Adaptive Neural Network Algorithm for Power Control in Nuclear Power Plants

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Abstract. The aim of this paper is to design, test and evaluate a prototype of an adaptive neural network algorithm for the power controlling system of a nuclear power plant. The task of power control in nuclear reactors is one of the fundamental tasks in this field. Therefore, researches are constantly conducted to ameliorate the power reactor control process. Currently, in the Department of Automation in the National Research Nuclear University (NRNU) MEPhI, numerous studies are utilizing various methodologies of artificial intelligence (expert systems, neural networks, fuzzy systems and genetic algorithms) to enhance the performance, safety, efficiency and reliability of nuclear power plants. In particular, a study of an adaptive artificial intelligent power regulator in the control systems of nuclear power reactors is being undertaken to enhance performance and to minimize the output error of the Automatic Power Controller (APC) on the grounds of a multifunctional computer analyzer (simulator) of the Water-Water Energetic Reactor known as Vodo-Vodyanoi Energetichesky Reaktor (VVER) in Russian. In this paper, a block diagram of an adaptive reactor power controller was built on the basis of an intelligent control algorithm. When implementing intelligent neural network principles, it is possible to improve the quality and dynamic of any control system in accordance with the principles of adaptive control. It is common knowledge that an adaptive control system permits adjusting the controller's parameters according to the transitions in the characteristics of the control object or external disturbances. In this project, it is demonstrated that the propitious options for an automatic power controller in nuclear power plants is a control system constructed on intelligent neural network algorithms.

1. Overview
Adaptive control, being one of the primary tasks of intelligent control principles, was created to ensure the quality of the control process in conditions of non-stationary parameters of the control object. Therefore, modern researchers use adaptive controls which are characterized by the ability to correct the parameters depending on the level of external disturbances and the current state of the control object. The process of adaptation of any technical system can be divided into two phases; firstly, to compile information about the state of the control object and secondly, to determine the control parameters of the system. In the former stage, the collection of the system information and the operational analysis regarding the status of the inputs and outputs of the control object, as well as the levels of environmental disturbances are determined. The latter stage is to define the controlling parameters by minimizing the selected quality criteria. For each adaptive control system a designer should ascertain the objectives of the system according to an adaptation strategy as a whole. However, the purpose of an adaptive control system for some difficult and dangerous objects which are under the
influence of non-stationary disturbances of the environment, is extremely difficult to be determined in quantitative terms. In this case human factors in the control process of the dynamic object play a crucial role by identifying the correct solution as qualitative assessments and to retain and achieve the goal of the control algorithm expeditiously. This corroborates the effectiveness of these algorithms and the necessity of building control systems and mechanisms based on artificial intelligent principles.

The main features of intelligent control systems are the ability to learn, self-organize and change behavior but more specifically, according to the change in circumstances, by using mechanisms similar to those of the human mind which is based on how to learn and how to use the experience attained in the future [1].

Data for design, test and evaluation of the adaptive system for the APC reactor will be obtained from the multifunctional simulated computer analyzer of the VVER. The analyzer of operating nuclear power is a full scope, high fidelity and certified simulator for those types of reactors [2]. MATLAB and Neural Network Toolbox (software provided by MathWorks Inc) will be used for designing and modeling the system.

2. Introduction

A traditional approach to design any adaptive control system is to obtain the initial characteristics of the control system and subsequently perform an analysis to determine their nature. Secondly, based on the results of the analysis, a suitable adaptive strategy should be suggested to improve the quality of the regulation process.

2.1. Methodology and tools used in the project

The analysis of the adaptive control system was conducted under varied settings of the APC in the multifunctional computer analyzer of the VVER, which allows changing the complete controller’s parameters for the purpose of researching and analyzing the functioning principle of the entire system. Figure 1 illustrates the interface of the automatic power controller’s parameters, such as the amplification gain $K$, the dead band $Z$ and the external perturbations (increment value of the reactor reactivity) or disturbances $A$.

![Figure 1](image-url)
Values of steady state error \textit{Epsilon} of the reactor power $P$ were obtained at various reactor power levels with diversity of the controller’s settings. This data is considered as a database for design, test and evaluation of the entire project. Table 1 illustrates part of the experimental results of the multifunctional simulated computer analyzer.

\textbf{Table 1.} Experimental results for the multifunctional computer analyzer of reactor VVER 1000.

| $P_d$ | $K$ | $Z$ | $A$ | Epsilon | $P_r$ |
|------|-----|-----|-----|---------|-------|
| 90   | 0.1 | 1   | 3   | 2.45    | 92.45 |
| 90   | 0.1 | 1   | 2   | 1.58    | 91.58 |
| 90   | 0.1 | 1   | -3  | -2.08   | 87.92 |
| 90   | 0.1 | 1   | -2  | -1.27   | 88.73 |
| 90   | 0.1 | 2   | 3   | 1.86    | 91.86 |
| 90   | 0.1 | 2   | 2   | 1.56    | 91.56 |
| 90   | 0.1 | 2   | -3  | -2.59   | 87.41 |
| 90   | 0.1 | 2   | -2  | -1.75   | 88.25 |
| 90   | 0.1 | 3   | 3   | 2.44    | 92.44 |
| 90   | 0.1 | 3   | 2   | 1.66    | 91.66 |
| 90   | 0.1 | 3   | -3  | -2.53   | 87.47 |
| 90   | 0.1 | 3   | -2  | -1.82   | 88.18 |
| 90   | 1   | 0.1 | -3  | -2.07   | 87.93 |
| 90   | 1   | 0.1 | -2  | -1.25   | 88.75 |
| 90   | 1   | 0.5 | 3   | 0.2     | 90.2  |
| 90   | 1   | 0.5 | 2   | 0.38    | 90.38 |
| 90   | 1   | 0.5 | -3  | -2.11   | 87.89 |
| 90   | 1   | 0.5 | -2  | -1.29   | 88.71 |
| 90   | 1   | 1   | 3   | 0.23    | 90.23 |
| 90   | 1   | 1   | 2   | 0.4     | 90.4  |
| 90   | 1   | 1   | -3  | -2.06   | 87.94 |
| 90   | 1   | 1   | -2  | -1.27   | 88.73 |
| 90   | 1   | 2   | 3   | 1.12    | 91.12 |
| 90   | 1   | 2   | 2   | 1.07    | 91.07 |
| 90   | 1   | 2   | -3  | -2.09   | 87.91 |
| 90   | 1   | 2   | -2  | -1.5    | 88.5  |

The table shows the desired power level as $P_d$ and actual power level as $P_r$. $A$ is the type and nature of the disturbance which acts on the reactor (increment value of the reactor reactivity), $K$ and $Z$...
are the automatic power controller’s parameters. \( \text{Epsilon} \) shows the difference between the desired and actual or real power values. The table demonstrates part of the complete experimental results with numerous diversities of reactor power levels and controller’s parameters.

Analysis of the results of experiments shows that there are a sufficiently large number of cases with finite control errors (Epsilon). Figure 2 shows histograms for \( \text{Epsilon} \) under different types of disturbances, where \( \mathcal{A}^+ \) is a positive perturbation and \( \mathcal{A}^- \) is a negative perturbation.

![Histograms](image)

**Figure 2.** Histogram of the experimental results for different kinds of disturbances obtained in the multifunctional computer analyzer.

### 2.2. Analysis of experimental results

The analysis of the experimental results shows that there are a sufficiently large number of cases with \( \text{Epsilon} \), approximately 2 – 3% of the reactor power value. To improve the quality of regulation or the
control process it is paramount to decrease the steady state error. As a solution, implementation of the algorithm based on neural network techniques was offered. In order to use the implementation of neural networks as an intelligence approach, it is necessary to select the structure of the neural network (topology), form a training set and to choose the learning algorithm. The process of building, training and testing the designed model was undertaken using Neural Network Toolbox in MATLAB. Neural Network Toolbox provides functions and applications for modeling a variety of complex and non-linear systems which are problematic to be described by equations [3].

3. Design of the adaptive neural network controller

3.1. Neural network model

The aim of designing an adaptive neural network for the APC system is to improve the control quality by decreasing \( \text{Epsilon} \). Therefore, it is suggested to design an adaptive model that can give a suitable power correction value (suggested correction power value \( C_v \)) based on the history and the working principle of the APC to compensate and reduce the control steady state error.

Based on the design, a neural network model was created to study the APC behavior and to construct a database of all possible control cases which can help to make a decision about the suitable power correction value. This model will be the core to design the adaptive controller which can act to correct the power value and minimize \( \text{Epsilon} \).

The experimental data which was obtained in the APC simulator will be the base to train the neural network model. To construct such a neural network model, it is necessary to select the input and the output and to choose the network topology and structure. Figure 3 shows the general scheme for the suggested model, which illustrates the input-output relation.

![Figure 3. Structural diagram of the neural network model.](image)

The task of this model is to determine the suggested correction power value \( C_v \), based on the controller’s current parameters \( K \) and \( Z \), the external perturbations or disturbances \( A \) and the current power value \( P_d \). The primary concept of the learning process of this neural network model is to provide input data which contains all possible situations and incidences including a variety of the controller’s configurations, divergent types and amplitude of the disturbances. The input parameters of this model consist of the controller’s parameters \( K \) and \( Z \), the external perturbations or disturbances \( A \) and the desired power value \( P_d \), which was determined to be the real power value \( P_r \) in the learning
process of the neural network model as illustrated in figure 3. The output of this model will be the correction power (pre-adjusted) value $C_v$, which is the desired power value $P_d$ as illustrated in table 1.

A two-layer four inputs and one output feed-forward network was chosen with 24 sigmoid hidden neurons and linear output neurons (newfit), which can fit multi-dimensional mapping problems arbitrarily, given consistence data and sufficient neurons in its hidden layer. The network will be trained with Levenberg-Marquardt backpropagation algorithm (trainlm). Figure 4 shows the block diagram of the suggested model, which was designed using Neural Network Toolbox in Matlab [3].

![Figure 4](image)

**Figure 4.** Block diagram of the designed model in neural network toolbox in Matlab.

Figure 5 illustrates the performance evaluation of the neural network model. In the evaluation, available experimental data obtained from the APC simulator was divided into three subsets, the first being training which was utilized for computing the gradient and updating the network weights and biases.

![Figure 5](image)

**Figure 5.** Performance evaluation of the neural network.
The second subset, validation, ascertained that when validation error increased for a determined number of iterations training was terminated, and the weights and biases at the minimum of the validation error were returned. The third subset, test, was utilized to substantiate the network design. Figure 5(a) illustrates the best validation performance demonstrating mean squared error of the network beginning at a significant value and decreasing to an insignificant value and plots subset errors. The distribution of subset errors in ranges of instances in the modeling process are illustrated in Figure 5(b). Figure 5(c) shows regression plots between the network outputs and the subsets. The performance and training state of the network is demonstrated in Figure 5(d) [3].

3.2. The adaptive algorithm for the automatic power controller APC

The task of the designed adaptive power controller is to measure the current power level \( P_r \) of the reactor based on the controller’s current parameters \( K \) and \( Z \) and the external perturbations or disturbances \( A \) and suggest a correction power value (pre-adjusted value) \( C_v \) based on the knowledge and experience gained by the neural network model (the adaptive algorithm), in order to compensate the error signal before entering the controller. In this way \( \text{Epsilon} \) can be minimized. Figure 6 shows a general block diagram of the system structure.

![Figure 6. Block diagram of the adaptive power controller.](image)

Using the pre-adjusted value \( C_v \) obtained from the adaptive neural network algorithm to correct the controller’s input value by compensating a correction value \( \Delta e \) which can add or subtract a certain value from the error signal \( e \), \( \text{Epsilon} \) can be minimized.

4. Project results

As a result of the adaptive power controller system simulation after using the adaptive values recommended by the neural network algorithm, it is evident that the final \( \text{Epsilon} \) decreased significantly compared to the classical controller without utilizing adaptive principals. A more decisive comparison of the simulation results of the adaptive neural network algorithm is shown in table 2 and figure 7. Table 2 illustrates an arbitrary chosen part of the complete results of the adaptive control algorithm based on neural networks, where \( P_d \) is the desired power level and \( P_r \) is the actual or real output power level without using an adaptive control principle. In other words the ordinary output power level using the classical APC, \( C_v \) is the recommended power level by the adaptive algorithm, \( P_a \) is the actual output power level of the control process after using the recommended power level by the adaptive algorithm, and \( \text{Epsilon 1} \) and \( \text{Epsilon 2} \) are the steady state errors before and after using the principle of adaptive algorithm.
It is evident from table 2 that comparing \textit{Epsilon 1} and \textit{Epsilon 2} of the APC for both cases before and after using the adaptive algorithm, shows an obvious enhancement to the quality of the control process by decreasing \textit{Epsilon}. Figure 7 illustrates a clearer picture of the comparison between the two cases for APC of the reactor.
5. Conclusions
The analysis of the project results shows that using adaptive control algorithms for the automatic power controller based on neural network principles can offer a significant improvement to the quality of the control system in comparison with conventional or classical control methods.

References
[1] Gavrilova T.A, Khoroshivsky V.F. Bazy znanij intellektual'nyh sistem - SPb.: Piter, 2000 (in Russian).
[2] Vaykovcke S.A., Karalov S.A., Chernov E.V. ychobnaya labratornaya na baze mnogophunkcanalna analzatora reaktorne uctanovak AES VVER [EDUCATIONAL LABORATORIES BASED ON MULTIFUNCTION ANALYZER THE REACTOR VVER] [VESTNIK NIYAU MIFI], 2012. V. 1, № 1, p. 104-110. (in Russian)
[3] Neural Network Toolbox User’s Guide © COPYRIGHT 1992 - 2009 by The MathWorks, Inc