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Research Article

Simulating operation of power units 1 and 2 at Novovoronezh NPP II with two electrical feed pumps disabled and the backup pump not enabled*

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Abstract

Introduction. The article analyzes the operation of Unit 1 and 2 of Novovoronezh Nuclear Power Plant II (equipped with VVER-1200 reactors) with two electrical feed pumps disabled and the backup pump not enabled. These operating conditions are subsequently simulated using the power unit model software-hardware package (PUM SHC) developed by LLC IF SNIIP ATOM.

Research objectives. The objective of this work was to check the reliability of the forecasts of changes in the power unit parameters obtained using the PUM SHC, based on operational data.

Methods. The simulated power unit parameter changes in transient conditions were in good agreement with the data collected in real tests. During the simulation, the power unit dynamic stability was preserved, i.e., the operational parameters were within the design limits and did not exceed the protection operation set points.

Results. The results of the work suggest the possibility of using current NPP power unit simulations:

- for developing proposals for adjusting the operation control algorithms in case of malfunctions and emergency modes with the main equipment shutdown and power unit protection actuation; and
- for verifying design solutions for updating the power unit systems, which are associated with the use of new equipment or changes in flow diagrams.

Conclusion. Current power unit models can be applied both for existing power units and for new ones that are being commissioned.

Keywords

VVER-1200, power unit model, control algorithm, dynamic stability, tests, electrical feed pump

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Introduction

The dynamic stability of a power unit in transient modes is the ability of its systems and equipment to provide the design limits for changing process parameters without actuating the reactor protection system and disconnecting the power unit from the network (Kazakov et al. 2014).

An urgent task is to ensure and improve the power unit dynamic stability (Podshibyakin et al. 2005, Kamnev et al. 2011, Filipchuk 2012, Gusev et al. 2017). One of the ways to improve the dynamic stability of NPP power units taking into account (IAEA 2003, NP-001-15 2015, Krushelnitsky and Topchiyan 2007) is to optimize the algorithms for controlling the main equipment, including the development and implementation of proposals for adjusting the existing process protections and interlocks. The need to adjust the algorithms of process protections and interlocks becomes evident during commissioning works and tests both at newly commissioned power units (Asmolov et al. 2017) and at operating ones when they are in modes with abnormalities.

Along with improving the power unit dynamic stability, it is no less important to check the correctness of design solutions for upgrading the power unit system, involving the use of new equipment or changes in plant flow diagrams.

The correctness of the proposed adjustments to the algorithms of process protections and interlocks or changes in design process engineering solutions can be confirmed by the use of current NPP power unit simulations based on various software and hardware tools.

During the work, calculations were made for the mode with two electric feed pumps disabled and the backup pump not enabled at NvNPP II-1 and 2. The calculations were carried out on the basis of the mathematical model of NvNPP II-1 developed by LLC IF SNIIP ATOM (Gusev et al. 2019).

Then the results of the performed calculations were compared with the results of tests carried out at the stages of pilot commercial operation of NvNPP II-1 and 2:

- at Unit 1, when two electrical feed pumps (EFP-1, 5) were disabled and the backup one was not enabled at a power level of 97.8% N_{rated} with the high pressure heaters (HPH) disconnected (01.27.2017); and
- at Unit 2, when two electrical feed pumps (EFP-1, 5) were disabled and the backup one was not enabled at a power level of 99.9% N_{rated} with the HPHs connected (08.26.2019).

Modes with deviations in the feed water system operation belong to the groups of modes with deviations of heat removal by the second circuit. In accordance with the NvNPP II design (Atomenergoproekt 2010), the feed water system provides for the installation of five electrical feed pumps of the PEA 1840-80 type. At the rated power level, four pumps are in operation and one is on standby. If one of the operating EFPs is disabled, the backup pump is automatically enabled. If two EFPs are disabled and the backup pump is not enabled, the reactor is automatically unloaded by the combined action of the reactor accelerated preventive protection (APP) and reactor power setback and limiting (PSL) device. The reactor is unloaded to the permissible level of 50% of the rated power.

In the transient process, when one EFP is disabled and the backup pump fails to be automatically enabled, the flow rate of the pumps remaining in operation increases. The increased feed water flow rate in the pumps remaining in operation is determined by the following factors: the displaced operating point of the pump head-capacity curve, when not all pumps are in operation, and changed hydraulic characteristics of the network due to the operation of the feed water system regulators (Rabinovich 1977). The design algorithms for the feed water system control were taken as the initial data in the calculations.

Brief description of the power unit model

The mathematical model of NvNPP II-1 is implemented on the basis of the multi-platform version of the Kruiz software environment.

The power unit model (Report on Power Unit Mathematical Model 2020) includes:

- a distributed dynamic neutronic model of the core;
- a one-dimensional two-phase thermophysical model of the processes occurring in the main systems of the power unit; and
- a model of an automated process control system.

A characteristic feature of calculations related to reactor facilities is the mutual influence of neutronic and thermophysical processes in the core. This leads to the need for conjugate calculations, when the results of the neutronic calculation become the output parameters for the thermophysical calculation and vice versa. In addition to this, various regulatory influences from the automated process control system (APCS) have an impact on both neutronic and thermophysical processes. As a result, the procedure for calculating the development of the physical processes occurring in the power unit looks like a sequential cyclical call of all the three calculated components of the mathematical model. At the end of the calculation cycle, it is necessary to return to the beginning of the cycle and start the next cycle. The characteristic depth of calculation in time for one cycle is 0.1 of a second.

To carry out the predictive calculations, it is necessary to initialize the initial state of the power unit model. Initialization is based on data packages generated by the upper unit level system (UULS). As an initializing data package, it is possible to use the last one received from the UULS or one of the packages recorded in the archive.

The data packages are generated in the UULS; they are sent to the PUM SHC with a frequency of once a second and recorded in the archive; therefore, using the power unit model, it is possible to start the calculation from the power unit state to an arbitrary date and time with an accuracy of up to a second, for which there are archives of operational data.

The operation speed of the mathematical model depends on the performance of the equipment based on which the power unit model is implemented; however, in any case, the operation speed is an order of magnitude higher than real time.

Initial state of NVNPP II-1 and 2 before testing

Table 1 lists the main parameters and condition of the equipment of NvNPP II-1 and -2 before the tests on disabling two feed electric pumps without enabling the backup one were started.

The table shows that the main differences between the initial state of Unit 1 and Unit 2 are as follows:

- reactor power increased by 2.1%;
- turbine generator power increased by 2.9 %;
- HPH-5, 6 are in operation;
- SG inlet feed water temperature increased by 55 °C;
- total pump head feed water flow rate increased by 864 m^3/h;
- total SG feed water flow rate increased by 1295 m^3/h;
- SG MLC opening higher by 21%;
- SCV opening higher by 17%; and
- closed BRU-D and BRU-SN.

Table 1. Main parameters of NvNPP II-1 and 2

Parameter	Unit 1	Unit 2
Pumps disabled during the experiment	1, 5	3, 5
Backup pump	3	1
State of HPH-5, 6	Disabled	Enabled
Reactor power, %	97.8	99.9
Average thermal power, MW	3132	3197
TG power,%	92.0	94.9
Automatic power controller (APC) operating mode	T	T
Turbine governor electrical part (TGEP) operating mode	PC	PC
Above-core pressure, MPa	15.87	15.94
Average hot leg temperature, °C	326.2	326.0
Average cold leg temperature, °C	294.8	295.3
Pressurizer level, m	7.9	7.8
Average SG level, m	2.71	2.70
LPH-2 water level, m	3.44	3.34
LPH-4 water level, m	0.158	0.286
Deaerator water level, m	2.63	3.11
Total pump head flow rate, m^3/h	6298	7162
Pump head pressure, MPa	9.3	8.7
Average main level controller (MLC) opening in the steam generators (SG), %	39	60
Average startup level controller (SLC) opening in the steam generators (SG), %	28	27
Total SG feed water flow rate, m^3/h	6403	7698
Average SG inlet feed water temperature, °C	172	227
Main steam header (MSH) pressure, MPa	6.8	6.9
Fast acting steam dump valve with discharge to the deaerator (BRU-D) opening, %	5	0
Average turbine stop-control valve (SCV) opening,%	29	46
Fast acting steam dump valve with discharge to the auxiliary header (BRU-SN) opening, %	12	0

Numerical simulation of the transient mode at NvNPP II-1 with two electric feed pumps disabled and the backup pump not enabled at the power level of 97.8% N_{rated}

Numerical simulation of the transient state with disabled EFP-1, 5 was carried out to check the reliability of the forecasts of changes in the power unit parameters, obtained using the PUM SHC.

For a comparative analysis of the model data, the archival parameters of the UULS of NvNPP II-1 for January 27, 2017, were used.

In the course of the experiment, after the EFPs were disabled, the reactor thermal power decreased from 3150 to 1467 MW due to the APP operation. In Figure 1, the dashed line represents the archived values, and the solid line represents the calculated values obtained using the power unit model.

The feed water temperature at the steam generator inlet was kept constant about 174 °C.

Figure 2 shows the flow rates at the head of EFP-1, 3, 5. During the test, the backup pump was EFP-3. According to the UULS archival data, the feed water flow rate was 1700 m^3/h at the head of EFP-1 and 1516 m^3/h at the head of EFP-5, respectively, before they were disabled. In the calculation model, the flow rates at the head of EFP-1, 5 were 1512 m^3/h.

After EFP-1, 5 were disabled, negative flow occurred through them for a short time due to the fact that the check valve closing time was two seconds. The flow rates during the experiment at the power unit did not go into the area of negative values, apparently due to the filtering of the input data for the sensors measuring the flow rate at the pump head (10LAB01-05CF901_XQ01).

Figure 3 shows that before testing, according to the UULS archival data, the average flow rate was 1572 m^3/h in EFP-2, 4 and 1524 m^3/h in the calculation model. After EFP-1, 5 were disabled, according to the archival data, EFP-4 and EFP-2 reached the maximum flow rate of 2115 m^3/h and 2060 m^3/h, respectively. In the model, the maximum flow rate was 2098 m^3/h.

Prior to the test, the total feed water flow to the steam generators, according to the UULS data, was 6403 m^3/h; after the two EFPs were disabled, it was stabilized at 4180 m^3/h. The calculations of the transient mode in the power unit model with EFP-1, 5 disabled showed that the total

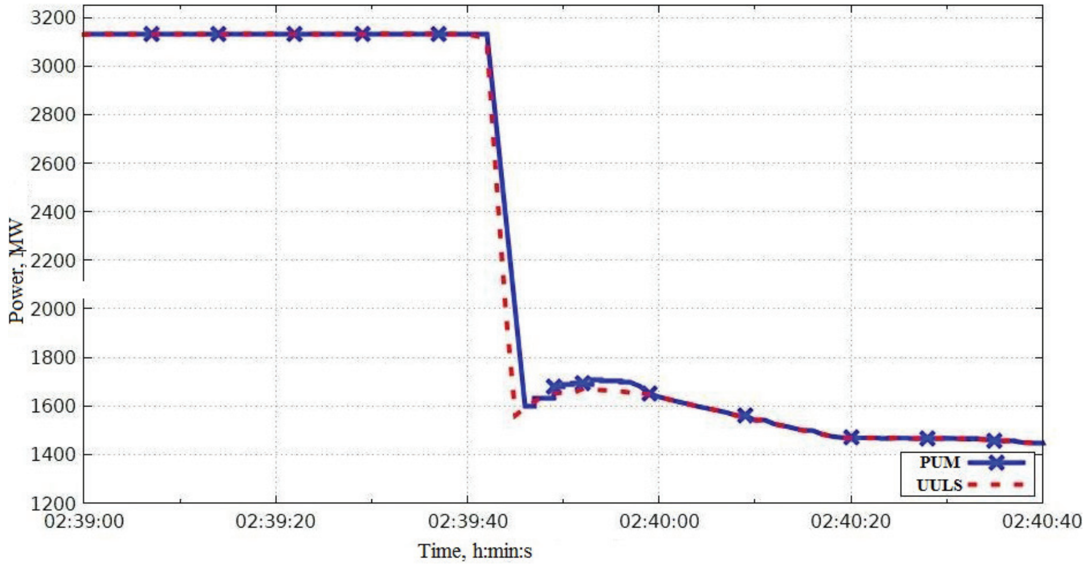

Figure 1. Reactor power dynamics.

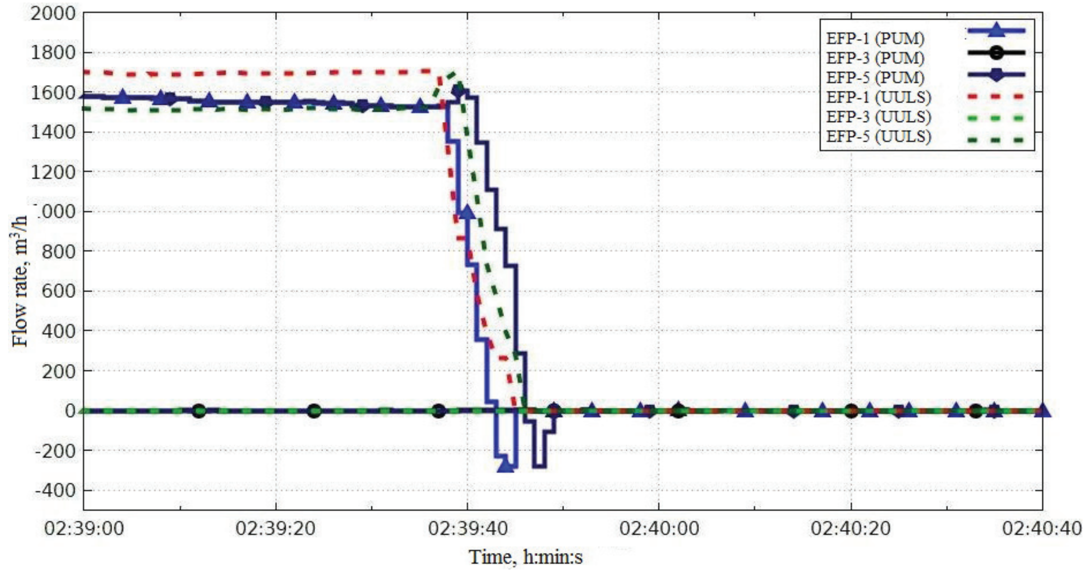

Figure 2. EFP-1, 3, 5: head flow rate.

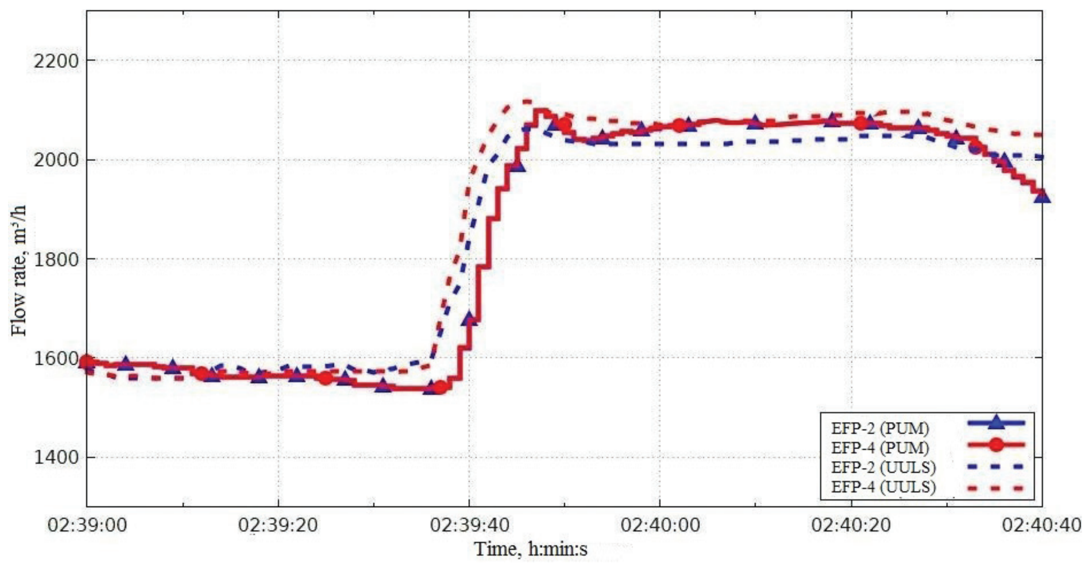

Figure 3. EFP-2, 4: head flow rate.

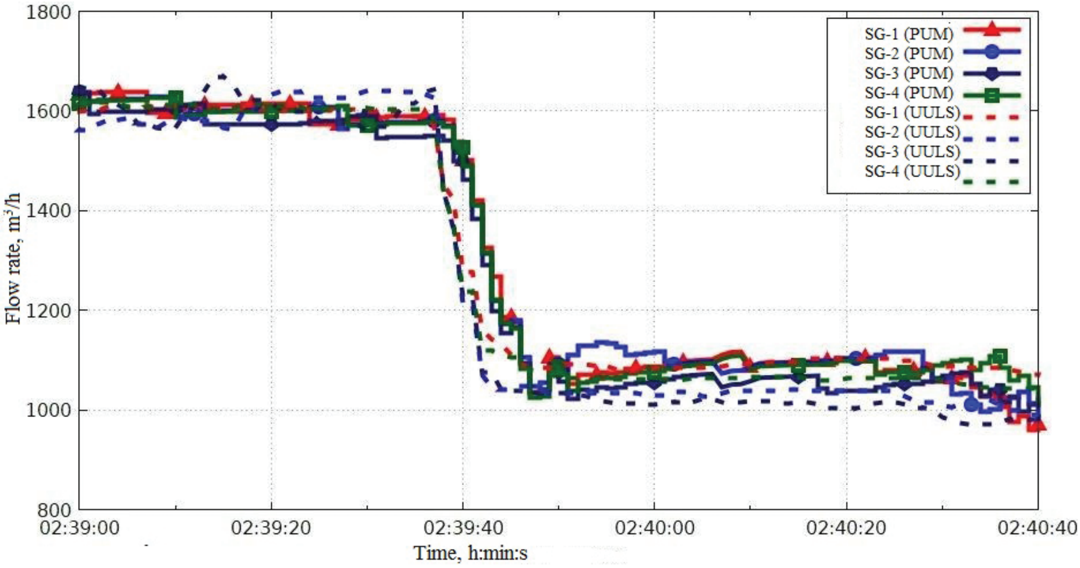

Figure 4. Feed water flow to the steam generators.

feed water flow to the steam generators decreased from 6301 m^3/h to 4200 m^3/h (Fig. 4).

It can be argued that both in the model and in the real power unit, the dynamic stability is preserved, i.e., the process parameters are within the limits established by the design and do not reach the protection operation trip set points. The changes in the transient mode parameters correspond to those observed in the real tests. During numerical simulation, the power unit parameters are stabilized at the same values as the real power unit parameters during testing.

Numerical simulation of the transient mode at NvNPP II-2 with two electric feed pumps disabled and the backup pump not enabled at the power level of 99.9% N_{rated}

Using the mathematical model of NvNPP II-1 in the Kruiz SHC, the authors simulated a transient process with EFP-3, 5 disabled and the backup EFP-1 not enabled, with the parameters of the initial state of Unit 2 at 16:15 on 26.08.2019. To simulate the physical processes occurring in Unit 2 using the model of Unit 1 is acceptable due to the fact that both power units are built according to the same design and have a high degree of identity.

To bring the parameters of the initial states into conformity in the numerical model, the reactor power was increased to 3205 MW (Fig. 5), HPH-5, 6 were enabled for heating feed water to 225 °C, EFP-3 was put into operation, and EFP-1 was in standby.

After two EFPs out of the four operating ones were disabled in the same way as it was done at Unit 1, Unit 2 was unloaded from 3200 MW to 1600 MW due to the APP operation. In terms of changes in the reactor power during unloading, the behavior of Unit 2 did not fundamentally differ from that of Unit 1.

Differences in the transient process parameters manifest themselves when the flow rate through the EFP is considered. Figure 6 shows the change in the flow rate at the head of EFP-1, 3, 5. The average flow rate according to the UULS data at the head of EFP-3, 5, before they were disabled, was 1788 m^3/h. In the power unit model, before the transient process, the average flow rate at the head of EFP-3, 5 was 1733 m^3/h.

Figure 7 shows that before testing, according to the UULS archival data, the average flow rate was 1790 m^3/h in EFP-2, 4 and 1732 m^3/h in the calculation model. After EFP-3, 5 were disabled, according to the archival data, EFP-2 and EFP-4 reached the maximum flow rate of 2150 m^3/h and 2148 m^3/h, respectively. In the model calculations, the maximum flow rate was 2176 m^3/h.

The total feed water flow to the steam generators, according to the UULS data, was 7698 m^3/h; after the EFPs were disabled, it was stabilized at 4317 m^3/h. The total feed water flows to the steam generators in the power unit model before and after the transient mode were 7737 m^3/h and 4551 m^3/h, respectively.

It can be noted that during the tests with high-pressure heaters involved in operation, both in the real process at the power unit and in the calculations in the power unit model at the head of the pumps remaining in operation, higher flows are realized. The main danger of an increase in the flow rate is that the achievement of the protection trip set points for disabling the EFP at the maximum flow rate at head (2250 m^3/h) will lead to the disabling of the EFPs remaining in operation, further reactor unloading, a decreased level in the steam generators, shutdown of the reactor coolant pump set (RCPS) by the action of protections, reactor scram and disconnection of the power unit from the network. In this experiment, the flow rate EFP protection setting is not achieved, which contributes to

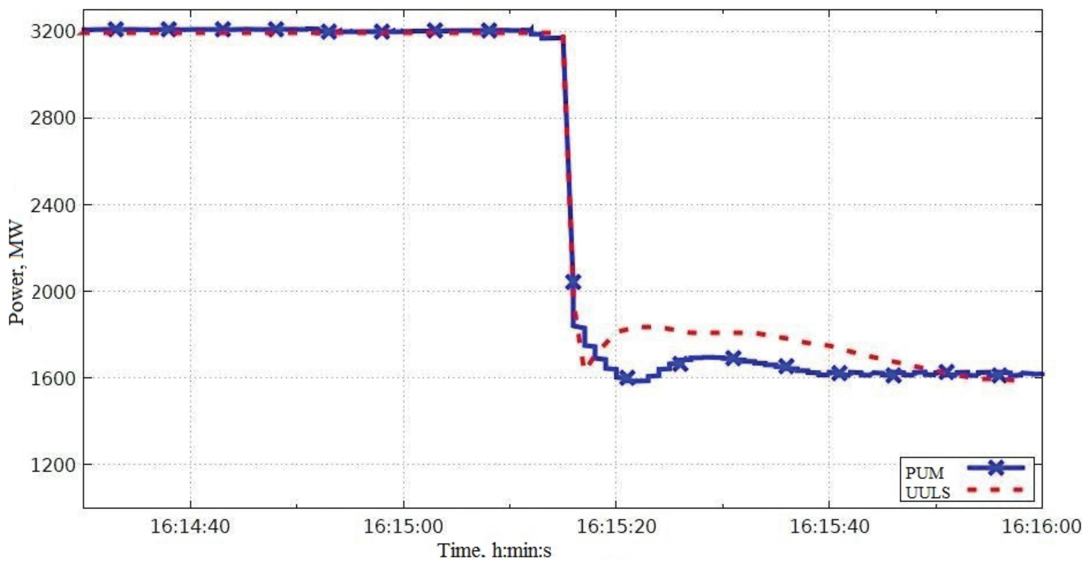

Figure 5. Reactor power dynamics with the modified parameters of the initial states.

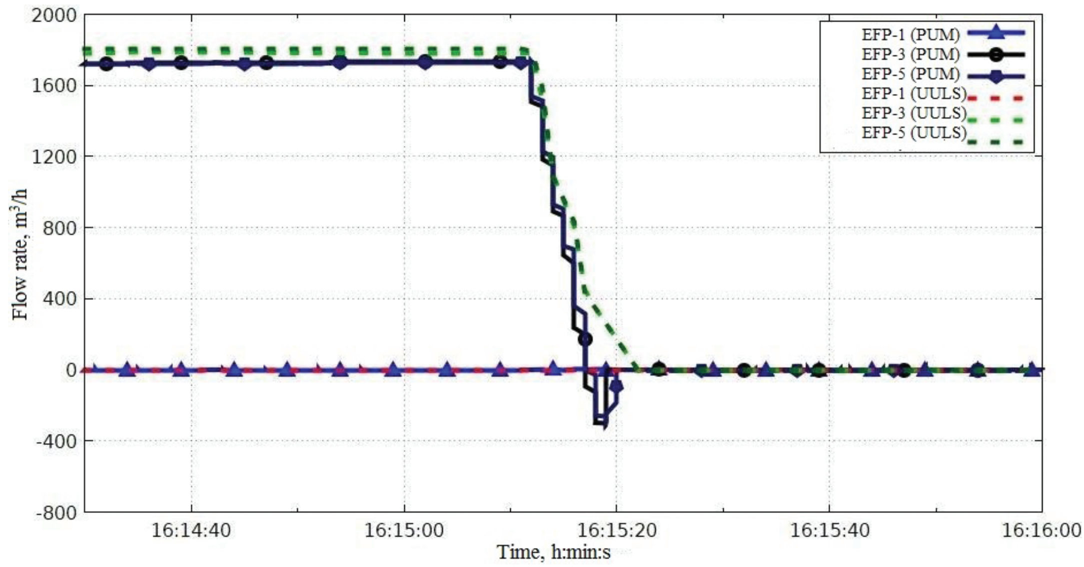

Figure 6. EFP-1, 3, 5: head flow rate.

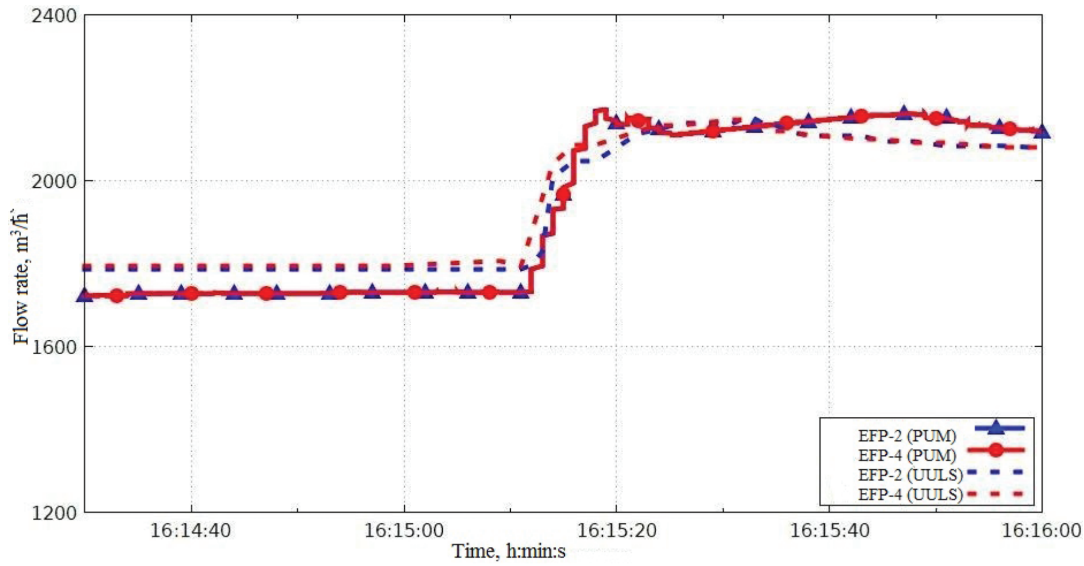

Figure 7. EFP-2, 4: head flow rate.

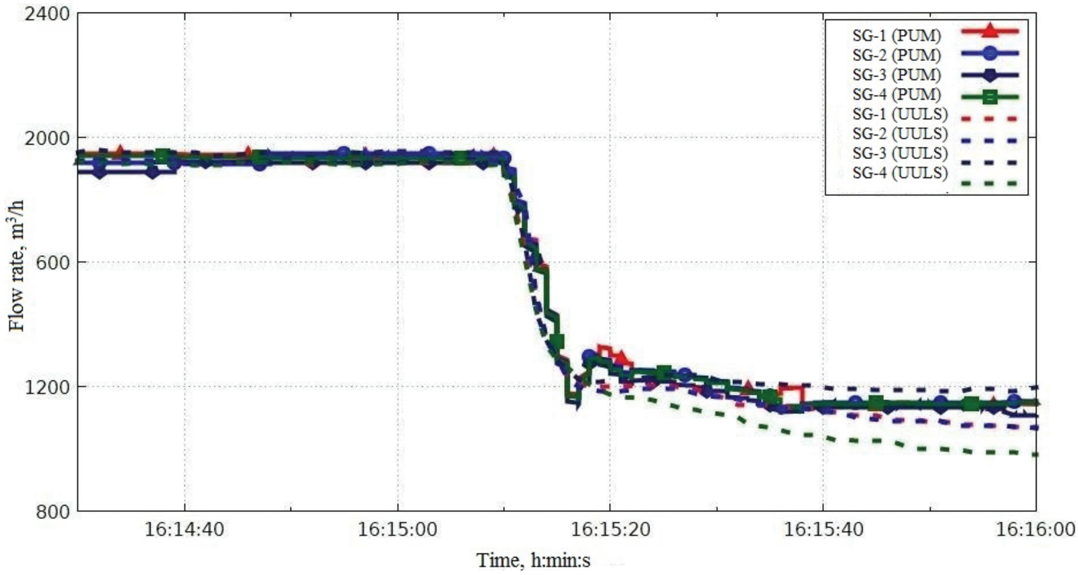

Figure 8. Feed water flow to the steam generators.

the preservation of the dynamic stability of the power unit and stabilization of the process parameters at a stationary level after testing.

Conclusion

The paper considered the course of transient processes during tests on disabling two electrical feed pumps without enabling the backup pump at NvNPP II-1 and 2. The authors analyzed the transient process by means of numerical simulation of NvNPP II-1 and 2 in the power unit model software-hardware complex (PUM SHC).

The tests at Unit 1 and 2 were carried out under different initial conditions, which influenced the achieved process parameters. In particular, Unit 2 had a higher reactor power (by 2.1%), HPH-5, 6 were in operation and, as a result, the feed water at the inlet of the steam generators had a higher temperature (by 55 °C). This led to increased steam generation in the steam generators and, consequently, to the increased total feed water flow through the feed pumps (by 864 m^3/h) in a stationary state.

It was shown that in both cases the dynamic stability of the power unit was preserved. Its operational parameters were within the design limits and did not reach the protection operation set points. In particular, the protection trip setting for disabling the EFP at the maximum flow rate at the head of the pumps remaining in operation is not achieved, which can lead to additional unloading of the power unit or its shutdown by the reactor scram and disconnection from the network.

A comparative analysis of the results of numerical simulation in the PUM SHC with operational data obtained during the tests at NvNPP II-1 and 2 showed the ability to perform calculations of transient modes in abnormal operation, such as disabling of electrical feed pumps, from the initiating event to the power unit stabilization in a stationary state. The results obtained were physically consistent. The changes in the power unit parameters qualitatively corresponded to those observed in the real tests. Some differences observed in the parameters during transient modes did not lead to failure of protections and interlocks implemented at the power unit, and there were no false alarms of protections and interlocks. The power unit parameters in stationary states before the initiating event and after the transient process quantitatively coincided in the calculations obtained using the PUM SHC and in the real tests.

It can be assumed that the PUM SHC will make it possible to obtain reliable forecasts of changes in the power unit parameters, which can be used in the analysis of equipment operation in various modes, for developing proposals for adjusting the control algorithms and checking the correctness of design decisions during the power unit modernization. This assumption requires additional verification of the model's operation in other transient modes of equipment operation.

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