



## ON THE POSSIBILITY OF PARTICIPATION OF NPPS WITH VVER IN EMERGENCY FREQUENCY REGULATION IN POWER SYSTEMS

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**Abstract:** The purpose of the article is to study the possibility and feasibility of participation of nuclear power plants (NPPs) with VVER in emergency frequency control in power systems with a high proportion of nuclear power units and, at the same time, of reducing the power consumption for the own needs of the main circulation pumps during modes with power below nominal. To solve these problems, it was proposed to increase the achievable speeds of power gain (load increase) due to the installation of frequency controlled drives of the MCP. Large system frequency variations (caused by large imbalances between generation and demand) may jeopardize electrical equipment, in terms of maintaining stable and reliable operating conditions. For NPPs, the task of preventing or localizing accidents is even more important than for TPPs, since in case of major system accidents, it is possible to completely stop external power supply of the NPPs own needs. Thus, besides the requirements for the primary control of the frequency of NPPs with VVER, today we need more stringent requirements for their emergency acceleration and mobility. The operation of NPPs with long-term non-recoverable active power shortage causes a decrease in the speed of the main circulation pumps of NPPs with VVER and a decrease in the coolant flow rate. It is shown that the installation of variable frequency drives of the MCPs at NPP with VVER is appropriate not only to save energy consumption for their drive in partial modes, but also to increase the power of NPP above the nominal (without reducing the reserve before the heat exchange crisis in the reactor core) for the elimination of system accidents, and thus to improve the safety of the NPPs included in the power system.

**Keywords:** nuclear power plant, power system, frequency, emergency control, main circulation pump, variable frequency drive.

**Acknowledgments:** The work was funded by the Russian Foundation for Basic Research (grant no. 17-08-00220 A).

**For citation:** Khrustalev VA, Garievskii MV, Rostuntsova IA, Portyankin AV. On the possibility of participation of npps with vverin emergency frequency regulation in power system. *Power engineering: research, equipment, technology*.2019; 21(3): 99-108. (In Russ). doi:10.30724/1998-9903-2019-21-3-99-108.

## О ВОЗМОЖНОСТИ УЧАСТИЯ АЭС С ВВЭР В ПРОТИВОАВАРИЙНОМ ЧАСТОТНОМ РЕГУЛИРОВАНИИ В ЭНЕРГОСИСТЕМАХ

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**Резюме:** Целью статьи является изучение возможности и целесообразности участия АЭС с ВВЭР в противоаварийном частотном регулировании в энергосистемах с высокой долей атомных энергоблоков, одновременно, снижения расхода электроэнергии на собственные нужды главных циркуляционных насосов на режимах с мощностью ниже номинальной. Для решения этих задач предложено повысить достижимые скорости набора мощности (наброса нагрузки) за счет установки частотно регулируемых приводов ГЦН. Изменение частоты в энергосистеме, вызванное большим дисбалансом между генерацией и потреблением, может поставить под угрозу электрическое оборудование с точки зрения поддержания стабильных и надежных условий эксплуатации. Для атомных электростанций задача предотвращения или локализации аварий представляется еще более важной, чем для ТЭС, т.к. при крупных системных авариях возможно полное прекращение внешнего энергоснабжения собственных нужд АЭС. Таким образом, кроме требований к первичному регулированию частоты АЭС с ВВЭР нужны более жесткие требования к их аварийной приемистости и мобильности. Работа АЭС при длительном невосстанавливаемом дефиците активной мощности вызывает снижение числа оборотов главных циркуляционных насосов АЭС с ВВЭР и уменьшение расхода теплоносителя. Показано, что установка частотно-регулируемых приводов главных циркуляционных насосов на АЭС с ВВЭР целесообразна, в перспективе, не только для экономии расхода энергии на их привод на частичных режимах, но и для повышения мощности энергоблоков АЭС выше номинальной (без уменьшения запаса до кризиса теплообмена в активной зоне реактора) для ликвидации системных аварий, а значит, и для повышения безопасности входящих в ОЭС энергоблоков АЭС.

**Ключевые слова:** атомная электростанция; энергосистема; частота; противоаварийное регулирование; главный циркуляционный насос; частотно-регулируемый привод.

**Благодарности:** Исследование выполнено при финансовой поддержке РФФИ в рамках научного проекта № 17-08-00220 А.

## Introduction

Attempts to normatively involve nuclear power plants (NPPs) in the regulatory process, including emergency ones, have been implemented for a long time. One of them was undertaken in 2002 by RAO UES Order No. 524 dated September 18, 2002. In accordance with RAO UES Order No. 544 "On improving the quality of primary and secondary frequency regulation of electric current in the UES of Russia", the main condition for connecting power plants, including the nuclear ones to the power system is their participation in the primary frequency regulation in the power system.

The requirement for the participation of nuclear power units in the dispatch load schedule has recently been accompanied by the requirement to involve NPPs in the primary regulation of the current frequency in the network [1, 2]. In accordance with the standard of the organization of JSC "SO UES" (Company's Code STO 59012820.27.120.20.004-2013. Norms for the participation of power units of nuclear power plants in the normalized primary frequency regulation), the maximum required change in power is  $\pm 2\%$  of  $N_{\text{nom}}$  for the normalized primary regulation of frequency (NPRF) and  $-8\%$  of  $N_{\text{nom}}$  for the general primary regulation (GPRF), moreover, in the first 10 seconds at least 50% of the required power change should be fulfilled.

However, due a number of reasons noted earlier in the Russian studies [3], this,

apparently, is also not enough, since the requirements do not stipulate the gradually growing need for participation of large nuclear power units in emergency frequency control in the UPS. For such participation, the speeds and ranges mentioned in [3] are clearly not enough. Large hydroelectric power stations (*HPS*) and even hydroelectric pumped storage power stations (*HPSPS*) do not possess maneuvering properties previously assigned to them, mainly due to the large inertial delay at the derivative spillways, as well as due to their overregulation by numerous requirements of the System Operator.

With the development of accidents with a steady decrease of *UPS* current frequency, a serious contradiction is that in *UPS* with a high proportion of nuclear power plants during accidents with a decrease in the frequency, *NPPs* should increase generation. Unfortunately, *MCPs* make it impossible, since they reduce power and flow rate of the pumped coolant proportionally to the decrease in mains supply frequency. This was noted in [4]. In case of emergencies with increasing frequency (increased generation over the consumer load), such nuclear power plants also run the risk of stopping external and then internal power supply.

One of the most efficient technologies that can fundamentally solve the problem of maneuverability of nuclear power plants with *VVER* is a smooth change in the flow rate of the coolant by controlling the rotation frequency of the *MCP* electric drives (Fig. 1) [5–8].

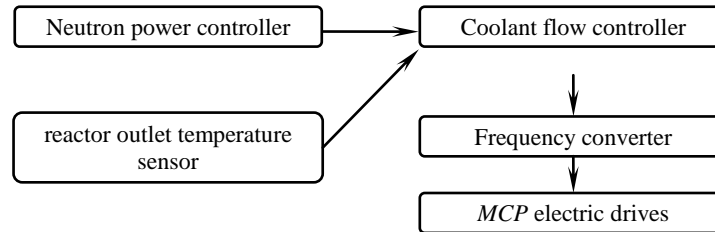


Fig. 1. The block diagram of the flow rate control

### Theoretical basis

The *NPP* operation with a long unreplaceable shortage of active power causes a decrease in the number of *MCP* revolutions and a decrease in the coolant flow rate. The use of special frequency converters can eliminate this contradiction [9], since the operation of thyristor converters does not depend on the mains supply frequency. When using them, the power of the unit can be increased to a supernominal value to eliminate system accidents without reducing the supply before the heat transfer crisis in the reactor core [10]. Moreover, this maneuver can be implemented in the long-term mode (monitoring the load) and during participation in the regulation of the emergency frequency drop (dynamic load surge).

Studies have shown that a smooth change in the coolant flow rate by controlling the rotational speed of the *MCP* electric drives allows one to obtain the specified steam parameters and, due to this, the efficient energy characteristics of the turbines during the *NPP* modes of partial power, start and stop, and significantly reduce temperature and pressure fluctuations in the main circuits. This leads to a decrease in the ranges of changes in the average temperature of the core and mitigation of neutron-physical disturbances in the core. At the same time, resource-saving internal devices are achieved, reliability, durability and efficiency are improved by reducing low-cycle fatigue of metal of power equipment and increasing the efficiency of the net unit in the power range of 60–100% of  $N_{\text{nom}}$  and above the nominal one [11].

The most important *MCP* advantage achieved with a variable frequency drive (*VFD*) is the possibility of an additional (to 4% of  $N_{\text{nom}}$  achieved by today) power increase up to 7-10% above the nominal level. It is based on the possibility of maintaining the same safety factor before the heat transfer crisis *DNBR* (*Departure from nuclear boiling ratio*) by

correspondingly increasing the coolant weight velocity [11].

The main circulation pumps are most strictly regulated for operation in case of emergency frequency deviations in the network (for power units with a VVER-1000 reactor unit):

- A) From 50 to 51 Hz - up to 10 s and not more than 60 s or 10 times in total per year;
- B) From 49 to 48 Hz - up to 5 minutes and not more than 26 minutes or 20 times in total per year;
- C) From 48 to 47 Hz - up to 1 min and not more than 6 min or 15 times in total per year;
- D) From 47 to 46 Hz - up to 10 s and not more than once every three years.

The literature gives an example [3] of the need to increase the rate of the generation shortage elimination in order to maintain the stability of power units operation. This problem becomes especially urgent in connection with the increase in the share of *NPPs* in many *UPSs*, since it is known that in case of system accidents with breakdown of external power supply, there arises a task of reliable and long-term (up to 72 hours) removal of residual heat generation from the reactor core due to internal power supply. Many *NPP* sites with reactor units (RU) of Russian architecture, namely *Akkuyu NPP* (Turkey), *Ruppur NPP* (Bangladesh), *Kudankulam NPP* (India), Jordan, Egypt, Finland, etc. turn out to be “inside” energy regions with relatively weak transmission capacities of electrical connections.

At the same time, it is known that reserves of transmission capacities above 20% of  $P_{max}$ , when implemented, can “shift” the calculated phase angle to an unacceptable zone  $\Theta > 70^\circ$  with occurrence of amplitude fluctuations and even flow vectors, which can cause an avalanche-like accident. If the initial phase angle  $\Theta$  is  $60^\circ$  and there is a generation shortage in comparison with consumption, and the generators rotors in the *UPS* receiving part are “slowed down a little” when entering the dead zone of the turbine regulators (for example,  $\Delta h = -1$  rpm), then the receiving system rotors will “turn around” due to a lag to the critical value of the phase angle of  $90^\circ$ . If it is 1 rpm ( $360^\circ$  per minute), then a thirty-degree ( $30^\circ$ ) limit excess of the angle  $\Theta$  will be achieved in just 5 s [ $60/(360/30) = 5$  s], which requires very high loading speeds to prevent a system accident [3].

On the other hand, the relationship between active power  $N_{act}$  and frequency in the case of rotating *MCP* injection machines is established from simple reasons:

$$N_{act} = af^3 \text{ or } \frac{dN_{act}}{df} = 2af^2 df = 3 \frac{af^3}{f} df = 3N_{act} \frac{df}{f}, \text{ but as } af^3 = N_{act}, \frac{dN_{act}}{N_{act}} = 3 \frac{df}{f}.$$

Modern *VVER* reactors also have a certain maneuverability with stabilizing negative feedback between the average temperature of the active zone and reactivity [12–13]. This connection is much more stable today during the operation time due to the addition of gadolinium to the fuel compositions, so the fuel rods today are often called gadolinium fuel rods. Such fuel and the active zone based on it are much more stable and safer during operation.

With tertiary regulation in such *UPSs*, a high emergency response rate (rate of shortage or load surge) should be provided and there should be a margin for the upper power level [3]. However, this reduces the installed capacity utilization factor (*ICUF*). But if *ICUF* is determined by the initial level of nominal power, then its value is sometimes greater than 1. This was shown by the operational practice of a number of *NPP* units in separate temporary operation areas during operation at 104%  $N_{nom}$ .

This problem can also be successfully solved when the power units will have a significant margin to increase power above the nominal. Such a reserve is quite real when equipping a *MCP* with a converter with a high-voltage variable frequency drive (converter with *HVVFD*).

In the absence of adjustment range and the occurrence of an unforeseen power shortage

under conditions of full load of the units (generators), an unrecoverable decrease in frequency occurs (Table 1, Fig. 2):

$$f_2 - f_1 = -\Delta f \left( 1 - e^{-t/T_f} \right) \text{ or vice versa } f_2 - f_1 = +\Delta f \left( 1 - e^{-t/T_f} \right),$$

where  $T_f$  is the frequency constant of the power system,  $T_f = 10 \div 15$  s;  $\Delta f$  is the final value of the frequency change due to a shortage (–) or an excess (+) of power, i.e. the difference between generation and load  $\Delta P = P_g \pm P_{load}$  in % or infractions  $\Delta f\% = \frac{\Delta P\%}{K} = \frac{100}{K} \cdot \frac{\Delta P}{P_{load.nom}}$ ;  $K = 1 \div 3$

is the frequency factor of the power system [14]

$$f_2 - f_1 = -\frac{\Delta P\%}{K} \left( 1 - e^{-t/T_f} \right) = \frac{100}{K} \times \frac{\Delta P}{P_{load.nom}} \left( 1 - e^{-t/T_f} \right)$$

Table 1

Frequency drop in UPS at various factors K and resulting shortage

Power shortage $\Delta P$ , %	Frequency drop $\Delta f$ , Hz (%)		
	$K=1$	$K=2$	$K=3$
2	1 (2%)	0.5 (1%)	0.33 (0.7%)
4	2 (4%)	1 (2%)	0.67 (1.3%)
6	3 (6%)	1.5 (3%)	1.00 (2%)
8	4 (8%)	2 (4%)	1.33 (2.7%)
10	5 (10%)	2.5 (5%)	1.67 (3.3%)

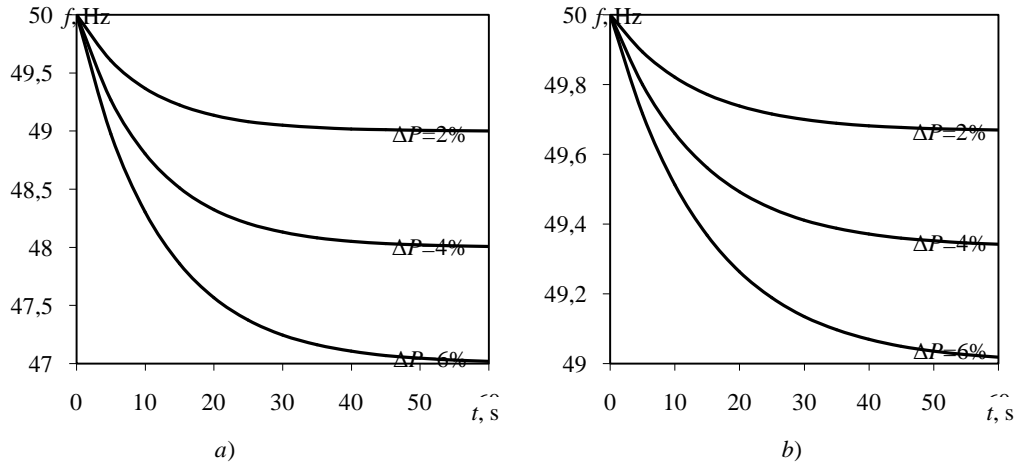


Fig. 2. The frequency drop after an accident with nonrecoverable power shortage (2, 4 and 6%) for various power systems: a - frequency factor of the power system  $K=1$ ; b -  $K=3$

Operational experience shows that in most power systems, a sudden loss of 5% of the generating power will not lead to an unacceptably low frequency, while a loss of 20% of the generating power will almost certainly cause the system collapse. The practical limit of sudden losses and, therefore, the maximum power of one generating unit is about 10% of the minimum system demand [15]. Figure 3 shows the change in frequency when a 10% power shortage occurs in the power system (according to [15]).

The transition time from one mode to another when working on a schedule is minutes. In emergency situations that may occur in the power system or at the plant with its equipment, a limited change in power is required in a very short time (gaining up to 10% of the nominal power in no more than 2 s; short-term pulse unloading of the turbine) or a complete shutdown of the unit. Moreover, temperature limitations do not play such an important role [3]. The rate of

change of power is determined mainly by the dynamic characteristics of the units and automatic control systems. The ways to increase the emergency intakes of blocks are fundamentally different from the ways to improve the remaining maneuverable characteristics, and in some cases the improvement of the latter is accompanied by a significant deterioration in the emergency intake. Therefore, although throttle response is certainly one of the components of maneuverability, often maneuverability and throttle response (which is understood as emergency throttle response) are considered as independent characteristics [3].

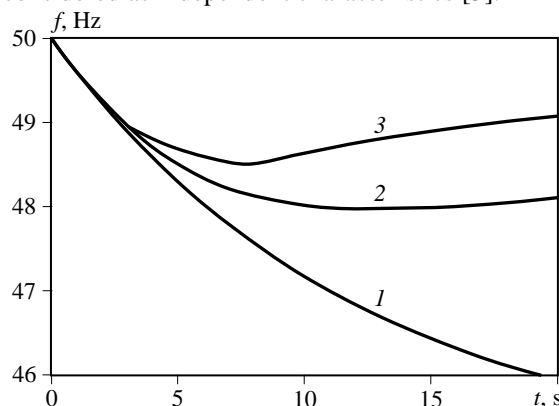


Fig. 3. Frequency change when a 10% power shortage occurs in the power system:

- 1 - frequency drop; 2 - frequency change with increasing production at operating power units;
- 3 - with an increase in production and disconnection of a group of consumers

Obviously, a compromise is needed between the growing need for the active participation of *NPP* units with *VVER* reactors in the regulation of load schedules and the desire to keep their average annual installed capacity utilization factor (*ICUF*) high and economically-acceptable [16]. In this regard, in most cases, it may turn out to be economically more profitable to transfer the regulation region to the near-base, that is, to the sub- and supernominal range of permissible power [17, 18]. The speed of power gain by *NPP* power units during the elimination of emergency power shortages in receiving power systems or systems that are separated from the power connection with the power shortage is to ensure a rapid increase in the generated power by 10% in 1–2 s.

For *NPP* units, the task of preventing or localizing systemic accidents seems even more important than for *TPPs* [15]. This is due to the need for emergency cooling of the reactor after it is stopped. As the lessons of major system accidents show, it is possible to completely stop the external power supply of the station's own needs. Thus, it is obvious that in addition to the requirements for *NPRF NPPs* with *VVER-1000*, 1200 (projects of *NPP-2006*, *NPP-TOI*) nowadays it is necessary to present more stringent requirements for emergency intake and mobility.

In this regard, it is also advisable to transfer the *MCP* in the 1st circuit to a variable frequency drive through a converter device and provide a bypass contactor to return to the normal network in the event of a scheduled repair or failure.

## Results

The results of calculations of characteristic values when changing the frequency of the supplying *MCP* current in the range from 46 to 53 Hz are presented in Table. 2. Figures 4 and 5 show the relationships between the coolant flow rate and power of the *VVER-1000* and *VVER-1200* power units and the frequency of converter with *HVVFD MCP* in the range of load reduction with the *MCP* frequency drive from ~ 0.92 and increase to ~ 1.06.

Note that, the results shown in rows 5 and 6 of table 2 prove that the formula of *MCP* power proportionality to the 3rd power of frequency gives a fairly accurate result. At the same

time, it should be borne in mind that  $K=1\div 3$  is the conditional frequency factor of the power system, depending on the composition of the consumer equipment.

Table 2

The results of calculations of characteristic values when changing the frequency of the supplying MCP current

Characteristics	Frequency, Hz (AC current at MPC)							
	46	47	48	49	50	51	52	53
1. Relative coolant consumption	0.92	0.94	0.96	0.98	1	1.02	1.04	1.06
2. Flow through MPC (VVER-1000): m <sup>3</sup> /h kg/h*	20010 14407	20445 14720	20880 15034	21315 15347	21750 15660	22185 15973	22620 16286	23055 16600
3. Network pressure, m Network 1 Network 2 Network 3	59.2 71.9 76.2	61.9 75.1 79.5	64.5 78.3 82.9	67.2 81.6 86.4	70 85 90	72.8 88.4 93.6	75.7 91.9 97.3	78.7 95.5 101.1
4. Relative power of MPC	0.78	0.83	0.88	0.94	1	1.06	1.12	1.19
5. MPC power (VVER-1000), kW	3582	3821	4070	4329	4600	4882	5174	5479
6. MCP pump power according to the exact formula for the network 3	3590	3827	4075	4341	4608	4889	5182	5488
7. MPC electrical power (VVER-1000), kW**	5840	6229	6636	7059	7500	7959	8436	8933
8. NPP power, MW*** for VVER -1000 for VVER -1200	920 1104	940 1128	960 1152	980 1176	1000 1200	1020 1224	1040 1248	1060 1272
9. NPP power taking into account changes in the MCP power, MW for VVER -1000 for VVER -1200	925 1110	944 1133	963 1155	981 1178	1000 1200	1019 1222	1037 1245	1056 1267

\* the density of water at  $p=160$  at,  $t_{av}=305^{\circ}\text{C}$

\*\* power was determined for the ration  $N_{el}/N_{MPC}$  for the designed frequency of 50 Hz

\*\*\*  $\eta_{NPP}=\text{const}$  adopted for a relatively small range of frequency and load conditions 0.92–1.06 of  $N_{nom}$

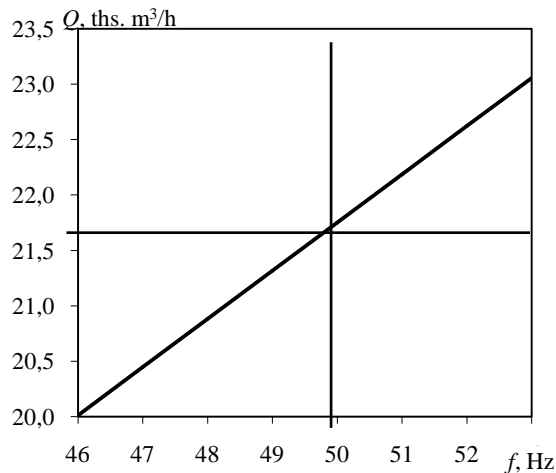


Fig. 4. Relationship between coolant consumption and the frequency of converter with a high-voltage variable frequency MPC drive of the VVER-1000 power unit

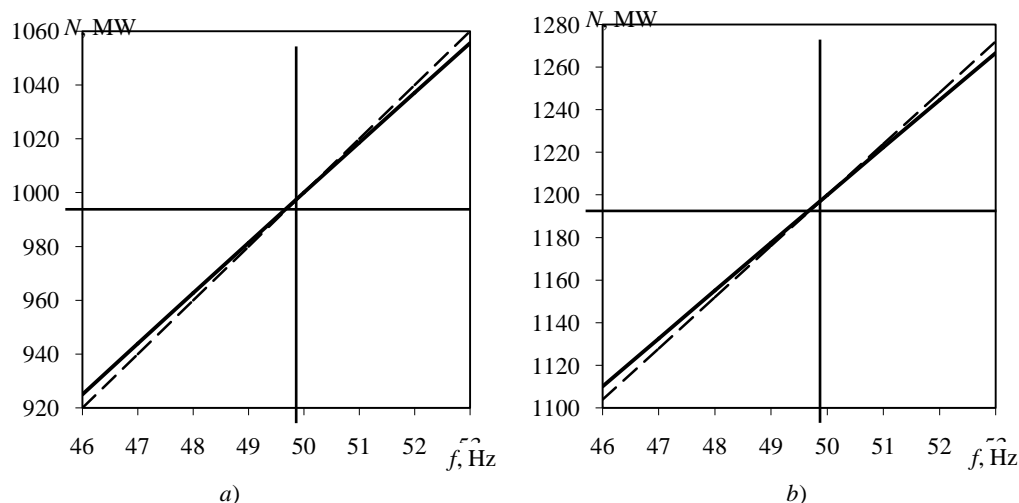


Fig. 5. Relationship between power of the VVER-1000 (a) and the VVER-1200 (b) power units and the frequency of the MCP supply current: — — taking into account MPC power change; - - - without taking into account MPC power change

### Conclusions

1. If the frequency-controlled drive is used only for saving expenses for pumping the coolant in the load range below  $N_{\text{nom}}$ , then the *MCP* and the converter are selected according to  $N_{\text{nom}}$ , and the savings depend on the area below  $N_{\text{nom}}$  and are associated only with the energy consumption for drive of 4 *MCP*.

2. A greater impact can be achieved when installing *MCP* and converter devices with high-voltage frequency-controlled drive, providing increased power above  $N_{\text{nom}}$  and even higher than those achieved today at VVER-1000 without *MCP* replacing. This is acceptable due to the fact that with an increase in the coolant flow rate above the calculated (nominal) one, an additional reserve is formed before the heat transfer crisis of the second kind *DNBR*. At the same time, the expenses of *MCP* supplying above  $N_{\text{nom}}$  will increase, and when adjusting schedules below  $N_{\text{nom}}$ , they will fall. The final effect in this case will be significantly greater due to the replacement (in a less capital-intensive way) of new construction, as well as due to displacement of gas from the Russian energy sector, as a more valuable export resource. However, in this case, it is necessary to select the *MCP* and *HVVFD* of the highest power.

3. When the frequency changes by 1 Hz, the coolant flow through the *MCP* changes in direct proportion to this change in the 1st degree, that is, through the active zone of the reactor (VVER-1000)  $4 \times 435 = 1740 \text{ m}^3/\text{h}$  or at a water density of  $720 \text{ kg/m}^3$  for 1253 t/h. Since at the first stage of the assessment it is possible to take the efficiency of nuclear power plants to be constant in a close to basic mode, it is easy to see that such a decrease in flow rate also causes a corresponding change in the thermal power transmitted from the 1st to 2nd circuit, i.e. 1 Hz corresponds to  $1253/62646 = 0.02$  or a 2% change in thermal power. For a unit with a 1000 MW RU, this corresponds to (at  $\eta_{\text{AES}} = \text{const}$ ) 2% of electric power or 20 MW, for a VVER-TOI unit it is equal to 24 MW.



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**Received**

**April 16, 2019**