Nucl. Sci. and Tech., Vol.7, No. 1 (2017), pp. 10-20

Nuclear Science and Technology

Journal homepage: https://jnst.vn/index.php/nst

Comparative analysis of reactor coolant pump coastdown transient using VVER-1200 NPP simulator

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Abstract: Verification has been performed to check the VVER-1200 NPP simulator installed at Nuclear training Center, VINATOM by comparing main parameters in nominal power operation with design data given in safety analysis report of VVER-1200/V392M as well as Ninh Thuan FSSAR. A good agreement was found between the VVER-1200 NPP simulator and VVER-1200/V392M. In this study, the reactor coolant coastdown transient is investigated using the VVER-1200 NPP simulator in comparison with SAR documents. The real time feature of the simulator as well as simulated results performed in the simulator through switching off one reactor coolant pump in comparison with VVER-1000 experiments are given. A good agreement between the measured and simulated results shows that the thermal hydraulic characteristics and the control protection systems are modeled in a reasonable way. The analysis gives a good basis for the further studies on the simulator.

Keywords: *real time simulator, human machine interfaces (HMI), VVER reactor, reactor coolant pump, axial offset, control rod bank.*

I. INTRODUCTION

In the design of pressurized water reactor (PWR), the reactor coolant pump (RCP) is an important component in the nuclear steam supply system (NSSS). The RCP forces the coolant through the reactor core and steam generator to maintain a balance of heat transfer in a coolant loop. The operating conditions of the RCP have an important influence on the coolant mass flow rate and thermal behavior of the NSSS. For instant, in accident conditions with loss of power supply, the RCP ensures coolant circulation in the coastdown to permit a smooth transition to the natural circulation mode.

Investigation of flow transients in reactor coolant system due to the RCP coastdown is not only important in the safety analysis, but also in normal operations of VVER as well as Western PWR reactors due to decrease of coolant flow through the core. For PWR, such as KWU PWR design, one RCP trip did not make reactor trip, instead operation is continued at reduced power [1]. However, in Westinghouse design, if a RCP trips at power levels greater than 10^{-4}% of nominal power, a reactor trip will occur [2]. So, operation with one or two RCPs switched off is a noticeable feature of VVER nuclear power plant (NPP). Several reactor operation transients and international benchmarks for investigating and evaluating the RCP switching off and on have been performed based on the VVER-1000 NPPs by switching off one of four working RCPs in commissioning experiment at Balakovo-1 [3], switching off of one of two working feed water pumps in the EU-PHARE SRR 195 project at Balakovo-4 [3], switching on of one from three working RCPs in the EU VALCO project at Kozloduy-6 [3] and switching-off of one of four operating RCPs at Nominal Reactor Power in the Coolant Transient Benchmark – Kalinin-3 (NEA/OECD) [4]. The transients were initiated by switching off / on one RCP when other three RCPs are in operation. Comparison between experimental and computational results is performed to verify

https://doi.org/10.53747/jnst.v7i1.114
Received 13 March 2017, accepted 18 May 2017

the models used in simulation codes. Many experiments and simulations are also carried out by Russian researchers on the VVER-1000/V320 NPPs. In this study, the measurements carried out in Rostov unit-1[5] are used and the results are compared with those obtained in the simulator. It is also noted that the first VVER-1200 NPP has been put into operation since August 2016 [6].

II. VERIFICATION OF SIMULATOR IN NOMINAL POWER OPERATION

VVER-1200 as an evolution of VVER-1000 reactor

According to PSAR and FSSAR of VVER-1200 [7, 8], the reactor is operated with four loops at nominal power. At the reduced power levels of 67%, 50% and 40% the reactor is operated with three loops, two opposite loops and two adjacent loops, respectively.

The VVER-1200 reactor is an evolution of the VVER-1000 reactor. VVER-1200 and NSSS are designed by GidroPress in an attempt to improve the performance and safety of the reactor. The design of VVER-1200 is based on more than 1400 reactor-year experiences in operation of VVER [9]. There are two versions named VVER-1200/V491 and VVER-1200/V392M with different designs of safety systems developed by JSC SPbAEP, St.Peterburg and JSC AtomEnergoProekt, Moscow.

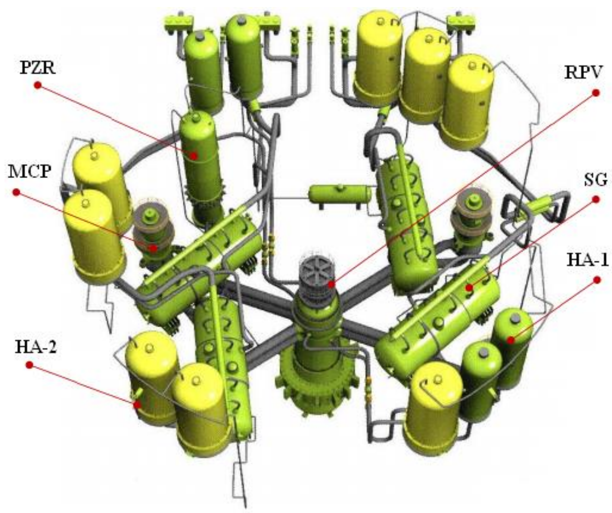

Fig.1. VVER-1200 Nuclear Steam Supply System

The main differences between two designs are the safety systems. For example, in the VVER-1200/V392M design, the safety system consists of two-stage Hydro Accumulators (HA-1 and HA-2) as seen in HMI of the simulator [10] (Fig.2.)

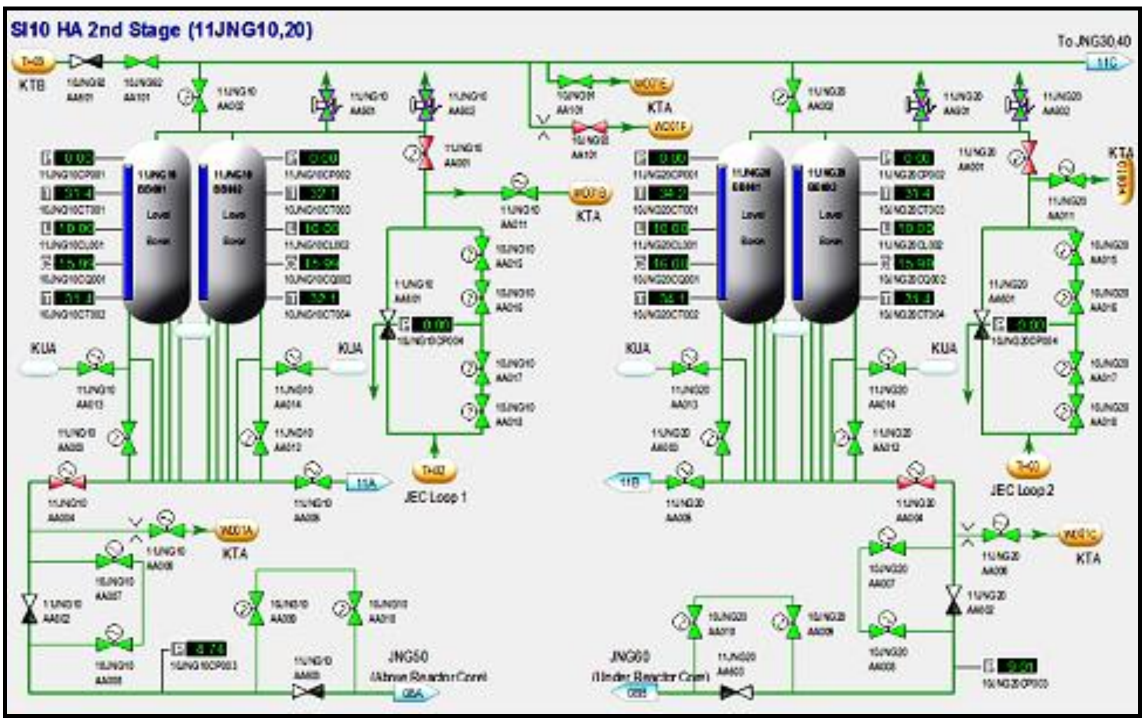

Fig. 2. HMI of second stage Hydro accumulators (HA-2) in the simulator

For the reactor pressure vessel (RPV) of VVER-1200, the major developments based on VVER-1000 are:

- The increase of RPV dimensions provides essential decrease in radiation impact on the RPV wall [11] with the height from 10897 mm to 11185 mm, inner diameter from 4150 mm to 4250 mm and wall thickness (core shell) from 192.5 mm to 197.5 mm. The fuel length changes from 3530 mm to 3730 mm, so that the reactor power increases while the total number of fuel assemblies (FA) in reactor core is kept unchanged (163 FAs).

- In VVER-1000, there are 61 control rods divided into 10 groups (banks) while there are up to 121 control rods divided into 12 groups in VVER-1200 design (Fig.3.). The absorbing materials are B_4C and $Dy_2O_3TiO_2$ while only B_4C used in VVER-1000.

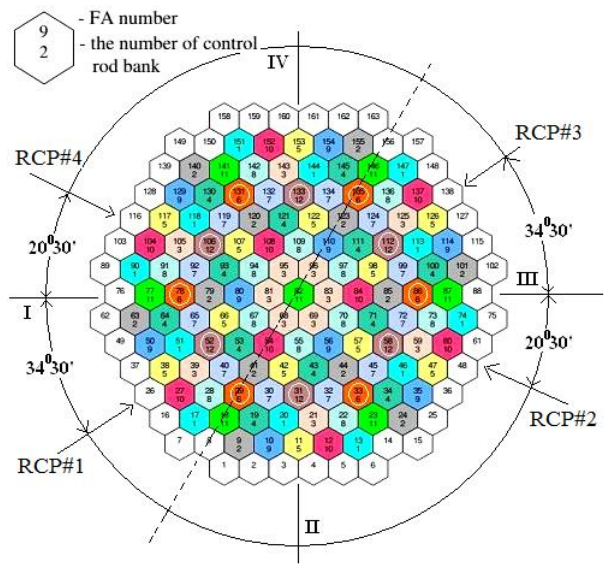

Fig.3. Reactor core with control rod banks (The arrows show the nominal positions of the inlet nozzles)

Technical features of the simulator

In 2010 the Ninh Thuan-1 NPP project had been approved with two units of VVER-1200, there have been several studies performed by VINATOM [12, 13] to study, evaluate and compare between NPP technologies with AES-91, AES-92 and AES-2006.

In the framework of the IAEA TC Project VIE2010 on Developing Nuclear Power Infrastructure, the Generic VVER-1200 Simulator [10] was supplied for Vietnam and installed in the Nuclear Training Center, VINATOM in December 2015. Vietnam Atomic Energy Institute (VINATOM) in cooperation with Vietnam Atomic Energy Agency (VAEA) conducts the utilization of the simulator.

The simulator is supplied by Western Service Co. (WSC), US with 3KEYMASTER™ modeling tools which include 3KEYMASTER™ Instructor Station, reactor core and thermal-hydraulics, Balance of Plant (BOP) simulations using CMS code developed by VNIIAES, Russia. The 3KEYMASTER™ Instructor Station is used to control the simulator and run training scenarios, to monitor and record student and instructor actions. The simulator covers the full range of plant operations from plant cold shutdown to hot standby, hot zero power, and to full range of power maneuvers as well as all possible transients in BOC, MOC and EOC life cycles. These models combine to form the engineering simulator as defined by IAEA [14].

The simulator is operated in real-time mode. The advantage of using a real-time simulator is that user can understand the response of the systems which correctly represents the real system, without delay or limitations as pre-recorded scenarios. In order to check the real-time feature of the simulator, the resulting parameters in the simulator are compared with PSAR[8] and measurements performed in VVER-1000 [5]. It is also noted, that the Russian verified and certified computer codes are used in analysis of thermal hydraulic characteristics to produce the results given in PSAR [8].

The simulator is intended to simulate the VVER-1200/V392M technology [10]. It consists of more than 150 human machine interfaces which represent the technology schemes of NPP. The HMIs cover from component cooling system (CC), containment (CH), condensate pump (CP), reactor core (CR), chemical and volume control system (CVCS), condenser water (CW), electrical systems (ED, EG), feedwater (FW), heating and ventilation system (HV), instrumentation air (IA), main steam (MS), control system (Control), safety systems (RD, SI), service water (SW), turbine systems (TC, TU) and waste processing systems (WD).

Tentative plan for utilization of the simulator is to train staff of related organizations like technical support engineers, operations management and research engineers has been proposed. There were several training courses hold by VAEA and VINATOM to provide practical training in the simulator. The working group was established to devote for the simulator deployment. For the R&D works, it is also useful for strengthening of capacity through carrying out research/study supporting activities such as safety analysis. By using the simulator, an instructor can introduce a malfunction or accident scenarios in the server computer and thereby allowing students to realize the phenomena and propose actions to react to unknown and identify cause and corrective actions. For advanced users like researchers the simulator is also employed in research to evaluate human performance in case of accident scenarios.

The purpose of this work is to verify operation parameters of the simulator to confirm that the VVER-1200/V392M is simulated in the simulator through comparison with VVER-1200 SAR [7, 8]. The real-time simulation was also investigated through switching off one RCP in comparisons with PSAR[8] and experiments conducted in VVER-1000[5] .

Verification of the simulator in nominal power operation

Verification of simulator for normal operation and transients has been performed. To shorten the time to start-up and bring the reactor into critical state and full power operation, the ICs (Initial Condition) are set up so that user can start operate the reactor in predefined scenarios. The beginning of cycle (BOC) is initiated and main parameters for normal operation are reported in Table I. The parameters are in compliance with design data [7, 8]. So, it is expected to ensure that specified learning objectives can be achieved and the simulator performs in accordance with VVER-1200 NPP design. The following section describes a transient with one RCP-coastdown. This is intended to verify a real-time simulation as well as response of the simulator.

III. SIMULATION OF REACTOR COOLANT PUMP COAST-DOWN TRANSIENT

RCP coastdown transient and sequence of events

In the operation of VVER-1200 which permits one or two RCPs to be switched off, the reactor control is equipped with preventive emergency protection system [8]. The signals from the system initiates control protection system (CPS) with control rods and drives will reduce power or prohibit power rise, so that it can avoid the reactor trip and prevent violation of safety limits and conditions. Fast power setback (FPS) system automatically reduces reactor power by insertion of automatic control banks by power setback-1 (PS-1) and prohibits reactor power rise by prohibiting withdrawal of the CPS rods. Fig.4 shows the flow rate of RCP-1391 used in VVER-1200 NPP and its rotation speed when one of the four operating RCPs trips compared with the results obtained in the simulator. RCP#3 as seen in Fig.3 is switched off in the simulator for analysis.

Table I. Comparison of NPP parameters in nominal power operation

Parameter	VVER1200 Simulator	Ninh Thuan Project [7]	NNPP-2 PSAR [8]
Reactor thermal power, MW	3212	3212	3200 + 128
Nominal electric power, MW	1178 - 1183	1186	1198
Reactor Outlet pressure, MPa	15.9÷16.1	16.2 ± 0.3	16.2 ± 0.3
Reactor coolant flow rate, m^3/h	86333±5	88000(+2100-3100)	86000 ± 2900
Reactor coolant inlet temperature, ^0C	297.6	298.2 +2 / -4	298.2 +2 / -4
Reactor coolant outlet temperature, ^0C	328.8	328.6 ± 4	328.9 ± 5
Reactor heat up, ^0C	30.5	30.7	30.7
Pressurizer level, m	8.13 ± 0.01	8.17 ± 0.15	8.17 ± 0.15
SG water level, m	2.7 ± 0.01	2.7 ± 0.05	2.7 ± 0.05
SG steam pressure, MPa	7.0 ± 0.02	7.0 ± 0.1	7.0 ± 0.1
Feed water temperature, ^0C	226.8± 0.15	225 ± 5	225 ± 5
Feed water flow in SG1/2/3/4, t/h	1614÷1668	1602 (+ 112)	1602 (+ 112)
Operation at load of (% Nnom): - 4 RCPs - 3 RCPs - 2 RCPs (opposite) - 2 RCPs (adjacent)	 100% 66% 49.5% 40%	 100% 67% 50% 40%	 100% 67% 50% 40%

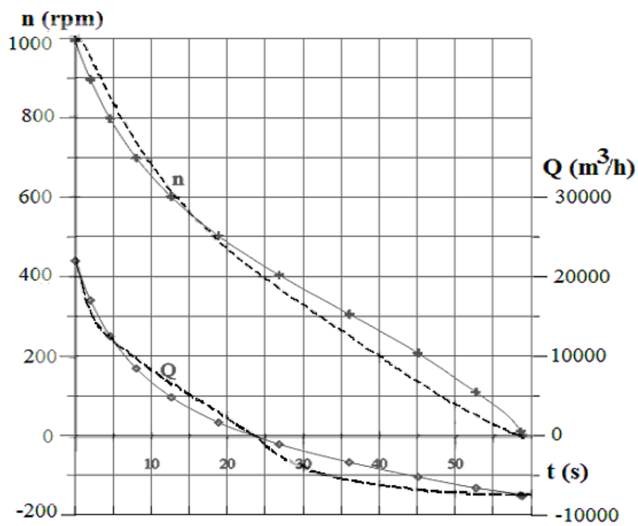

Fig. 4. Mass flow rate of RCP and rotation speed when one of the four operating RCPs trips [8] (dotted lines are obtained from the simulator)

Two seconds after the RCP switch-off, the power control system responded by inserting the control rod bank #7 from top to bottom within four seconds. As a result, the core power decreased down to about 61% of the nominal power within 10s. Also the control rod bank #12 started moving in at a rate of 2 cm/s. The initial axial position was at 317.2 cm. The slow insertion of control rod bank #12 down to an axial position of 281 cm resulted in a further power decrease to about 55% of nominal power. The reactor was stabilized at the level of 64% by the automatic power control with the move up of bank #12 to the position of 327 cm. Due to RCP-3 switch-off, the mass flow rate decreases and then the reverse flow from cold leg to hot leg of this loop is started within 23 seconds. Initially, the primary pressure decreased, later on the primary pressure increased again to maintain the heat balance. The sequence of main events is given in Table II.

Table II. Sequence of main events

Time, s	Event
0	RCP#3 is switched off
2	Control rod bank#7 drops into the core within 4s
3	PZR heater (Group#1) is on
10	Bank#12 moves in at a rate of 2cm/s
13	PZR heaters (Group#3, 4) are on
23	Reverse flow from cold leg to hot leg of loop#3 started
35	Temperature in hot leg #3 decreases lower than cold leg
55	Mass flow rate through reactor core reaches steady state
285	PZR heaters (Group#3, 4) are off
350	PZR water level and core pressure are stabilized
420	End of transient

Variation of operation parameters during transient

The decrease of mass flow rate through reactor core (Fig.5) will make fuel and coolant temperatures slightly higher, resulting in a small negative reactivity insertion within 30 seconds as seen in Fig.6. However, the negative reactivity insertion is resulted by the drop of control rod bank #7 (Fig.7b). From Fig.6, it is seen that the reactivity insertion by control rods get the maximum value of -0.4 %Δk/k within 1.5 seconds.

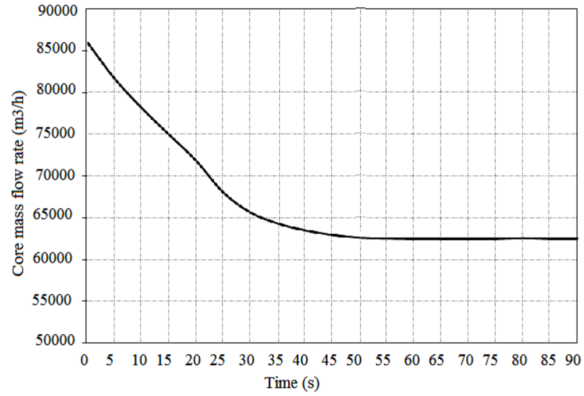

Fig. 5. Coolant mass flow rate through reactor core

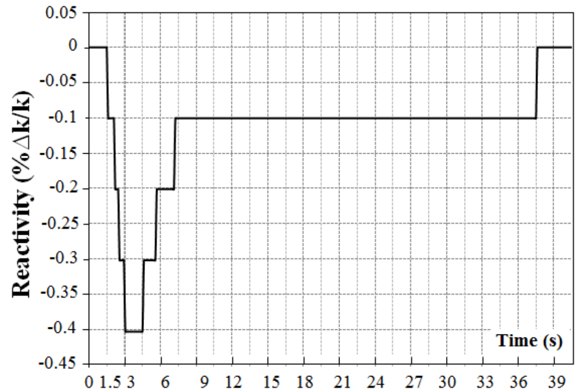

Fig. 6. Variation of reactivity during transient

The most noticeable change is temperature difference for part of core in conjunction with loop #3. It is presented by temperature difference of FAs arranged in line across the core center (dotted line in Fig.3) in Table III. From center of reactor core (FA#82), temperature difference between core inlet and outlet dT(B) in case of RCP #3 switched off has skewed distribution as compared with dT(A) in nominal power operation. Temperature differences between FAs in the region of loop #3 (RCP is switched off) from FA# 96 to FA#156 are about 1^0C higher than opposite FAs in region of loop #1 with RCP still running (FA#8 to #68). This is due to the reverse coolant flow in the loop #3 with non-operated RCP#3. As seen in Fig.9b the temperature in cold leg (inlet nozzle) at first decreases as reactor power decreases. After that it increases due to RCP coastdown finished within 23 seconds and reverse flow through the loop is initiated (Fig.4b.). This results in the decrease of average temperature in upper plenum and difference in the thermal power of SG in the operating loops.

As three main coolant pumps continued operating, the temperature differences between these hot legs and the corresponding cold legs decreased proportionally to the thermal power reduction. Then temperature in the loops stabilized at a new level. The temperature difference between cold legs and hot legs is similar for simulator and VVER-1000 measurements as seen in Fig. 7a.,7b and Fig.9a, 9b, respectively.

Table III. The temperature difference (^{0}C) in FAs across the core

FA No.	dT^1(A)	dT^2(B)	dT [(A)-(B)]
8	31.76	30.87	0.89
18	29.95	26.3	3.65
29	29.96	26.24	3.72
41	29.96	26.38	3.58
54	33.82	31.76	2.06
68	33.88	31.81	2.07
82	33.9	31.82	2.08
96	33.88	31.81	2.07
110	33.82	31.77	2.05
123	29.43	25.47	3.96
135	29.43	25.33	4.1
146	29.42	25.4	4.02
156	30.6	28.86	1.74

1-Operation of 4 RCPs (100% nominal power)
2-Operation of 3 RCPs (66% nominal power)

Real-time simulation of movement of control rod banks

In the design of control and protection systems (CPS), the drives of control rods are grouped into 12 groups (banks) which can be controlled independently. The group banks #1-8 are for protection and banks #9-12 are for control and protection. Banks #9-12 are used to control reactor power following scram or power setback signals sent by automatic controller as mentioned above. When reactor is being operated at the rated power, all of control rod groups are in the top position above the core, except for group #12. At the full power, this bank is maintained within the control range, at the core height from 70 to 95% [8]. This is similar to group #10 in VVER-1000 [5].

The design requirement for control rods drop into the core is from 1.2 to 4.0 seconds after reactor SCRAM actuation [8]. In the transient, bank #7 was fully inserted into the core from 100% to 0% within 4 seconds as observed in the simulator (Fig.9b). According to the measurement system established at the NPP, the positions of control rod bank are given with respect to the position of the lower end switches. In the simulator they are located at 380 cm higher than the bottom of the reactor core. The length of the reactor core is 373 cm (375 cm in hot condition) and the position of control rod corresponds to the bottom of the core. That means at 100% insertion of control rod the indicator is zero as seen in HMI of the simulator.

The difference in movements and positions of control rod banks in VVER-1000 and VVER-1200 should be investigated in more detail. However, it is seen that the position of bank #10 for VVER-1000 changes corresponding to power change (Fig.9a) while in case of VVER-1200 NPP simulator, Fig. 9b shows that the control rod bank #7 dropped into the core to lower the reactor power within 4 seconds and after 10 seconds from first position of 317.2 cm (83%), bank #12 moves down to compensate with power decreasing tendency, then after stabilization of temperature in reactor core bank #12 reached the last stable position of 327 cm (86%). In average, the moving speed of bank #12 is about 2 cm/s and compatible with design [8].

As pointed out above, although there are minor changes in NSSS designs between VVER-1200 and VVER-1000 reactor, the results obtained on the simulator are in good agreement with the experiment and design data.

Axial offset and reactor stability

During normal operation and transients the control rod banks are moved in their control range to maintain power distribution within the predefined limits. The axial offset (AO) is defined as difference between power density in the upper and lower parts of the core with the current reactor power. The value of AO higher than recommended range may result in non-uniformity of the neutron flux and axial xenon oscillations, the occurrence of which will negatively affect the time duration for reaching stabilization of the reactor. Under certain circumstances, non-uniformity of the neutron flux in the reactor core can lead to transient situations. Therefore, for the safety and efficient operation of the reactor it is necessary to minimize the deviation of AO, especially when reactor power is 80% of nominal power or higher [8]. The variation of AO in this case and the limits for VVER reactor [15] are shown in Fig.10a and Fig.10b, respectively. The variation of about ± 0.2% is quite acceptable in comparison with ±5% as recommended.

The mismatching of the turbine-generator load and the reactor power at the beginning of transient results in the change of steam pressure in the SGs and in the main steam line. The vapor pressure change in the SGs is given in Table IV. Three seconds after RCP switched off, as PZR pressure decreased to the set point of heater, heater group #1 is on. The heater groups #3 and #4 are on when set points reached within 13 seconds. This results the increase of primary pressure as seen in Fig.11b. After 30 seconds the heater groups #3 and # 4 are off and primary pressure became stable.

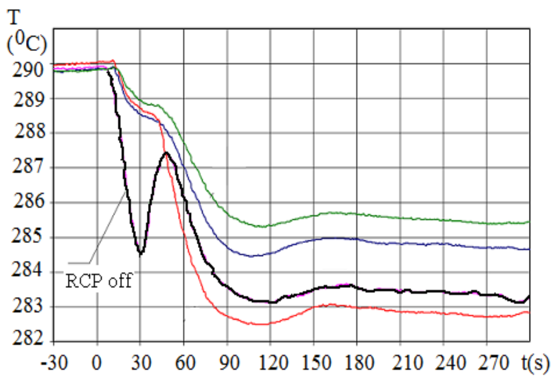

Fig.7a . Changes of coolant average temperature in cold legs measured in VVER-1000[5]

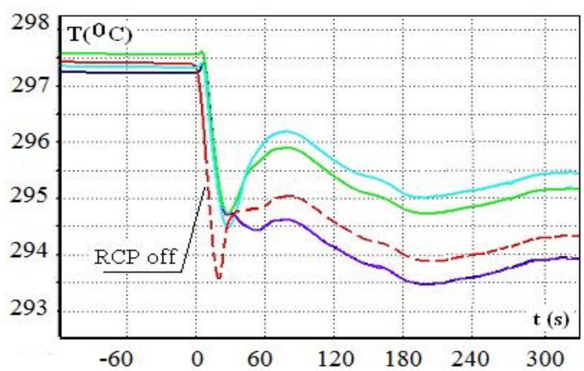

Fig.7b . Changes of coolant average temperature in cold legs simulated by the simulator

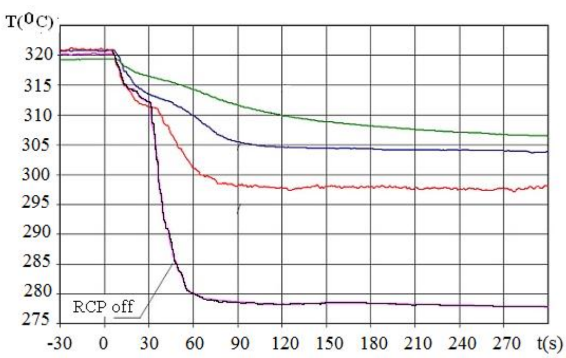

Fig. 8a . Changes of coolant average temperature in hot legs measured in VVER-1000[5]

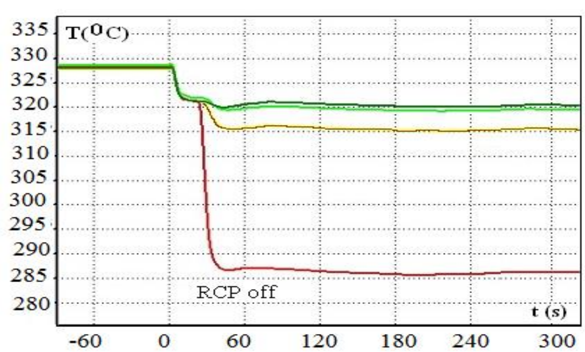

Fig. 8b . Changes of coolant average temperature in hot legs simulated by the simulator

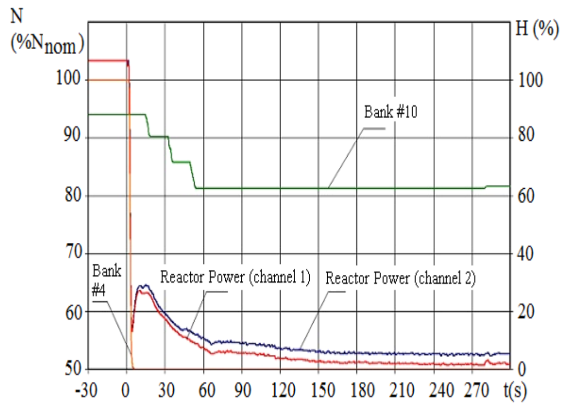

Fig. 9a. Changes of reactor power and positions of CR banks #4 and #10 measured in VVER-1000[5]

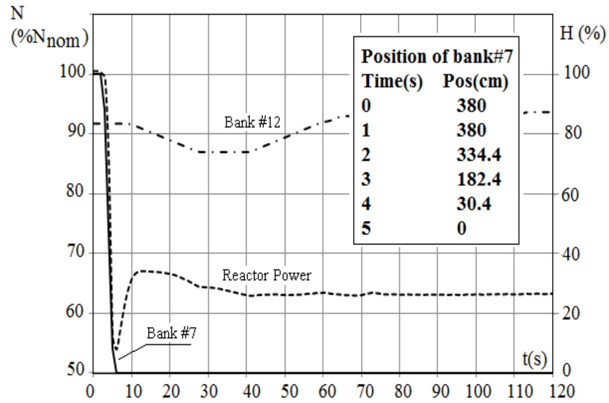

Fig. 9b. Changes of reactor power and positions of CR banks #7 and #12 simulated by the simulator

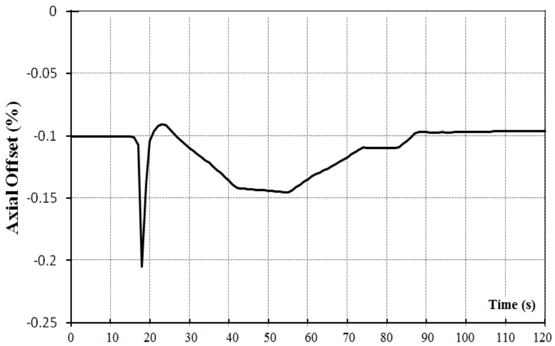

Fig. 10a. Axial Offset in RCP coastdown transient in the simulator.

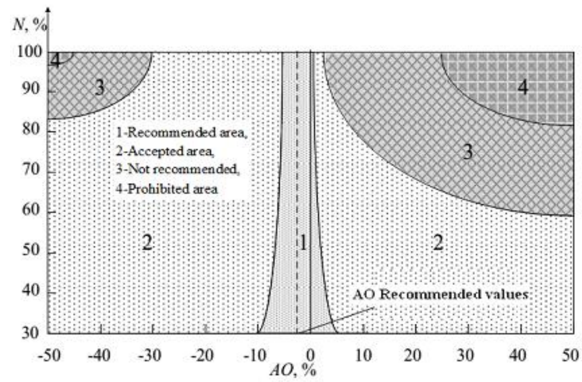

Fig. 10b. Recommended AO domain values depending on the power level of the VVER reactor [15]

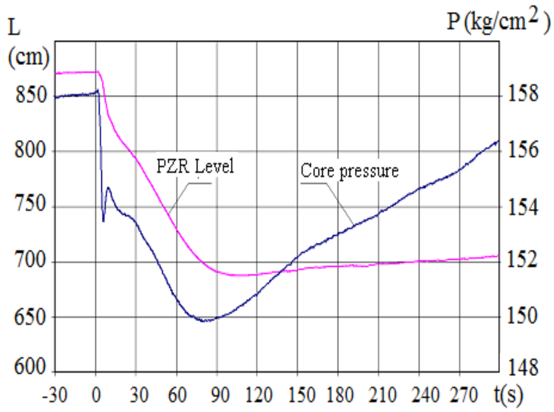

Fig.11a. The changes of water level in PZR and Core pressure measured in VVER-1000[5]

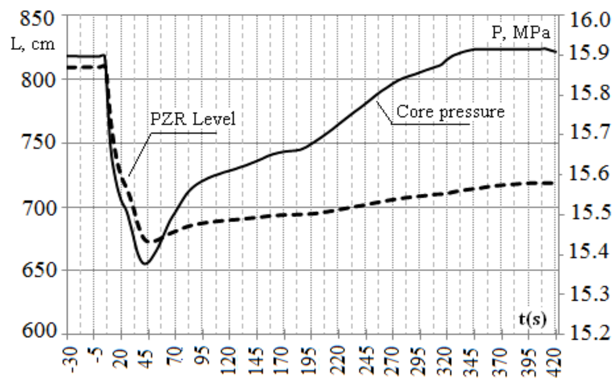

Fig.11b. The changes of water level in PZR and Core pressure simulated by the simulator.

Table IV. Pressure change in the SGs

Parameter	Simulator	PSAR[8]
Loops with operating RCPs, MPa	6.95	7.0
Loop#3 with switched off RCP, MPa	6.78	6.8

The coolant flow through a loop #3 (RCP switched off) into the upper plenum does not influence on the coolant flow on the opposite side due to the fact, that the azimuthal angle between the two neighboring loops of one half is 55°, the angle to the next loop is 125° (Fig. 3).

However, this makes change in upper plenum average temperature due to the reverse flow from cold leg to hot leg of loop #3, especially the change in the upper plenum average temperature results in the change of water level in PZR (Fig. 11a, 11b.).

IV. CONCLUSIONS

The verification has been performed to check the VVER-1200 NPP simulator by comparisons main parameters in nominal power operation with design data given in safety analysis report of VVER-1200/V392M [8] as well as Ninh Thuan FSSAR[7]. A good agreement was found between VVER-1200 NPP simulator and VVER-1200/V392M.

The requirements for power unit load follow operation are high reliability and safety which depend on stability of the reactor in transition from a power level to another one. The changes in thermal hydraulic parameters in the case of RCP-coastdown transient simulated in the simulator are given under comparative analysis with VVER-1000 experiment data [5]. The axial offset which is a quantitative measure of the reactor stability has been investigated to ensure the operation of VVER reactor with one or two RCPs switched off.

The difference in control rod numbers and groups divided in VVER-1000 and VVER-1200 as well as automatic control procedures may lead to the different response of working bank #12 as observed. There is the similar insertion of protection control rod bank #4 (VVER-1000) and bank #7 (VVER-1200). Further studies on the control and protection systems of VVER-1200 should be performed to confirm their validity.

A good agreement in phenomenology between the measured and simulated results shows that the thermal hydraulic characteristics and the control protection system are modeled in a reasonable way in the simulator. This work is expected to be a good basis for further studies using the simulator. A real-time process is verified in which drop time of control rod banks is within a range specified by design. As the results, it is concluded that the implementation of the simulator is not only used for education and training, but also for R&D with better understanding of operation processes and safety systems in modernized VVER nuclear reactors.

ACKNOWLEDGEMENTS

The author would like to thank Oleg Ivanov, WSC, USA and Alexander Markov – Executive Director of Institute of NPP Operation Support, Kiev, Ukraine for their supports and recommendations during working on the simulator. Special thanks is due to the reviewers of Journal of Nuclear Science and Technology (NST), VAES for valuable comments and corrections. Useful discussions with colleagues in the simulator group at Nuclear Training Center, VINATOM are acknowledged. This work was supported by Ministry of Science and Technology of Vietnam under grant number DTCB.13/16/TTNTC.

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