On the efficiency of variable frequency drives of the main circulating pumps of nuclear power plants with water-cooled (VVER) and fast neutron reactors (BN)

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Abstract. In case of communication losses with the power system and violations of external power supply, difficulties arise with the removal of residual heat generation of stopped reactor plants of NPP with water-water power reactors (VVER). The structural share of these power units grows. That is why they should be responsible for successful emergency frequency control, preventing the collapse of the power system. This is especially important when the frequency decreases with a prolonged growing generation deficit. In this article, we consider the possibilities of increasing the acceleration of NPP with VVER due to the implementation of fast load surges, as well as through prolonged operation with a power higher than the nominal. In both cases, an increase in the rotational speed of the main circulation pumps by the regulation of their drive motors by frequency converters is proposed for NPPs with VVER to increase the values of the crisis heat flow and increase the permissible temperature at the outlet from the core for the same safety reserves. The article briefly analyzes the experience of the introduction and operation of the variable frequency drive of the main circulation pumps at nuclear power plants with fast neutron reactors BN-600 and BN-800. It is noted that due to the smooth regulation of the flow of sodium coolant by the pumps in the main circuits, the problem of the maneuverability of nuclear power plants with BN reactors was largely solved. These decisions, taken already at the design stage of the third and fourth power units of the Beloyarsk NPP and proven positively in operation, were implemented in the project of the 5th power unit with a fast neutron reactor BN of 1200 MW.

Modern operating conditions of power systems force nuclear power plants, especially where their share is high, to participate in the regulation of load schedules. In the near future, it is projected to increase capacity and increase the generation of electricity at nuclear power plants in the energy systems of European part of Russia. As their specific weight increases, the need for partial regulation of NPP capacity increases. At the same time, it was traditionally believed that, for economic reasons, nuclear power plants should operate primarily in the base mode [1].

Serious emergency situations in the power system include a power shortage, for the elimination of which the power plants in the power system must have the ability to rapidly increase power. Scientific research has shown that VVER reactors, as objects of automatic regulation, have good acceleration
capability, and in the event of a power deficit in the power system due to accumulating power and self-regulation, they react quickly enough to system disturbances [2]. At the same time, to prevent major system accidents, automatic frequency unloading devices disconnect less responsible consumers. Then, after eliminating the power deficit, the protection devices perform automatic re-activation of previously disconnected installations and restore the normal operation of the power system. The faster the balance and, consequently, the frequency is restored, the less the load is switched off by automatic frequency unloading devices (damage and probability of system accidents, including separation of NPP units from it, is minimized). In addition to the general damage caused, the latter type of accidents are especially dangerous for the nuclear power plant itself, since in the absence of external power supply, there is a de-energization of own needs, and it takes a certain amount of time to start a backup power supply (diesel generators). In this situation, difficulties arise with the removal of residual heat from the shutdown reactors.

In power systems with TPPs, NPPs, HPPs and PSPs, which differ in power generation technology, condensing power plants with direct-flow boilers for supercritical parameters (with a relatively high share of power in the power system structure) are poorly adapted to high-speed load fluctuations. For example, under the conditions of load regulation in power systems in emergency modes, loading speeds of power units (within their adjusting range) up to 5% of rated power per minute may be required. The loading speed of the power unit is limited by the maneuvering properties of both the boiler and the turbine [3].

The most maneuverable and, therefore, the most adapted for frequency control in the power system are hydroelectric power plants – HPPs and, above all, PSPs. Standard functionality allows reversible hydro units of such power plants to provide frequency and power balance regulation in the power system in the motor (pump) and generator (turbine) operating modes, i.e. with consumption and output of power [4].

In emergency modes in the power system, the pumped storage power plants provide rapid power backup (load / generation), boosting the reactive power to increase the stability limits. Due to their inherent multifunctionality, PSPs, performing the function of the consumer-regulator and participating in the regulation of frequency and active power, are capable of: increasing the loads of thermal power plants and nuclear power plants in the night part of the daily load schedule, i.e. artificially increase the basic part of the load schedule and reduce its unevenness, work in the peak or half-peak part of the load schedule, provide a high-speed emergency and load reserve of the power system. Obviously, pumped storage power plants, especially in conditions of lack of maneuvering capacities, have become multifunctional sources of system services and, as a source of maneuver capacity, today have practically no alternative.

The rate of regulation of the active power of hydraulic units in power plants of this type is limited by the limiting opening / closing speed of the guide device, the conditions for the formation of a hydrostatic shock, the parameters of the regulating apparatus and other hydrodynamic characteristics, and can reach, in some cases, 500 MW/min [4].

At the same time, the actual regulating effect of only one Zagorskaya pumped storage power plant with six reversible hydroelectric generators with a total turbine power of 1200 MW for the operation of the NPP of the European part of Russia in the base part of the load schedule is insufficient. At the same time, the work of NPP power units with a variable load schedule, as studies and practical experience show, can prove to be not only situationally necessary, but also economically profitable.

Consider the possibility of compromises in this aspect. Speaking about the maneuverability of nuclear power plants, one should keep in mind the two most important aspects of this problem: first, to what extent the change in capacity and, accordingly, the reduction in the number of hours using the installed capacity of nuclear power plants is economically feasible, and secondly, to what extent the change in power is permissible under conditions of ensuring reliability and safety of operation. It is obvious that an increase in the share of electricity generated at nuclear power plants will force NPP power units to perform the functions of regulating the load schedule of the power system. For this reason, one of the priorities is the adaptation of nuclear power plants to variable loads. The most adapted for
this are NPPs with water-cooled reactors on thermal neutrons (VVER), which have good acceleration and self-regulation, as well as fast neutron reactors of new generation (BN-600, BN-800, BN-1200) [5–9].

In the power systems of some countries, nuclear power plants, originally designed for operation in basic modes, have been switched to maneuver operation. The most representative example is the experience of Électricité de France, where 58 power units producing about 75% of electricity are operated today, and in which studies of the maneuverability of PWR reactors (analogues of Russian VVERs) have been started since the 1970s [5, 10]. In 1983, the possibility of attracting such power units to regulating the frequency in the power system was successfully demonstrated (tests were carried out, in particular, at the power unit No. 3 with a capacity of 900 MW(e) of the Tricastin NPP). As a result, the French PWR reactors with a capacity of 1400 MW(e) of the fourth generation (project series N4) were designed (their began to build since 1984) from the outset to operate in the load-tracking mode, taking into account a change in power in the range of 30 to 100% during the day with sustainable system mobility and acceleration capability for emergency control of frequency with load variation in near-nominal range, for example, by the type “+4%–8%” [10].

The necessity to fulfill the “Norms for the participation of power units of nuclear power plants in the normalized primary frequency regulation” in the design, construction and operation of nuclear power plants is also recorded in the Standard of OAO “SO UES” (approved on August 19, 2013, No. 314) [11].

The adjustment range of the NPP depends on the type of reactor. For example, in a nuclear power plant with VVER-440 reactors, the adjustment range in the first period of the working campaign (up to 150 days) is approximately 70%, in the subsequent period it decreases and before the next fuel overload approaches zero. For NPPs with VVER-1000 reactors in the first period, a wider range of regulation can be achieved due to some measures. The dynamic characteristics of NPPs with VVER reactors are quite high: these power units are quickly moving to new load levels. When regulating the VVER reactor, it is allowed to change the load of the power unit at a rate of 3–5% per minute. According to their regulatory characteristics, NPP with VVER reactors can operate in modes with variable loads [5, 7, 10].

The required primary power of the NPP power unit with participation in the rated primary frequency control is calculated by the formula:

\[
\Delta P = -\frac{2}{S\%} \cdot P_{\text{rated}} \cdot \Delta f , \text{ MW or } \Delta P\% = -\frac{200}{S\%} \cdot \Delta f ,
\]

where \(P_{\text{rated}}\) – the rated capacity of the power unit, MW; \(f_{\text{rated}}\) – rated frequency, Hz; \(\Delta f\) – the magnitude of the frequency deviation from the nearest boundary of the “dead band”, Hz; \(S\% = \frac{\Delta f / f_{\text{rated}}}{P / P_{\text{rated}}} \cdot 100\) – statism of primary regulation of the power unit, %.

The permissible ranges of the primary capacity of power units at \(\Delta P = -8\% P_{\text{rated}}\) and at \(\Delta P = \pm 2\% P_{\text{rated}}\) with a rapid decrease and increase in frequency are presented in the form of a shaded area in figure 1 [11]. The zone of insensitivity of the primary frequency control should not be more than 0.02 Hz, that is, the value of the “dead band” of the primary control of the frequency of the power unit participating in the rated primary control should not exceed 50 ± 0.02 Hz.

As can be seen in figure 1, with the participation of NPPs with VVER-440, VVER-1000, VVER-1200 reactors, the regulation of the primary power requires a speed, represented for different values \(\Delta P\) in the intervals (table 1). It should be taken into account that at constant relative speed of maneuver by power, absolute rates of its change depend on nominal value \(P_{\text{rated}}\). At the same time, the rate of frequency change in the power system is determined by the share of power units falling out of the balance of generation or consumption.

Obviously, a compromise is needed between the growing need for active participation of NPP power units with VVER reactors in regulating load schedules and the desire to maintain a high average annual utilization factor of an installed capacity that is acceptable for economic reasons. In this connection, in most cases it may be economically more advantageous to transfer the regulatory area to near-base, that is, to the pre- and super nominal range of permissible power [1, 6, 12].
Figure 1. The permissible range of the primary power of a nuclear power plant at ΔP = –8% P\textsubscript{rated} with a rapid increase in frequency (a) and ΔP = ±2% P\textsubscript{rated} with a rapid decrease and increase in frequency (b) (according to [11]).

Table 1. Required rates of load change for power units of NPPs with participation in the rated primary frequency control (according to [11]).

| Power reduction in the interval | Speed of maneuver |
|--------------------------------|-------------------|
| from 0 to –4% P\textsubscript{rated} | Increase frequency for the first 10 seconds – 0.4% P\textsubscript{rated}/s |
| –4 to –8% P\textsubscript{rated} | next 10 seconds – 2 minutes – 0.036% P\textsubscript{rated}/s |
| in the range from 0 to ±1% P\textsubscript{rated} | Increase / Decrease frequency |
| from ±1% to ±2% P\textsubscript{rated} | the first 10 s ± 0.1% P\textsubscript{rated}/s |
| subsequent 10 – 30 seconds | subsequent 10 – 30 seconds ± 0.05% P\textsubscript{rated}/s |

One of the most effective technologies that allows solving the problem of maneuverability of VVER and BN reactors in principle is a smooth change in the coolant flow rate in the main circuits of the reactor by controlling the rotational speed of the drives of the main circulation pumps [7, 8, 13–16]. Studies have shown that a smooth change in the flow rate of the coolant by regulating the rotation speed of electric drives of the main circulation pumps (MCP) makes it possible to obtain specification parameters of the steam and, due to this, the effective power characteristics of turbines in partial power modes, in the startup and shutdown modes of the power unit of the nuclear power plant, and also significantly reduce the temperature and pressure fluctuations in the main circuits. This leads to a decrease in the range of changes in the average core temperature and to mitigation of neutron-physical disturbances in the core. At the same time, the resource of the reactor internals is saved, reliability, durability and economy are increased due to the reduction of the low-cycle fatigue of the metal of the power equipment and the growth of the NPP net efficiency in the power range of 60–100% and above the nominal [1, 8, 13–16]. The effective power characteristics of the turbine are due to the possibility of changing the flow rate in the circuits in direct proportion to the change in the reactor power and, on average, the power produced by the power unit as a whole.

The possibility of reducing the rotation speed of the MCP and, consequently, the power consumption of the electric drives of the MCP, makes it possible to reduce the level of electric power losses for own needs and to increase the efficiency at partial power levels [8, 15]. The power of electric drives of MCPs makes a significant share in the total power of consumers of own needs. So, for example, the total capacity of the asynchronous electric drives of the MCPs of the first and second circuits of the power unit with the BN-600 reactor is 15300 kW, i.e. ~ 2.5% of the rated capacity of the power unit, and the power of the
electric drives of the BN-800 MCPs is 22500 kW, i.e. almost 2.8% of the rated capacity of the power unit [15]. Accordingly, annual energy savings can be very significant.

A smooth change in the flow rate of the coolant in the main circuits of the reactors makes it possible to reduce the thermal loads in the process equipment in the main and transient modes of the NPP and ensures a more gentle course of emergency modes, excluding thermal and hydraulic impacts on the equipment and facilitating the development of a natural circulation of the coolant with circulating pumps switched off [8, 9]. Figure 2 shows the results of simulation of thermophysical processes in the modes of normal maneuvering (reducing and lifting power) using the example of the BN-800 reactor for smooth and stepwise control of the rotation frequencies of the pumps of the first and second circuits. It can be seen from figure 2 that, with a smooth change in the rotational speed of the MCP-1,2, the temperature deviation in the core of the reactor is much less than in the stepwise control of the MCP-1,2 [9].

The most important advantage of using the variable frequency drive (VFD) of the main circulation pump, as noted in [7, 13, 15, 17, 18], is the possibility of an additional (to the already achieved 4%) increase in power to 7–10% above the nominal level. At the same time, it is possible to maintain the same safety factor before the heat exchange crisis (DNBR – Departure from nucleate boiling ratio) by a corresponding increase in the speed of the coolant.

In connection with the actualization for the Russian nuclear power industry of the requirements [11], it is important to take into account that the installation of the VFD improves the acceleration capability of the NPP, which is especially important for preventing accidents with a frequency drop. In the standard scheme, when the automatic power control system is activated, the coolant flow is reduced (in proportion to the frequency of the mains supply feeding the MCP) and it is necessary to provide the required input power speed, overcoming the decreasing flow of the coolant. By using the VFD of the MCP, a faster increase in the flow rate of the heat carrier is possible, and therefore a faster increase in the load with a smaller increase in the upper and middle temperatures of the coolant in the core.

It should be noted that the block diagram of the system evaluation of the advantages of the VFD of the MCP (figure 3) does not mention all possible situations associated with ensuring the electromagnetic compatibility of the VFD of the MCP with the power supply network, as well as the reliability of variable frequency electric drives.

The tasks of ensuring electromagnetic compatibility and reliability improvement are analyzed and successfully solved for each specific project for the use of variable frequency electric drives both at TPPs for energy efficient control of the performance of numerous technological mechanisms for own needs – nutritional, circulating, network pumps and traction mechanisms, and at NPPs for smooth
change the heat carrier is controlled by the speed control of the circulation pumps in the main circuits. This is evidenced by the long experience of wide application and operation of variable frequency electric drives for the own needs of TPPs and NPPs [17–26].

**Figure 3.** Scheme of the system analysis of the efficiency of the variable frequency drive of the main circulation pump at NPPs with VVER.

As an example, table 2 shows the evolution of the electric drives of the MCP of nuclear power plants in Russia and China [15].

The reliability of the operation of variable frequency electric drives in the event of failure of frequency converters is provided by the backup system. For example, the reservation of failures of frequency-controlled electric drives at TPPs is provided by bypassing – switching on of the circuit breaker, shunting the failed frequency converter and switching the drive asynchronous electric motor to the network of own needs. The performance of a particular technological mechanism of its own needs in accordance with the regime of the power unit is provided by throttling the working medium (water, air, flue gases) with the help of mechanical regulators (control valves, directing devices) that are in the open state during operation of the variable frequency electric drive.

Redundancy in the event of failures of regulated electric drives at NPP depends on the type of electric drive used. For example, in the electric drives of the main circulating pumps of the Beloyarsk NPP reactor BN-600, designed according to the asynchronous-valve cascade scheme using an asynchronous motor with a phase rotor, to compensate for the failure of the asynchronous-valve cascade converter in the rotor circuit, calibrated resistors are connected. These provide discrete (stepwise) control of pumps with fixed speeds of rotation [22, 23].

For electric drives MCPs with asynchronous short-circuited electric motors, adjustable frequency converters, reservation is more difficult. First, the induction motor is performed with two windings on the stator, namely, one high-voltage, to which a frequency converter is connected, which provides normal regimes for regulating the MCP in the specified range of the coolant flow rate (liquid metal sodium), and another low-voltage unregulated electric drive at a rotational speed of 25% of the rated speed, designed to ensure the cooling of the reactor [18]. Secondly, for redundancy of the frequency converter connected to the high-voltage winding of the electric motor, in the electric drive of the MCP
in any loop a “one by three” backup scheme is used, according to which, if any frequency converter fails, it is disconnected from the electric motor and the latter, by the command of automation, is picked up by coasting by a standby frequency converter [15, 18, 27, 28]. Such variable frequency electric drives are operated at Beloyarsk NPP with the BN-800 reactor.

| Reactors          | BN-350 (USSR) | BN-600 (USSR) | BN-800 (Russia) | BN-25 (CEFR) (China) |
|-------------------|---------------|---------------|----------------|---------------------|
| NPP power, MW     | 350           | 600           | 890            | 25                  |
| Number of pumps   | 2             | 6             | 3              | 2                   |
| Power, kW         | 1700          | 3500          | 5000           | 160                 |
| Rotational speed, rpm | 1000/250     | 250–970       | 250–980        | 150–1000            |
| Engine            | Asynchronous motor with squirrel cage rotor (2 speed) | Asynchronous motor with phase rotor | Asynchronous motor with squirrel cage rotor with additional speed winding | Asynchronous motor with squirrel cage rotor with additional speed winding |
| Regulation system | Direct start  | Asynchronous-valve cascade | Static frequency converter | Static frequency converter |

As shown by the thirty-year experience of operating the electric drives of the main circulation pumps of the BN-600 reactor and the two-year experience of operating the electric drives of the main circulating pumps of the BN-800 reactor, the proposed technical solutions have significantly increased the reliability of the operation of these power units at Beloyarskaya NPP, practically eliminating the unfavorable mode for shutting down one loop from the first and second circuits.

It should be noted that the equipment of the variable frequency drive for the MCP of VVER reactors is still being studied only in the scientific aspect. At the same time, as shown in the studies, in many respects the advantages of the VFD of the MCP achieved on BN reactors are also preserved for reactors of this type. Here we give only some of the results achieved.

Saratov State Technical University and the Saratov Scientific Center of the Russian Academy of Sciences have developed a program for calculating the parameters of the VVER-1000 steam generator, which takes into account the presence of a VFD for regulating the MCP [29]. Calculations were performed with a change in the coolant flow and feed water for different ratios between them.

Simplified approximation equations for the dependence of the average heat transfer coefficient in the steam generator \(k_{SG}\) on the speed (flow rate) of the coolant at the frequency regulation of the reactor coolant flow rate and on the change in the feed water flow allowed obtaining a nomogram of values of \(k_{SG}\) for arbitrary values of feed water and coolant flow rates. These data make it possible to clarify the value of \(k_{SG}\) for combinations of feed water and coolant flow rates required for the implementation of specific highly effective control programs.

The values of heat transfer and thermal conductivity coefficients depending on the wall thickness of the pipes and the contamination layer, are calculated or adopted in accordance with [30], table 3. From the analysis of the data in table 3, it follows that the approximations \(\alpha_{1} = \alpha_{1} \cdot G_{1}\) correspond with
sufficient accuracy to the purposes of calculation, where \( \overline{G}_{r.w} \) – the relative flow rate of the coolant (reactor water). If to accept: \( v \) – average specific volume of the heat-carrier in an active zone of the reactor, \( \text{m}^3/\text{kg} \); \( F_{\text{core}} \) – the cross-sectional area of the core, for the same reactor (may vary slightly with different types of fuel assemblies). The value \( G_{r.w} v / F_{\text{core}} \) – the weight flow of the heat carrier per 1 m\(^2\) of the core section – is used as one of the factors affecting the values of the critical level of heat exchange in the core of the VVER reactor.

**Table 3. Dependence of the coefficient of heat transfer from the coolant to the wall of the tubes of the steam generator.**

| Calculated parameter                              | Coolant speed (reactor water) \( W_{f.w} \), m/s |
|---------------------------------------------------|-------------------------------------------------|
|                                                   | 3.5    | 4.42  | 5.53  | 6.64 \(^a\) |
| The coefficient of heat transfer from the coolant to the wall of the tubes of the steam generator \( \alpha_{f.w} \), kW/(m\(^2\)·K) | 25.3   | 30.7   | 36.8   | 42.6   |
| Thermal resistance \( R_{r.w} \), (m\(^2\)·K)/kW | 0.04   | 0.033  | 0.027  | 0.023  |
| Relative coolant flow rate \( \overline{G}_{r.w} \) | 0.63   | 0.80   | 1.0    | 1.2    |
| Relative value of heat transfer coefficient \( \alpha_{f.w} \) | 0.69   | 0.83   | 1.0    | 1.16   |

\(^a\) at these speeds, additional anti-vibration stability measures may be required

From the analysis of the data in table 4 it follows that for the heat transfer coefficient from the surface of the steam generator tubes to the boiler water the approximation is applicable \( \alpha_{f.w} = \alpha_{f.w.0} \cdot Q_{\text{core}}^{0.7} \), where \( Q_{\text{core}} \) – relative reactor thermal power. With a heat conductivity coefficient of 0X18H10T steel (\( t = 295^\circ \text{C} \)) \( \lambda_{st} = 0.188 \text{ kW/(m}^2\cdot\text{K}) \) and a wall thickness of \( 1.4 \cdot 10^{-3} \text{ m} \), the thermal resistance of the wall is \( R_{st} = \delta_{st}/\lambda_{st} = 0.0745 \text{ (m}^2\cdot\text{K})/\text{kW} \). Thermal resistance of oxide films (external and internal) is as follows: \( 2R_{ox} = 2\delta_{ox}/\lambda_{ox} = 0.015 \text{ (m}^2\cdot\text{K})/\text{kW} \) and the total coefficient of thermal conductivity \( R_z = 0.0895 \text{ (m}^2\cdot\text{K})/\text{kW} \).

**Table 4. Dependence of the heat transfer coefficient from the walls of the steam generator tubes to the boiler water.**

| Calculated parameter                              | Feed water speed \( W_{f.w} \), m/s |
|---------------------------------------------------|-------------------------------------|
|                                                   | 0.85  | 1.15  | 1.55  | 1.71  |
| Coefficient of heat transfer from the wall of the pipe to the boiler water \( \alpha_{f.w} \), kW/(m\(^2\)·K) | 10.7   | 14.7   | 17.9   | 19.1   |
| Thermal resistance \( R_{f.w} \), (m\(^2\)·K)/kW | 0.093  | 0.068  | 0.056  | 0.051  |
| Relative reactor thermal power \( Q_{\text{core}} \) | 0.55   | 0.74   | 1.0    | 1.1    |
| Relative value of heat transfer coefficient \( \alpha_{f.w} \) | 0.60   | 0.82   | 1.0    | 1.07   |

The acceptability of approximation by exponential functions of heat transfer coefficients in the steam generator depending on the flow rate of the heat carrier and feed water (from the thermal power of the steam generator) follows from the criterion equations [30], is used for illustrative purposes and is applied also by other researchers (for example, in [7] for the VVER-440 reactor). The error consists, in this case, in the unambiguous correlation between of the feed water circulation ratio in the steam generator and the flow of working steam from the steam generator to the steam turbine.

Table 5 shows the results of calculations of the heat transfer coefficient in the steam generator for several values of the velocities of the coolant \( W_{f.w} \) and water in the tube space \( W_{f.w} \), that are real according to the operating conditions of the reactor. The values of \( k_{SGC} \) in table 5 for the values of \( W_{f.w} \) and \( \overline{G}_{r.w} \) correspond to a different variation of \( W_{f.w} \) and \( Q_{\text{core}} \) for power regulation by the variable frequency drive of the main circulation pump.
The control system in this case can be improved. In [7], for example, in analyzing the efficiency of the variable frequency drive of the MCP of the VVER-440 reactor, the problem of minimizing the deviation of the temperatures at the inlet and outlet from the core and the pressure in the second circuit (with a constant reserve before the heat exchange crisis) was solved (for the range of 10–120% \( \overline{P} \)).

For powerful units of NPPs with VVER-1000 and VVER-1200, the priority task at the initial stage is to ensure their participation in emergency control of frequency in the European part of the Russian Federation, where the share of nuclear power plants is high and continues to grow. To this end, it is necessary to implement a control program that allows the reactor with high acceleration to increase power and to operate for a long time at a power above the nominal by 7–10% [6, 12].

The urgency of solving this problem is not excluded in other works [7, 30], where it is shown that additional factors should be taken into account: optimization of temperature and neutron-physical fields, prolongation of the reactor resource and increase in the utilization factor of the installed capacity of nuclear power plants. In the near-base zone of loads of NPPs with VVER reactors (for small deviations \( \overline{Q}_{SG} = 0.9 \pm 1.15 \) and \( \overline{G}_{i,w} = 0.9 \pm 1.2 \)) in accordance with the results of approximation with sufficient accuracy can be calculated by the formula:

\[
\kappa_{SG} = \left( \frac{1}{\alpha_{i,w} - \frac{3}{G_{i,w} \cdot \frac{\delta}{\alpha_{i,w} + \sum_{i=1}^{3} \frac{1}{Q_{b}^{2}}} + \frac{1}{\alpha_{i,w} \cdot Q_{b}^{2}}} \right)^{-1}. \tag{2}
\]

The formula (2) was obtained in the same form in [7] on the basis of the use of known criterial relations for the corresponding types of heat exchange [30] and was used in the calculation models of various control programs for the variable frequency drive of the main circulation pump.

One of the further achieved effects of using the variable frequency drive of the MCP of the VVER reactor is the optimal matching of the hydraulic and flow-pressure characteristics of the network and pumps. It is usually impossible to provide throttling of the coolant in circuits with VVER-1000 and VVER-1200 reactors because of the absence of regulating bodies on the pressure side of the MCP. The exact matching of the resistance of the pressure part of the MCP track changing due to differing resistances of fuel assemblies of different types and thermophysical characteristics of the core in operating modes with a network characteristic (which is also changing) is impossible. In practice, pumps are designed with a flow reserve. In this case, it is possible to ensure better matching of pump head and real (lower) network resistance by reducing the flow rate (with a certain reduction in the head and the number of revolutions of the pump, permissible balance).

As a typical example in table 6, the characteristics of the normal operating mode of the BN-800 power unit of the Beloyarsk NPP with a capacity of 861 MW are given. The nominal parameters of the PowerFlex 7000 electric drives of the first and second circuits, respectively: power 5000/2500 kW, voltage 6000 V, rotation speed (synchronous) 1000 rpm [15, 18].

Due to the decrease of inconsistency of the discharge-pressure characteristics of centrifugal pumps with the hydraulic characteristics of the reactor cooling loops and taking into account the pump design

| Table 5. The values of \( k_{SG} \) at different speeds of the coolant (or its relative flow rates) and feed water in the tube space (at different relative thermal load of the steam generator). |
|---|---|---|---|---|
| Coolant speed \( W_{i,w} \), m/s | Relative coolant flow rate \( G_{i,w} = \overline{W}_{i,w} \) | Feed water speed \( W_{f,w} \), m/s | Relative reactor thermal power \( Q_{\alpha} \) |
| 3.50 | 0.63 | 0.85 | 4.49 | 0.55 |
| 4.42 | 0.8 | 1.15 | 5.07 | 0.74 |
| 5.53 | 1.0 | 1.55 \( ^{a} \) | 5.41 | 1.0 |
| 6.64 | 1.2 | 1.71 | 5.73 | 1.1 |

\( ^{a} \) basic speed of feed water in the circulation within the steam generator;  
\( ^{b} \) coolant base speed
stock, the actual powers consumed by the variable frequency drive were significantly reduced: in the primary circuit up to ~ 60%, in the second circuit up to ~ 54%. The deviation of the frequency of the variable frequency drive (maximum) from the nominal value, respectively, in the primary circuit is ~ 9%, in the second circuit ~ 5.7%.

**Table 6.** Performance characteristics of the normal operation mode of the main circulating pumps of the power unit with BN-800 reactors of Beloyarsk NPP.

| MCP of the first cooling circuit of the reactor | 1 MCP-1 | 1 MCP-2 | 1 MCP-3 |
|-----------------------------------------------|--------|--------|--------|
| Power of VFD of MCP-1, kW                     | 2934   | 2990   | 2887   |
| Rotational speed, rpm                         | 913    | 911    | 905    |
| MCP of the second cooling circuit of the reactor | 2 MCP -1 | 2 MCP -2 | 2 MCP -3 |
| Power of VFD of MCP-2, kW                     | 1243   | 1346   | 1367   |
| Rotational speed, rpm                         | 944    | 938    | 952    |

It should be emphasized that, as studies and practical experience of operation of power units with BN reactors have shown, smooth regulation instead of uncontrolled or stepwise regulation of the coolant in the first and second circuits provides a new quality of the power unit not only in terms of increasing its reliability and efficiency in starting regimes and partial power modes, but also significantly facilitates and accelerates the first start-up and accelerates the increase in the power of the power unit, simplifies the conditions of its operation [8, 9, 31].

For BN type reactors, smooth regulation of the rotation speed of the MCP is mandatory; allows reducing thermal loads in technological equipment in the main and transient modes ensures a gentler course of emergency modes, excludes thermal and hydraulic shocks, promotes the development of natural circulation of the coolant with disconnected circulating pumps [8, 9, 32].

Smooth regulation of the coolant flow rate can be used both in the static and dynamic modes of the reactor, providing, including:

– maintain steam parameters for high-energy performance of the turbines (only 3 in-circuit nuclear power plant);
– equalizing the coolant flow through the loops in order to eliminate the structural asymmetry of the heat exchange loops (instead of installing throttling devices in the loops of the second circuit to equalize the hydraulic resistances and outlet temperatures);
– maintaining the temperature difference between the coolant and the loops at the inlet to the reactor pressure collector within the permissible limits, as well as to maintain the optimal steam parameters when the steam generator sections are disconnected;
– exclusion of work at frequencies that cause equipment vibration due to resonance;
– maintenance of technological parameters that promote, for example, the development of natural circulation, reduction of thermal shock loads in cooling modes, emergency modes, when the electric drive control system is included in the automated process control system of the entire power unit.

Finally, the smooth regulation of the coolant flow rate, provided by changing the frequency of rotation of the drive motors of the main circulation pumps by frequency converters with the redundancy of any faulty converter in the first and second circuits in the “one by three” scheme, allows improving the operational reliability of the reactor, eliminating the disconnection of any loop in the event of operating transducers failures. The stop of the power unit is not required in this case, and the pickup of any of the electric motors of the main circulation pump is carried out on its run-out by a reserve frequency converter (“on-the-fly start”) with operating loops. This also makes it possible to consider such a regime more economical and, in terms of thermal cycles, more preferable. In general, all these advantages allow increasing the resource and utilization factor of the installed capacity of the NPP.

The achieved cost savings is confirmed by the operation of the sodium main circulation pumps of Beloyarsk NPP equipped with variable frequency drives, as well as by a significant number of variable frequency pumps of thermal power plants, technical water supply pumps of those NPPs where variable frequency drives have been installed for a long time already [8, 19–21, 23, 31, 32].
When analyzing the characteristics of the MCPs of NPPs with VVER-1000, 1200, it is necessary to more accurately account for the efficiency of the pump in real operating conditions. Figure 4 shows the flow-pressure characteristics of the GTSN-195M with impeller 195-42-0016 (tests at the stand D = 500, data of the Central Design Bureau of Machine Building) with calculation of them for the rotary speed \( n = 0.94+1.15 \cdot n_{\text{rated}} \) (\( n_{\text{rated}} \) – rated frequency of the network 50 Hz). This is only true when the pressure characteristic of the network is subject to the laws of a quadratic parabola \( H = m \cdot Q^2 \), i.e. in the network there is no static head. Note that the pressure scale given in meters of water column should be recalculated in kgf/cm\(^2\) based on water density at 300 °C and pressure of 15.6 MPa (bench test parameters).

The most important characteristics of circulating pumps of the first circuit of NPP units with the VVER-1000 reactor are shown in table 7.

**Table 7. The main technical characteristics of the MCP NPP with the VVER-1000 reactor.**

| Characteristics                  | GTSN-195M | GTSNSA |
|---------------------------------|-----------|--------|
| Productivity, m\(^3\)/h        | 20 000    | 21 500 |
| Rotational speed, rpm           | 1000      | 1000 / 750 |
| Suction pressure, kgf/cm\(^2\) | 156       | 163.5  |
| Water temperature at suction, °C | 286.2     | 298.6  |
| Head, kgf/cm\(^2\)             | 6.75 ± 0.25 | 6.75 ±0.25 |
| Coolant speed:                  |           |        |
| – between fuel rods, m/s        | 5.6       | –      |
| – in branch pipes, m/s          | 10.0      | –      |
| The water temperature at the reactor outlet, °C | 320 | 329.7 |
| Power, kW                       | 5 300     | –      |
| Efficiency, %                   | 77        | –      |
| Drive motor power, kW           | 8 000     | –      |
| Runtime of the rotor, min       | 3 – 4     | –      |
| Moment of inertia of rotating mechanisms, ton·m\(^2\) | 7.5 | – |

The variable frequency drive of the MCP at the NPP with the VVER reactor not only reduces the power consumption for own needs and improves the regulating characteristics of the power units, but also makes it possible to significantly increase the power above the nominal (higher than achieved today). This is necessary to increase the utilization factor of the installed capacity, to reduce the high payback periods of nuclear power plants and to create operational reserves of capacity for readiness to participate in emergency frequency control (in the most difficult situation with the frequency drop in the power system).

Here are some other system advantages associated with the use of the variable frequency drive of the main circulation pump at nuclear power plants (not only with VVER reactors):

1) improvement of transient processes in the reactor core due to large possibilities of thermal stabilization of the core by the condition of minimizing the deviations of mean values of temperatures in the core;
2) lower maintenance costs;
3) for newly designed power units with variable frequency drive – simplification of the technological scheme (there are no check valves in the pumps, fewer valves and throttles);
4) increase in capacity even at the nominal mode by 1–2% due to the exclusion of sealing connections in the waterways;
5) integral significant decrease in power consumption of own needs when operating at reduced power;
6) reduction of wear of the main equipment due to smooth start-ups with a decrease in starting electric currents by 5–6 times;
7) the possibility of complex automation using in addition to two significant impulses: pressure and average temperature in the core of another parameter – the flow rate of the coolant.
Figure 4. Characteristics of GTSN-195M with impeller 195-42-0016 when operating in the “hot mode” on the basis of tests at the stand D = 500, CDBMB.
The above-mentioned many years of successful experience in the use of a variable frequency electric drive for the MCP of BN reactors requires some rethinking in relation to VVER reactors with a different physical concept, with a much higher need for a single MCP capacity for pumping a water coolant.

The available positive experience of using a VFD on medium and high-power pumps of fast neutron reactors in Russia and abroad makes it possible to consider this innovative area to be promising and economically justified also for NPPs with VVER reactors. The greatest technical and economic effect can be ensured by the application of a VFD of MCP with the participation of nuclear power plants in the indirect regulation of load schedules. In this case, it is envisaged to work at overcapacity during peak periods, i.e. ensuring the required regulatory range while maintaining high levels of the utilization factor of the installed capacity of the NPP, and not just the reactor (with the loading of the reactor by heat during the hours of reducing the electric load in the power system).

The achieved rated power of VVER-1000 104–107% can be increased due to the application of the variable frequency electric drive of the main circulation pumps. When transferring the power units of the NPP from VVER-1000 to a power of 104–107%, the equipment of the MCP remained the same. At the same time, with a significant increase in the flow rate of the coolant, it is possible to replace the MCP with new ones with increased flow rate or to preserve the previous MCP, but with the replacement of impellers with increased diameters in the previous snails (Bohunice NPP experience). To increase thermal output at the same level of safety, it is possible to raise the critical heat load by increasing the flow at the same speed in a new or upgraded main circulation pump or by increasing the pump speed.

Thus, the advantages of using the V of the MCP at NPPs with VVER can be manifested in partial load regimes: reduction of electric power consumption for NPP own needs; maintenance of the best temperature conditions of work of the case and the internal equipment (because of stabilization of temperature fields); and in load modes above the nominal with increased flow rates, where the cost of a high-voltage VFD of the MCP is higher than in the conventional version, but there are conditions for raising the power above the nominal one.

In the power systems with their high share of NPP, the maneuverability and acceptability of the power units become necessary for emergency control of the frequency by a rapid increase and decrease in the load, for example, in the range from +2 to −8% \( P_{\text{nom}} \). With a variable flow rate of the coolant in the primary circuit with a variable frequency drive of the main circulation pump, it is always advisable to keep the power reserve by 2–4% towards increasing it (including when working at a power above the nominal). The power reserve should be quickly implemented with minimal inertia. This is ensured by the opening of stop-control valves (with the dynamics at the initial moment higher than necessary) in the process of increasing the capacity due to increments in the flow of coolant to the steam generator, steam to the head of the turbine and the steam pressure in front of it. These increments should be correlated with each other, meet the equations of state of the coolant and working fluid, heat transfer and heat balances in the steam generator and ensure the necessary initial steam pressure (without throttling) to the turbine.

The concept of a new proposed control program with an increased steam flow rate to the turbine (without throttling) in order to increase the power of the VVER reactors will require a transition to another system for controlling the steam pressure ahead of the first stage, changes in the schemes for generating multi-pulse controlled signals, and solving other issues of power electronics and automation [1, 13, 14, 16].

Conclusions

1. The experience of introduction and operation of variable frequency electric drives of the main circulating pumps of NPPs with BN-600 and BN-800 reactors is analyzed; positively proven solutions that are implemented in the developed BN reactor 1200 MW are noted.

2. Advantages of control systems for a steam generator unit using frequency-controlled drives of the main circulation pumps of VVER-1000 and 1200 reactors are shown. To overcome the existing difficulties, joint efforts of specialists in the field of reactor and steam generator construction, power
electronics, automated process control system, reliability and safety in nuclear energy, the economics of nuclear power plants and power systems should be applied.

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