and technology constraints.

The results of reliability assessment of the basic variant of Russia's UPS expansion till 2020, suggested in [6], are presented in Table 4.

Analysis of the results shows that the basic variant supposes a high margin of system reliability which is determined by the rated reserve of generation capacity and transfer capabilities of tie lines.

There are good grounds to suppose that the UPS expansion strategy was created by supporters of self-balancing in regional IPSs, therefore, some benefits of the UPS as a single electric power space of the country were ignored. One of the benefits is, first of all, a decrease in generation capacity reserves at a set (standard) level of power supply reliability.

Table 4 shows that in all interconnected power systems the reliability indices **P** in the suggested variant of expansion considerably exceed the standard value (0.9996) assumed in developed countries.

Table 2. Main parameters of IPSs, 2020

NODE NUMBER	IPS	REQUIRED ELECTRICITY OUTPUT E_R, BILLION KWH	LOAD MAXIMUM $P^l_{\max}$, MW	INSTALLED CAPACITY P_{INS}, MW	AVAILABLE CAPACITY, P_{AV}, MW	FULL SYSTEM RESERVE, R_{FULL}, MW
1	NORTHWEST	177.8	29960	35400	33130	3170
2	CENTER	409.1	72000	83500	80560	8560
3	MIDDLE VOLGA	115.9	19470	27100	24170	4700
4	SOUTH	120.2	20665	26100	23850	3185
5	URAL	415.4	60730	65400	62510	1780
6	SIBERIA	376.4	55835	79400	72000	16165
7	EAST	84.3	13850	15780	14864	1014
UPS		1699.1	267967	332680	311084	43117

The study on Russia's UPS reliability with a 1800 MW pilot unit installed in the IPS of Ural, 2020 (for* P = 0.9996*).

For this case in the initial variant of expansion part of capacity of newly constructed power plants with units of relatively small capacity, was replaced by a 1800 MW double-unit installed at one of the Ural nuclear power plants. This unit was assumed to be a pilot one and according to the recommendations [1] should be characterized by higher unreliability as compared to the large-scale production of equipment. Besides, it was assumed in the calculations that reliability characteristic of the double-unit is represented by the distribution series of three unit states with their probabilities (Table 5).

Table 3. Transfer capabilities of tie lines, 2020

CONNECTED NODES (IPS) NUMBER (NAME)	TRANSFER CAPABILITIES (MW), DIRECTION	
	DIRECT	REVERSE
1 (NORTHWEST) – 2 (CENTER)	3600	3600
2 (CENTER) – 3 (MIDDLE VOLGA)	3500	3500
2 (CENTER) – 4 (SOUTH)	2000	2000

2 (Center) – 5 (Ural)	**6000**	**6000**
2 (Center) – 6 (Siberia)	**5700**	**5700**
3 (Middle Volga) – 4 (South)	**1500**	**1500**
3 (Middle Volga) – 5 (Ural)	**2500**	**2500**
5 (Ural) – 6 (Siberia)	**12850**	**12850**
6 (Siberia) – 7 (East)	**900**	**900**

Table 4. Calculated reliability of the initial UPS expansion variant, 2020

Node number	**IPS**	**Probability of deficit-free operation P, p.u**	**Coefficient of consumer provision with electricity π^*, p.u.**	**Electricity undersupply E_{und}, MWh**	**Total system reserve in % of load maximum $P^l_{\max}$, IPS**
1	**Northwest**	**0.999966**	**0.999999**	**193.2**	**10.58**
2	**Center**	**0.999999**	**0.999999**	**1.5**	**11.89**
3	**Middle Volga**	**0.999999**	**0.999999**	**0**	**24.14**
4	**South**	**0.999977**	**0.999999**	**84.4**	**15.41**
5	**Ural**	**0.999999**	**0.999999**	**4.3**	**2.93**
6	**Siberia**	**0.999999**	**0.999999**	**0**	**28.95**
7	**East**	**0.999983**	**0.999999**	**0**	**7.3**
UPS (without IPS of East)		**0.999942**	**0.999999**	**283.4**	**16.06**

* $\pi=E_a/E_r=(E_r-E_{und})E_r$.

Table 5. Probability distribution series of the 1800 MW unit states

Production	**Full failure, 0 MW**	**Failure of either half of the unit, 900 MW**	**Full availability, 1800 MW**
Pilot unit	**0.035**	**0.090**	**0.875**
Commercial units	**0.025**	**0.075**	**0.900**

The resulting reliability calculations for this variant of UPS expansion are presented in Table 6.

The specific feature of the calculations made is the fact that the compared variants differ only in the parameters of a small part of generation capacity (in this very case 1800 MW out of 62510 MW in Ural, i.e. only 2.88 %). The analysis can reveal only whether the calculated reliability is higher or lower than the rated level. Changes in the indices of fault-free operation in the 5th – 6th digit after the point and mathematical expectation of undersupply at the level of hundreds of megawatt- hours are comparable with an error in calculations (3–5 %) that are determined on the basis of Monte Carlo method for choosing the system states by the random number generator. Calculation of operation conditions with the accuracy up to 1 MW, the computer and algorithmic rounding of calculation results, etc. do not naturally allow a quantitative conclusion on higher or lower reliability of compared variants based only on the difference in the last two-three significant figures of the results (including calculated electricity undersupply).

In addition to this fact it should be noted that the probability of deficit-free operation of UPS as a whole that represents a sum of deficit-free states of individual IPSs incurs little information. In this context the probability of deficit-free state of UPS $\boldsymbol{P}_{\text{UPS}}$ will always be no less than the minimum probability among all probabilities for IPSs, i.e.

$$\boldsymbol{P}_{\text{UPS}} \leq \boldsymbol{P}_{\text{IPS}\ min}.$$

One should bear in mind the presented comments when analyzing the obtained results of reliability calculations.

Based on the above comments Tables 4 and 6 show that commissioning of the unit 2×900 = 1800 MW does not cause a noticeable decrease of reliability: probabilities of deficit-free operation change in the 5th – 6th digit after the point and still remain much higher than the standard value equal to 0.9996.

Moreover, if the 1800 MW unit is represented as a single-unit with the emergency rate q=0.125, calculations of UPS reliability have not resulted in essential decrease of system reliability, i.e. the probability of deficit-free operation of all IPSs remained above 0.9996. The system reliability was also calculated for the initial conditions of UPS expansion, when the 3000 MW single-unit with q_{unit} = 0.135 was installed in IPS of Ural. In this case the design reliability index was not below 0.9996. (The calculation results of reliability for the variants with the single-units of 1800 and 3000 MW are not given in the paper by virtue of obvious impossibility to manufacture units with such characteristics by 2020).

Table 6. Calculation results of reliability of Russia's UPS expansion variant at installation of the 1800 MW unit in IPS of Ural, 2020.

NODE NUMBER	IPS	PROBABILITY OF DEFICIT-FREE OPERATION P, P.U.	COEFFICIENT OF CONSUMER PROVISION WITH ELECTRICITY π, P.U.	ELECTRICITY UNDERSUPPLY $Э_{нед}$, MWH	FULL SYSTEM RESERVE IN % OF MAXIMUM LOAD $P^{l}_{\max}$, IPS
1	NORTH-WEST	**0.999964**	**0.999999**	**182.0**	**10.58**
2	CENTER	**0.999999**	**0.999999**	**0**	**11.89**
3	MIDDLE VOLGA	**0.999999**	**0.999999**	**0**	**24.14**

4	**SOUTH**	**0.999976**	**0.999999**	**96.7**	**15.41**
5	**URAL**	**0.999996**	**0.999999**	**87.4**	**2.93**
6	**SIBERIA**	**0.999999**	**0.999999**	**0**	**28.95**
7	**EAST**	**0.999980**	**0.999999**	**0**	**7.30**
UPS (WITHOUT IPS OF EAST)		**0.999936**	**0.999999**	**366.1**	**16.06**

From the reliability standpoint the problem of sudden failure of the whole 1800 MW unit by some reason is of interest. The main criteria for admissibility of such a failure are:

– frequency decrease not below an admissible level for the emergency situation in the system;

– inadmissibility of overloading the tie lines at redistribution of power flows in the network because of abrupt tripping of the unit;

– probability of the event occurrence at the period most dangerous for system operation.

Analysis of the considered situation leads to the following conclusions. Since for UPS the droop of load with respect to frequency $K_f = \Delta P / \Delta f$ lies in the range 1–2, i.e. generation decrease (load growth) by 1–2 % leads to a 1 % frequency decrease [8], then at failure of the whole unit (1800 MW) a relative value of decrease in load covering during its maximum will make up $P_{unit} / P^{l}_{\max} = (1800/267967)\cdot 100 = 0.67\ \%$.

In this case a relative frequency decrease in UPS will reach at the initial instant of sudden tripping of the 1800 MW unit:

$$\overline{\Delta f} = \frac{\Delta P}{K_f} = \frac{0.67}{1 \div 2} = 0.670 \div 0.335\ \%,$$

which corresponds to the frequency decrease by

$$\Delta f = (0.670 \div 0.335)\frac{50}{100} = 0.335 \div 0.168\ \text{Hz}.$$

As is known, at system failure the frequency decrease is assumed to be up to 49.5 Hz, i.e. $\Delta f_{dec} = 0.5\ \text{Hz}$. Hence, an abrupt tripping of the whole 1800 MW unit is admissible. Since the control range of power plants supporting frequency in UPS should not be lower than 1–2 % (the so-called spinning reserve) during the maximum load, which exceeds the relative unit capacity 0.67 %, the frequency will decrease for a rather short term.

Frequency variation in UPS by 0.05–0.1 Hz and more (see [9]) changes the backbone network operation so much that it leads, as a rule, to a dangerous change in power flows over the majority of tie lines between IPSs and possible splitting of UPS by weak ties. In the case of ineffective operation of emergency control devices parallel operation will also be violated over the relatively strong tie lines.

Calculation of load flow for the event of the 1800 MW unit tripping in IPS of Ural has shown that transfer capabilities of tie lines accepted in "The General Scheme of development" [6] ensure an admissible distribution of flows for the studied conditions.

In accordance with the basic concepts of the probability theory the probability of the whole unit tripping at the most critical time of UPS operation, namely during the maximum load without capacity reserves in the system is determined as follows

$$\boldsymbol{P}_{dang} = \boldsymbol{P}_{unit}\cdot \boldsymbol{P}_{\max}\cdot \boldsymbol{P}_{def},$$

where $\boldsymbol{P}_{unit} = 0.035$ – emergency probability with complete failure of the unit (see Table 5); $\boldsymbol{P}_{\max}$ –

probability for UPS to be under maximum daily load (for 1 hour a day) $\boldsymbol{P}_{\max} = 1/24 = 0.042$; $\boldsymbol{P}_{def}$ – probability of a deficit state of UPS:

$$\boldsymbol{P}_{def} = 1 - \boldsymbol{P}_{norm} \leq 1 - 0.9996 = 0.0004.$$

Then $\boldsymbol{P}_{dang}$, i.e. the probability of a *dangerous* state, is very low (at a level of probability of a sudden natural disaster):

$$\boldsymbol{P}_{dang} = 0.035 \cdot 0.042 \cdot 0.0004 = 0.0000006.$$

Thus, it is safe to assume that the use of 1800 MW units is quite admissible in terms of reliability at the current stage of Russia's UPS expansion (even without consideration of its joint operation with other EPSs of the NIS and European countries).

Calculation results of Russia's UPS reliability for particular conditions of system expansion.

The above analysis was an official variant of Russia's UPS expansion to be considered as an optimistic variant. The crisis conditions, however, can essentially influence a development pattern of the national economy as a whole and electric power industry, in particular. Therefore, it seems appropriate to analyze admissibility of putting large units into operation during the period 2020–2030, supporting power supply reliability at the lower level **P** = 0.996. Consider the most severe conditions, when power consumption levels remain at the former level, but the available generation capacity considerably reduces from 311084 MW (see Table 2) to 287380 MW. In this case the capacity reserve to maintain **P** = 0.996 will be equal to 19413 MW.

For these heavier conditions different variants for commissioning of large units in different regions of UPS were studied:

1. Commissioning of a 3500 MW single-unit in IPS of Ural.
2. Commissioning of one 1800 MW double-unit in IPS of Ural and one – in IPS of Center and two double-units in IPS of North-West.
3. Commissioning of one 1800 MW double-unit in IPS of Ural and two double-units in IPS of North-West and three – in IPS of Center.

The variants were compared with reliability of the initial variant (without commissioning of large units). The calculation results have shown that the full reserve available in UPS at a level of 7.6 % of the coincident annual maximum of load in the considered variant proves to be sufficient for UPS reliability support at the given level, when in accordance with variants 1–3 large units are put into operation instead of traditional ones of lower capacity. Hence, it is possible to conclude that for Russia's UPS use of the units from 1800 to 3500 MW does not cause an essential reliability decrease.

General conclusions on the results of studies on system reliability of Russia's UPS at commissioning of the units 1800–3000 MW for 2020 and 2030.

1. The calculations have shown that the presented variants of using large units in the schemes of Russia's UPS expansion for the time period till 2020 (one pilot unit in IPS of Ural), four and even six units after 2020 in different IPSs virtually do not decrease an assumed system reliability in the General Scheme [6].

2. It should be noted that in reliability calculations account was taken first of all of unfavorable factors of using large units. At first an "isolated" operation of Russia's UPS was studied. Based on the parallel work of UPS with power systems of Baltic states, Belarus, Ukraine, Kazakhstan, Tajikistan, etc. conditions for using large units would be even more favorable by virtue of both an essential growth of system capacity and a weak effect of random failure of the whole unit capacity on UPS.

3. The study also shows that failure of the 1800 MW unit at the most unfavorable time of UPS operation (at maximum load with no generation capacity reserves in the system) has a

probability of about 10^{-7}, which corresponds to probability of a rare natural disaster, such as earthquake, volcanic eruption, hurricane, etc. A simultaneous failure of two and more units is practically excluded as an improbable event.

4. Additional calculations have also revealed that the use of single-units with the capacity up to 3500 MW is admissible in Russia's UPS in the years 2020–2030.

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Thus, from the system reliability considerations the use of large units up to 3500 MW in Russia's UPS for the time horizon 2020–2030 is surely admissible and expedient. Moreover, for economic efficiency reasons it can be recommended with confidence to design both double-units and single-units with a capacity of 3000–3500 MW for their application during the period 2030–2050.

The study performed assesses only system adequacy of UPS. However, later on the study on operating condition reliability for Russia's UPS should be carried out in terms of stability of parallel operation and transients [10].

The suggested technique and model can be applied for similar studies in other systems.

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A RELIABILITY MODEL FOR "SAFETY SYSTEM-PROTECTED OBJECT" COMPLEX WITH MULTIPLE SAFETY SYSTEMS

A. I. Pereguda, D. A. Timashov
•
Obninsk Institute for Nuclear Power Engineering, Obninsk, Russia

e-mail: pereguda@iate.obninsk.ru

ABSTRACT

The paper presents a new reliability model for "safety system-protected object" complex with multiple safety systems. It is supposed that the complex consists of one protected object and multiple independent safety systems with complex structures. Scheduled periodic inspections of safety systems are also taken into account. Asymptotic estimates of the mean time to accident and the probability of the accident prior to time *t* are obtained under some assumptions on operation process of the complex.

1 INTRODUCTION

Hazardous facilities use a variety of systems concerned with safety, with safety systems being the most important of those. Safety systems are provided to detect potentially dangerous protected object failures or conditions and to implement appropriate safety actions. Protected object may have several types of hazardous deviations of protected object operation process that require their own safety systems. Some reliability models for the elements of safety systems were introduced by Hansen and Aarø (Aarø & Hansen 1997), Corneliussen and Hokstad (Corneliussen & Hokstad 2003), Høyland and Rausand (Høyland & Rausand 2004). In this paper we propose a different approach to reliability assessment of "safety system-protected object" complex based on asymptotic properties of alternating renewal processes.

In the present study we set out to analyze the reliability of the automated "safety system-protected object" complex with multiple safety systems. Systems of such kind are quite common in the nuclear power engineering, because safety systems of nuclear power plant should employ diversity in the detection of fault sequences and in the initiation of the safety system action to terminate the sequences. We follow Pereguda (Pereguda 2001) in assuming that the operation of the complex can be described using a superposition of alternating renewal processes. Our objective is to provide an asymptotic estimation for such reliability indices as the mean time to accident and the probability of the accident prior to time *t*.

2 MODEL DESCRIPTION

Let us consider an automated complex of protected object and N safety systems. Safety systems and the protected object are repairable. They are restored to an as-good-as-new state. All failures are supposed to be independent. Let j-th safety system consists of M_j subsystems and k-th subsystem of j-th safety system consists of $C_{j,k}$ elements.