Software model in nuclear power design and control

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Abstract. The paper deals with results of hardware-software complex application in nuclear power units design tasks and control. Critical analyses of existing information systems applied in the global power engineering was made. It was demonstrated that the main task, to be solved, was aimed at parameters monitoring and not processes control in complex. Moreover, all existing systems have distinguished functions resulting in high information load on operating personnel if there is no established managerial decision. Authors proposed the approach based on the power unit software model and respective mathematical simulation hardware for the operating personal support system development and nuclear power units facilities designing. A list of function for such systems was developed. It is demonstrated that the basis of functioning in technological process control tasks is the power unit simulation model enabling modelling under different operation modes. The power unit of the state-of-the art nuclear facility evolves a complicated technical system. For presentation of the power unit formal structure an oriented graph is used. Mathematical model of the power unit process flow diagram presents formalized record of the system digital and logic variables. The power unit model includes a distributed dynamic neutronics reactor core model, one dimension two-phase thermal physical model of processes in the main power unit systems, I&C model. The approach of the software model integration in the design freeze tasks is shown.

1. Introduction
Process I&C of the cutting edge power unit shall be in compliance with safety requirements in the field of nuclear energy. The specific feature of advanced NPP is a huge number of parameters to be controlled, characterizing the power unit operation. Information load on operating personnel at steady operation state is estimated as 30000 events per 24 hours day with maximum possible 288/24 hours day in accordance with GOST R MEK 62682-2019 recommendations. Existing experience of advanced power units operation demonstrates that the operator – controlled facility interface is aimed at parameters monitoring and not processes in complex. NPP designers have a challenging task to create a way for information about current status of NPP safety consolidation, enabling the operation to quickly assess actual situation on the site based on a minimum number of generic parameters and make appropriate decision. However, for the time being the situation is as follows: great number of parameters to be controlled, events and diagnostic messages, lack of procedures for operator actions prevents from timely processing of incoming data and making faultless management decision. Solution of this issue requires
development and implementation of Intelligent decision support system for operating personnel of the main control room (IDSS) [1, 2].

2. Critical overview of existing information systems
At Biblis NPP in Germany in 80-th of the past century the analysis system of abnormal situations STAR [3] was implemented. For detection of abnormal situations so called models of deviations from normal operation modes were used. These include logic models (for instance, cause-effect diagrams), physical analogues (for instance, mass balance, characteristics of systems or components) or mathematical models.

Starting from 90-th of the past century development of emergency operating procedures and BDBA procedures in symptom oriented format started at Russian NPPs in compliance with methodological approach of Westinghouse (USA) and EDF (France). Moreover, procedures on personnel actions in BDBA management may be drawn up only in symptom oriented format.

At Kalinin and Novovoronezh NPP the real-time decision support system for nuclear plants diagnostics SPRINT [4,5] was implemented. SPRINT is the real time decision support system with intelligence search mechanisms, where knowledge was codified in predicate calculus language.

In SPRINT paradigm it is Knowledge + Logical conclusion = Diagnosis. One of the main principles applied in SPRINT-technology is decomposition of the object in component parts, meanwhile, each subsystem has its own data base and knowledge base [6].

After TMI accident Safety Parameters Display System (SPDS) was established, which was aimed at keeping track of critical safety functions and operator support in restoration of adequate level of these functions execution. Implementation of such systems made a reach to one more task – computerization of symptom based emergency procedures, intended for restoration of critical safety functions. Therefore, SPDS and computerized procedures were the first industrial samples of intelligent decision support system for operating personnel of the MCR in the USA at the beginning of 1980s.

For Unit 6 of Novovoronezh NPP within upper level unit control system an additional SPDS function was implemented, assuring continuous monitoring of the power unit safety barriers (the fuel matrix and fuel assembly, primary circuit and containment), predicting provision of information for operating personnel about the risk of failure of any safety barrier and provision of information how to cope in the optimal way with the situation arisen [7].

All considered above systems fulfil different functions. However there is no standardization of tasks to be solved, workload on operating personnel remains high and more important that out-of-the-box solutions for personnel actions in critical situations are not available.

3. Recommended list of functions of intelligent decision support system for operating personnel of the SSOP
Within RTD implementation plan of Rosenergoatom the following functions list of intelligent decision support system for operating personnel of the IDSS functions was developed:

- identification of the power unit mode (levels of defense-in-depth) and the power unit state;
- calculation of alarms set points depending on current state of the power unit;
- monitoring of operational limits and operational conditions, limits and conditions of safe operation;
- monitoring of the unit main equipment conditions;
- monitoring of safety systems;
- monitoring of equipment automatic control;
- forecast of the main technological process by means of the power unit model;
- provision to the operating personnel with interactive instructions for procedures of unit start-up/shutdown, putting in operation / putting out of operation, routine checks, try outs and testing, interactive analogue of actual emergency operating procedures and BDBA management procedures;
• online operational logbooks generation;
• provision to the operator of reference information about possible causes of alarms at the MCR panels (alarm response);
• suppression of outdated secondary alarms, being consequence of the primary alarm;
• recommendations on optimization of plant process control.

4. Simulation of the plant processes
The basis for intelligent decision support system for operating personnel of the IDSS functioning in tasks of the plant processes control is the power unit simulation model [8,9,10]. For simulation of the facility formal structure an oriented graph is used. Graph nodes are equipment incorporated in the flow diagram. Orientation of the graph arc coincides with coolants flow direction and mechanical, thermal and electrical power transfer in the plant process links. Mathematical model of the unit flow diagram is a formal record of the system digital and logical variables [11, 12].

The power unit model incorporates:

• distributed dynamic neutronics reactor core model;
• one dimension two phase thermophysical model of processes behavior in the main power unit systems;
• model of automatic control system of plant processes.

A specific trait of the design of reactor plants is the mutual influence of neutronics and thermophysical processes in the core. This leads to the need for conjugate calculations, when the results of neutron-physical calculations become output parameters for thermophysical calculations and vice versa. In addition to this, various regulatory influences from the Process I&C have an impact on both neutron-physical and thermophysical processes. As a result, the procedure for calculating the evolution of the physical processes of the power unit looks like a sequential cyclical call of all three calculated components of the mathematical model (figure 1). At the end of the calculation cycle, it returns to the beginning of the cycle and starts the next cycle. The characteristic value of the depth of calculation in time for one cycle is 0.1 seconds.

![Figure 1. Diagram of the basic calculation cycle.](image)

It is necessary to initialize the initial state of the power unit model for the forecast calculation. Data packages generated by the Digital Control System (DCS) are used for initialization. The last data packet received from the DCS and one of the packets recorded in the archive can be used as an initializing one. Data packets are formed in DCS and sent to the power unit model with a frequency of 1 time per second and recorded in the archive.

The response time of the mathematical model depends on the performance of the equipment on which the power unit model is implemented, however, in any case, the response time is rather higher than the real time.
4.1. Reactor core neutronics
The power unit model allows choosing one of the following models of the reactor core:

- point model of the core considering the reactor in point approximation;
- distributed neutronics model of the core.

The point model of neutron kinetics is used to simulate such transient modes of the power unit, in which the nonuniformity of the neutron field, and, consequently, the energy release field over the core does not affect ongoing processes significantly.

The distributed neutron-physical model of the core is implemented on the basis of the SVS-kr software complex, which includes software complexes SVL and SVC. The SVL software complex is designed to set neutron-physical constants. SVC software complex is used for three-dimensional neutronics calculation of the reactor core.

Discretization of the core for a three-dimensional neutronics calculation is performed on an assembly-by-assembly basis. Each fuel assembly is divided into 16 sections along the height. Since the core contains 163 fuel assemblies, the design model of the core consists of 2608 design prisms.

4.2. Thermohydraulic model
The thermohydraulic model is based on a self-engineered computer code. The computer code implements a one-dimensional two-phase thermophysical model that covers the main processes occurring in the power unit systems. The system of main equations describing the processes of heat and mass transfer in the first and second circuits of the power unit can be written as follows.

Continuity equation:

\[
\frac{\partial \alpha \rho_f}{\partial t} = -\text{div}(p_j v_f) \tag{1}
\]

\[
\frac{\partial (1-\alpha) \rho_g}{\partial t} = -\text{div}(p_g v_g) + \Gamma \tag{2}
\]

\[
\frac{\partial \rho_f v_f}{\partial t} = -\text{div}(p_f v_f \otimes v_f) + D_f - \nabla \rho - \rho \gamma_f \tag{3}
\]

\[
\frac{\partial \rho_g v_g}{\partial t} = -\text{div}(p_g v_g \otimes v_g) + D_g - \nabla \rho \tag{4}
\]

The momentum conservation equation (Navier-Stokes equation):

\[
\rho_f \frac{\partial h_f}{\partial t} = -\left(\rho_f v_f \nabla h_f\right) + Z_{\eta f} + \alpha \frac{\partial \rho_f}{\partial t} - Z_{\gamma f} \tag{5}
\]

\[
\rho_g (1-\alpha) \frac{\partial h_g}{\partial t} = -\left(\rho_g v_g \nabla h_g\right) + Z_{\eta g} + (1-\alpha) \frac{\partial \rho_g}{\partial t} - Z_{\gamma g} \tag{6}
\]

where \( v \) – velocity; \( \rho \) – density; \( \alpha \) – water volume ratio; \( \Gamma \) – interphase mass transfer; \( P \) – pressure; \( h \) – enthalpy; \( \lambda \) – thermal conductivity; \( \mu \) – coefficient of dynamic viscosity; \( T \) – temperature; \( D \) – dissipative term; \( Z_{\eta} \) – term that takes into account heat transfer through the wall and interfacial heat transfer; \( Z_{\gamma} \) – term that takes into account heat transfer when the phase state changes; \( g \) – free-fall acceleration; \( f, g \) – indices for liquid and vapor phases, respectively.

Due to the fact that the equations to be solved are non-stationary, the resulting solution is a set of states of the considered system for different time slices to an optional projection horizon forward from some given initial state. These equations after discretization are solved using numerical methods.
4.3. Process I&C model

The Process I&C model is implemented on the basis of a single program module that calculates the behavior of model control and monitoring schemes. A set of design diagrams for the APCS model is generated using the diagram editor, which is an integral part of the software environment “KRUIZ”. Sets of jointly compiled circuits reproduce the algorithms of operation of the main controllers of the power unit, as well as protections and interlocks. The calculation schemes are formed on the basis of GET schemes, as well as the engineering design of the power unit's Process I&C and the documentation of the General Designer of the reactor plant, therefore the Process I&C model as a whole repeats the logic laid down in the Process I&C of the power unit. The total number of the calculation models for the control system is 1000 pieces approximately. It is important to note that the algorithms for the operation of the power unit controllers embedded into the program model of the power unit have been verified based on commissioning results.

5. Application of the power unit programming model in the design freeze

The operating experience of NPP power units has shown that design conditions under normal technological processes and case of process upset often evolutes by an abnormal scenario. In this regard, studies with the aim of developing measures to improve the dynamic stability of NPP power units in modes of anticipated operational occurrences, as well as expert and design analyzes to justify the selection of the optimal algorithms for process protections and interlocks and ensuring reliability of the control systems are highly relevant.

In the "Forecast" mode, the power unit model can be used for the initial check of the Functional group control. It is proposed to form new, or adapt the existing Functional group control, and then test them on the model to establish the necessary time delays, as well as to optimize the number of switchovers.

Functional group control algorithms are based on stepwise principle. The whole process (startup, shutdown, mode-to-mode transfer) is divided into a number of stages (steps). The end of each step is specified by certain parameter values and the state of the unit set or the time passed since the previous operation. The operation of any Functional group control algorithms can be simulated using the software model of the power unit (figure 2).

![Figure 2. Integration of the software model into the tasks of design freeze.](image)

The power unit software model is a tool to improve design aspects related to the upgrade of equipment piping schemes, or a fundamental change in the heat diagram of various process systems. It is important to take into account that mathematical model of the power unit was validated by the operational data of the real power units.
6. Conclusion
The approach mentioned in this paper, based on the deployment of the program model of the power unit, makes it possible to expand the information support for decision-making in the challenging tasks for design and control of the nuclear power plants. The mathematical tools deployed make it possible to introduce an intellectual component into these challenges, thus minimizing the load onto the operating personnel and increasing level of safety of the plants under design and in operation. In addition, the function to predict abnormal evolution and generate necessary decisions automatically form a basis for the intelligent nuclear engineering.

References
[1] Danilov A, Povarov V, Burkovsky V, Podvalny S and Gusev K 2018 Intellectual decision-making system in the context of potentially dangerous nuclear power facilities MATEC Web of Conferences Volume 161 02009
[2] Povarov V, Danilov A, Burkovsky V and Gusev K 2018 Data support system for controlling decentralised nuclear power industry facilities through uninterruptible condition monitoring MATEC Web of Conferences Volume 161 02012
[3] Buettner V A 1985 Use of advanced computer-based auxiliary systems by German NPP operators IAEA Bulletin Autumn 15-20
[4] Gelovani V A 2001 Intelligent decision support systems in emergency situations using information about the state of the natural environment (Moscow: Editorial URSS) p 304
[5] Bashlykov A A and Eremeev A P 1994 Expert decision support systems in power engineering (Moscow: MPEI publishing house) p 216
[6] Povarov V P, Bakirov M B and Danilov A D 2017 Automated system of multiparametric monitoring of parameters of the state of nuclear power plants (Voronezh: Science book publishing house) p 245
[7] Terekhov D V, Sidorenko E V and Danilov A D 2017 Development trends of modern automated process control systems at Novovoronezh NPP Izvestiya Wysshikh Uchebnykh Zawedeniy: Yadernaya Energetika 3 66-76
[8] Lavrentiev D V and Tverskoy Yu S 2015 Mathematical model of the first circuit of an NPP power unit with a VVER-1000 reactor and estimation of its dynamic accuracy in variable modes IGEU Bulletin 6 1-12
[9] Zhukavin A P and Lebedev A O 2011 Using mathematical models of a power unit for testing the algorithms of control systems for the Kudankulam nuclear power station Thermal Engineering 5 399-403
[10] Zhukavin A P, Kroshilin A E and Fuks R L 2010 Development and verification of models used in training simulators for nuclear power stations Thermal Engineering 5 400-5
[11] Kothe D 2011 CASL and the virtual reactor Nuclear News March 88-90
[12] Larzelere A R 2009 Nuclear energy advanced modeling and simulation (NEAMS) https://www.energy.gov/sites/prod/files/NEAC042910-NEAM.pdf