Concept of instrumentation of digital twins of nuclear power plants units as observers for digital NPP I&C system

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Abstract. The relevance of the idea under consideration lies in the development of the use of digital twins of power units in the nuclear industry. With their help, we can not only predict the state of technological equipment, etc., but also solve the problem of parameter tuning of automatic regulators in different operating modes of NPP unit. Authors consider approaches to this problem based on optimal control theory, fuzzy logic and machine learning. Advantages and disadvantages of each approach are considered.

1. Introduction
The history of the use of mathematical modelling in science and engineering dates back several centuries. Even at the end of the 17th and the beginning of the 18th centuries, the problem of justifying the use of mathematical construction in mathematics arose [1]. At present days, it is difficult to imagine any field of science that does not use mathematical modelling - from building models of the Universe at time close to a big bang and ending with building social models describing the dynamics of behaviour of various social groups.

In the development of technical systems, mathematical modelling is used as the basis of model-oriented design at all stages of the system life cycle. Design engineer model as individual elements of the system, so and their work together. In the field of nuclear energy, this approach is also used to justify the safety of designed nuclear power plants, estimate the quality of technical projects, design safety systems, etc.

Application computing codes have been developed and are being used in nuclear power engineering in Russia and around the world. As a rule, these codes are oriented at a narrow range of tasks and intended for solving specific individual problems encountered in the NPP lifecycle. Many of these programs have not been integrated with the modern design and 3D modelling tools; as a result, conversion of design data into the format of initial data involves considerable efforts and may entail additional errors. As is well known, NPPs must comply with very stringent safety requirements, which are fulfilled primarily owing to appropriate design solutions. Until recently, only separate design solutions have been verified in constructing NPP power units by testing these solutions on models built in training simulators and on analytical mathematical models. This approach turned to be quite efficient because a lot of design errors were revealed and removed through its use. It is exactly the

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possibility to rectify the non-conformances revealed on a computer model and not in a real plant that confirmed practical advisability of carrying out such activity in the entire stage of designing an NPP power unit [2].

2. Virtual digital NPP and digital twin of NPP unit

2.1. Virtual digital NPP

With development of supercomputers, conditions have emerged for constructing the “Virtual Digital VVERBased NPP” unified computerized system and for carrying out a comprehensive calculated verification of solutions adopted in designing NPP power units and in substantiating their safety. Works on constructing this computerized system (CS) were commenced at the AllRussian Research Institute for Nuclear Power Plants Operation (VNIIAES) in the mid-2010th. In the first stage, the demonstration version of the CS was developed in 2011.

The demonstration version of the CS has shown the possibility in principle to set up a unified system of computation codes running in a common software environment and aimed at carrying out interconnected calculation of various physical phenomena at NPPs constructed according to the standard AES 2006 project. The demonstration version, which was developed jointly with the Nuclear Safety Institute of the Russian Academy of Sciences (IBRAE RAN), has been implemented on a single platform but in two versions: the design and the research ones. The design version uses the technologies and software products applied in constructing full scale NPP training simulators, and the research version incorporates software products developed on the basis of detailed modelling of a wide range of physical processes and phenomena occurring in NPP systems and equipment, also with due regard of 3D effects. The design and the research versions run independently on one supercomputer.

The CS design version is a high speed one and allows its users to obtain information on the project and on all of its changes in the online mode with subsequent processing and rendering computation support in the online mode or in an accelerated mode. At the same time, the CS design version is a full scale one; i.e., it allows the user to model all power unit process systems and the power unit as a whole with a high level of accuracy commensurable with that used in substantiating the NPP safety.

The main purpose of the CS design version is to render computation support to the power unit of a VVERBased NPP throughout its entire lifecycle (development of the basic and working design documentation, subsequent modernizations, introduction of new technical solutions and systems, and problems encountered in the course of operation), including the following tasks:
— verifying the design solutions adopted for individual process systems;
— verifying the monitoring and control systems during NPP operation;
— carrying out a preliminary safety analysis of the NPP project.

The application field of the CS design version can be extended to incorporate the following functions:
— checking new technical solutions at the power unit modernization stages throughout the entire service life;
— elaborating accident management guides;
— checking the efficiency of safety systems; and
— carrying out an analysis of incidents [2].

The design version will be used in project “Proryv” - one of the major advanced global projects in the nuclear power sector that is implemented in Russia by the leading sectorial scientists and specialists that provides for creation of the new generation nuclear power technologies on the basis of closed nuclear fuel cycle using fast neutron reactors [3], [4]. The main purpose for which the CS research version is developed is to construct a platform independent and alienable software system suitable for further development and modification in systems for collectively developing computation codes and
oriented at using a supercomputer [2]. However, mathematic models using in virtual digital NPP can be used not only for verification and validation of technical project.

2.2. NPP unit digital twin

The digital twin (DT) is one of the most promising technologies in the new technical revolution. A DT is a link between the physical reality and the cyberspace. Currently, the awareness and acceptance of this technology is growing both by research institutes and by industry, which is reflected in its implementation in various industries [5]. Digital twins are used by such large companies as General Electric and Tesla. There are concepts of digital twins of different cities [6].

Digital twin is a software analogue of a physical device that simulates internal processes, technical characteristics and behaviour of a real object under the influence of interference and the environment. An important feature of the digital twin is that the information from the sensors of a real device operating in parallel is used to assign input influences to it. Further, it is possible to compare the information of virtual sensors of the digital twin with the sensors of a real device, identifying anomalies and their causes.

DT of a NPP unit can be used for solving various tasks at all stages of the unit’s life cycle - for example, testing and improving control algorithms, diagnosing the state of technological equipment (pumps, electric motors, pipeline valves, etc.), testing programs of load following modes [7], etc. One of the most important tasks that the digital twin of the unit can help to solve is setting up automatic regulators of NPP unit at the stage of commissioning and in different operating modes. This is due to the fact that in various operating modes technological equipment is actually different control objects. For example, reactor reactivity effects, which are self-regulating properties, exert only in the energy range of power. Since the vast majority of regulators at nuclear power plants are variations of the classical PID controller, their parameters in different operating modes need to be dynamically changed. If we consider that each unit, even with the same reactor unit project, is unique (different amounts of technological equipment in the same places, different locations of the same control points, etc.), then this task is relevant for the start-up of each power unit. At present days, this task can be solved with the help of analytical simulators, however, often at the stage of commissioning, significant changes are made to the technical design, which leads to the fact that the analytical simulator does not correspond to the unit and needs to be improved. Thus, it is necessary to implement a software module into digital twins, which, on the basis of data from the sensors of the block entering DT, would allow to quickly find new values of parameters of automatic regulators. Within boundaries of this task, the DT of the block is a classic observer for control systems with which help it is possible to obtain estimates of the components of the state vector that cannot be measured directly for various reasons [8]. The DT of the unit is an observer as for individual automatic control circuits, and so as for the whole digital I&C system of NPP. Accordingly, it is necessary to implement a software module either on the basis of methods of the theory of optimal control, or using “intelligent” tuning blocks in order to improve the process of regulating the technological parameters of the unit.

3. Implementation variants of dynamic auto tune module

3.1. Auto tune module based on optimal control theory

The theory of optimal control presumes the synthesis of regulator parameters based on various quality criteria (overshoot, degree of oscillation, various integral criteria, etc.) [9]. However, the NPP power unit is a complex, multi-loop and nonlinear control object (this also applies to the subsystems of the NPP I&C system - for example, control system of feedwater lever in steam generator), therefore it is impossible to take into account all disturbances that have significant influence on the quality of control. Also, additional complexity is caused by the fact that the regulator needs to be configured for
different operating modes of the power unit - the nominal power level, MCRP (minimum controller reactor power), etc. In view of the complexity of this task, for some control loops, there are two regulators — routine and starting-stopping (for example, the automatic control circuit of the coolant level in the pressurizer). It is also necessary to take into account the mutual influence of control loops on each other in different modes. Also, far from all the interrelationships are obvious (which at one time led to the tragic accident at the Chernobyl NPP), therefore, the solution of the set task using the optimal control theory looks rather difficult. It is advisable to use "intelligent" methods of automatic regulators tuning.

3.2. “Intelligent” dynamic auto tune modules

The main two methods of “intelligent” regulators tuning are fuzzy logic and machine learning. The approach using fuzzy logic to solve the problem under consideration has almost the same drawbacks as the approach discussed in subsection 2.1 – expert needs not only extensive operational experience on various units, but also a great understanding of the design of all technological equipment of a power unit, which is expressed in a very large number of rules. At the same time, it is very difficult to tune the parameters of a fuzzy block - the more rules, the more difficult the setting [10].

Therefore, the use of machine learning to solve problem under consideration looks promising. Types of machine learning can be classified in various ways: supervised/unsupervised learning, batch and online learning, instance-based and model-based learning, deep learning, learning with reinforcements, etc. [11]. Each of these methods has its advantages and disadvantages. However, we can use the experience of developers of such systems in other branches of industry to simplify the searching process for a solution.

The explosion of machine learning popularity occurred after the publication of an article by Jeffrey Hinton et al. in 2006, in which authors showed how to train a deep neural network. Now the deep learning method is used to solve a large number of tasks - from the tasks of image classification and the issuance of personal recommendations to the buyer to the tasks of developing the autopilot of a car, etc. The main problems associated with the use of deep learning are the long learning time of the network with a large number of hidden layers of neurons and the high risk of retraining the model on the training set. Hinton provides several ways to resolve these difficulties in [11]. Incredible results are obtained by combining the methods of deep learning and learning with reinforcement. The most famous example of such a network is the development by the DeepMind startup the AlphaGo program, which won the world Go champion. Despite the fact that reinforcement learning is a rather old approach (it appeared in the 1950s), this is the most promising method in conjunction with deep learning. In fact, a control system built on the basis of training with reinforcement is an optimal control system for several criteria of the quality of the transient process. Thus, this approach can be applied to the problem of dynamic tuning of automatic regulators using the DT of the NPP unit as an observer.

However, deep learning with reinforcement has the following problem — a working environment is necessary for network training. And the following fundamental difficulty, which is relevant at the real moment, prevents the training of the network on the real equipment of the station — no one knows how a neural network with a large number of hidden layers makes decisions. We need more than just a glimpse into the AI’s thinking, and there’s no simple solution. It is the interaction of computations within the deep neural network that is crucial for making complex decisions, but these computations are the web of mathematical functions and variables [12]. This leads to the question of whether something unforeseen happens in modes with violation of conditions of normal operation of a power unit. This moment is the main difficulty for the implementation of this idea on any unit, but does not prevent to develop a neural network to solve the problem under consideration. Yes, we can’t train the network on a real power unit for security reasons. And the digital twin for these tasks is also not
suitable, since in its essence it is part of a real physical system. However, it is possible to simulate the physical environment under study. And as part of the task of tuning the parameters of automatic regulators of NPP power units, we can use either analytical simulators of various units (plus, we can add NPP unit archives), or the hardware-software complex Virtual-Digital NPP described above. This concept can help to solve not only the problem under consideration, but also help optimize the process of generating electricity in an unexpected way.

4. Conclusion

The relevance of the idea under consideration lies in the development of the use of digital twins of power units in the nuclear industry. With their help, we can not only predict the state of technological equipment, etc., but also solve the problem of parameter tuning of automatic regulators in different operating modes of NPP unit. To solve this problem, we can apply "intelligent" control systems based on fuzzy logic and neural networks, and also the theory of optimal control. The NPP unit is a multi-loop and nonlinear control object, which leads to the large labour intensity of designing rules for control systems based on fuzzy logic and to the high complexity of fast numerical synthesis of parameters of automatic regulators using the optimal control theory. However, using a combination of machine learning techniques such as deep learning and learning with reinforcement can solve this problem. This approach is complicated by the fact that due to the large number of hidden layers it is impossible to explain how the neural network makes decisions. Since the NPP has high safety requirements, it is not possible to use such a tool on a real unit at the real moment. However, it is possible to solve the problem of network training with the help of analytical simulators with testing of the network operation on full-scale simulators or on a hardware-software complex of a virtual-digital NPP. In the future, this may give impetus to the use of machine learning in such a conservative industry as nuclear energy.

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