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The Boundaries of Stability of the Dynamics Nuclear Reactor Model

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Abstract

One of the safety conditions for a reactor is the ability to maintain a stable steady state at a given level power. The presence of a set of feedbacks, which may include connections with a positive sign can destabilize a reactor. In that regard, the problem arises stability of the reactor in relation to random fluctuations of parameters. This work provides an assessment of the stability of the model of the dynamics of a nuclear reactor, including feedbacks on the temperatures of the fuel, coolant, and moderator.

Keywords: Nuclear reactor; Modelling; Lienard-shipard method; Adaptive ARS; Feedback, reactivity; TCR

Introduction

The most important direction of ensuring the safety and economical operation of NPP is the improvement of automated control systems for technological processes [1-3].

The efficiency of each innovative solution-technological, constructive, on automatic control - must be checked on a model based on the mathematical model of the controlled object. A model of an object can be obtained in two ways: as a result of a special experiment on a working object, or in an analytical (theoretical) way.

This paper provides a description of the stability range of the dynamics model for a nuclear reactor with lumped parameters. Application in python was written for accomplishment of this, which it involved in the graphic modeling directly.

The scope of this model confirms its relevance, for an example

Synthesis of an automatic regulation system for a nuclear reactor

It is possible to form an ARS in the future on the basis of this model, since it is dynamic and it can be corrected relatively fast to changes in a nuclear reactor.

Optimal control of a nuclear reactor

Based on the above, it is possible to develop algorithms for optimal control of the entire reactor, since the model can calculate a large number of different variants of values. Also, application has a function of checking the entered values of the reactivity coefficients for check to stability [4-5].

Avoidance the approach to the state of instant criticality

A positive reactivity close to the value of effective share delayed neutron mustn't be imparted to the reactor in no case. In this work, the range of the stability for a nuclear reactor are estimate, it helps to prevent an approach to the state of instantaneous criticality.

Nuclear Reactor Model

The model is based on the system of point kinetic equations for the nuclear reactor

$$\begin{cases} \dfrac{dn}{dt} = \dfrac{\rho - \beta}{l} n + \sum_i \lambda_i C_i + I, \\ \dfrac{dC_i}{dt} = \dfrac{\beta_i}{l} n - \lambda_i C_i, \end{cases} \#(1)$$

Where n–neutron density; l–prompt neutrons lifetime; Ci, λi–concentration and decay constant of core-emitters of the ith group; βi–share of the ith group delayed neutrons in fission; β–full share of delayed neutron, β=Σ βi; ρ–reactivity; I–neutron source power.

Simplified kinetic models with two or one group of delayed neutrons use for a qualitative or approximate analysis of nonstationary processes often. The model with one group of delayed neutrons is convenient so that it allows obtaining an analytical solution to the problem in some cases [6].

The model includes several feedbacks, in addition to the point kinetic equations: on the fuel temperature, moderator temperature and coolant temperature. It is assumed that fuel and moderator, in which it is energy release by energy of decelerating neutrons and absorbed gamma quantums, are cooled by the same coolant. Prototypes of this kind of systems can be, for example, channel reactors with a solid moderator-graphite, and they are cooled by boiling water. The energy share released in the moderator is denoted by the letter ε. In typical situations, this share is 5%-7% [7]. The dynamics model under these assumptions has the form.

$$\begin{cases} \dfrac{dW}{dt} = \dfrac{\rho(T) - \beta}{l} W + \sum_i \lambda_i c_i^* \\ \dfrac{dc_i^*}{dt} = \dfrac{\beta_i}{l} W - \lambda_i c_i^* \\ m_F C_F \dfrac{dT_F}{dt} = \varepsilon W - k_F (T_F - T_C) \\ m_M C_M \dfrac{dT_M}{dt} = (1 - \varepsilon) W - k_M (T_F - T_M) \\ m_C C_C \dfrac{dT_C}{dt} = k_F (T_F - T_C) + k_M (T_F - T_M) - C_C G_C (T_{C2} - T_{C1}) \\ T_C = \dfrac{T_{C2} + T_{C1}}{2} \rightarrow T_{C2} = 2T_C - T_{C1} \\ \rho(T) = \rho_0 + a_{T_F}(T_F - T_{F0}) + a_{T_C}(T_C - T_{C0}) + a_{T_M}(T_M - T_{M0}) \\ W = n v E \Sigma_f \\ c_i^* = c_i v E \Sigma_f \end{cases}$$

Where TF, TM, TC–average temperatures of fuel, moderator, coolant; mF, mM, mC, CF, Cm, CC–respectively, their mass and heat capacity; KF, Km–heat transfer coefficients from fuel and moderator to coolant; v, E, □f–neutrons velocity, neutron energy and fission energy, aTF, aTM, aTC-temperature coefficient of reactivity of fuel, moderator and coolant.

In this model, the heat transfer coefficients find in relation to the full power transferred by the fuel or moderator to the coolant. The model contains the following assumptions related to transient processes:first, during the time of transient processes, the shape of the neutron field in the reactor does not change, second, the concentration of boric acid, samarium-149 and xenon-135 remains constant [8].

The system needs to linearize to find the range of the stability. The canonical form of the linearized system equations

$$\begin{cases} \frac{dx_1}{dt} = a_{11}x_1 + a_{12}x_2 + a_{13}x_3 + a_{14}x_4 + a_{15}x_5 \\ \frac{dx_2}{dt} = a_{21}x_1 + a_{22}x_2 \\ \frac{dx_3}{dt} = a_{31}x_1 + a_{33}x_3 + a_{35}x_5 \\ \frac{dx_4}{dt} = a_{41}x_1 + a_{43}x_3 + a_{44}x_4 \\ \frac{dx_5}{dt} = a_{53}x_3 + a_{54}x_4 + a_{55}x_5 \end{cases} \#(3)$$

Where

$$x_1 = \delta W; x_2 = \delta c^*; x_3 = \delta T_F; x_4 = \delta T_M; x_5 = \delta T_C$$

$$a_{11} = -\frac{\beta}{l}; a_{12} = \lambda;\ a_{13} = \frac{a_{T_F}W}{l};\ a_{14} = \frac{a_{T_M}W}{l}; a_{15} = \frac{a_{T_C}W}{l}$$

$$a_{21} = \frac{\beta}{l}; a_{22} = -\lambda; a_{23} = a_{24} = a_{25} = 0$$

$$a_{31} = \frac{\varepsilon}{m_F C_F}; a_{32} = 0; a_{33} = -\frac{k_F}{m_F C_F}; a_{34} = 0; a_{35} = \frac{k_F}{m_F C_F}$$

$$a_{41} = \frac{1-\varepsilon}{m_M C_M}; a_{42} = 0; a_{43} = -\frac{k_M}{m_M C_M}; a_{44} = \frac{k_M}{m_M C_M}; a_{45} = 0$$

$$a_{51} = a_{52} = 0;\ a_{53} = \frac{k_F + k_M}{m_C C_C};\ a_{54} = -\frac{k_M}{m_C C_C}; a_{55} = -\frac{k_F}{m_C C_C}$$

To find the characteristic equation of the system, we compose a matrix and require that its determinant be equal to 0

$$det = \begin{vmatrix} a_{11}-\omega & a_{12} & a_{13} & a_{14} & a_{15} \\ a_{22} & a_{22}-\omega & 0 & 0 & 0 \\ a_{31} & 0 & a_{33}-\omega & 0 & a_{35} \\ a_{41} & 0 & a_{43} & a_{44}-\omega & 0 \\ 0 & 0 & a_{53} & a_{54} & a_{55}-\omega \end{vmatrix} = 0 \#(4)$$

Then we bring it to canonical view and we compile the Hurwitz determinant with the condition that it be equal to 0 to obtain the characteristic equation of the system

$$u_0\omega^5 + u_1\omega^4 + u_2\omega^3 + u_3\omega^2 + u_4\omega + u_5 = 0 \#(5)$$

We are interested in the ratio between the three reactivity coefficients at finding the range of the aTF; aTM; aTC All other coefficients included in equations and then in inequalities are understood as known.

Consider the conditions to provide the system stability of the Lienard-shipard method (since the system degree is bigger than 4, the Hurwitz method is extremely expensive in time and number of actions)

Necessary and sufficient conditions for a real polynomial of the form (3) to have all roots with negative real parts can to write in the form

$$\begin{cases} u_0 > 0, u_1 > 0, u_2 > 0, u_3 > 0, u_4 > 0, u_5 > 0 \\ \Delta_1 > 0, \Delta_3 > 0, \Delta_5 > 0 \end{cases} \#(6)$$

It results from this theorem that for a real polynomial (4), for which all coefficients are positive, the Hurwitz inequalities are not independent, namely:the positiveness of the odd Hurwitz determinants implies the positiveness of the even Hurwitz determinants and vice versa.

Thus, the set of TCR values, that it's satisfy condition (5), it will determine the range of the stability area for our model.

Modeling

The final view of the application for graphic modeling is shown in the Figure 1 below.

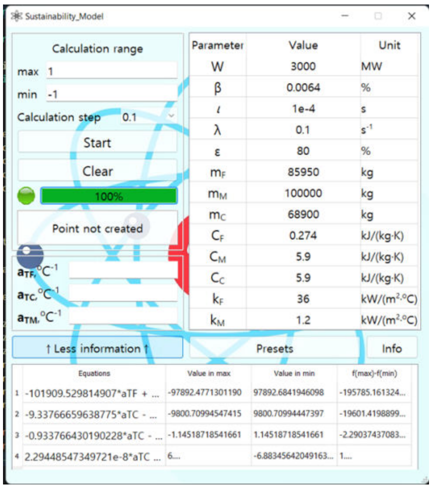

Figure 1: Test parameters.

In this image, we can also see the results of a test run using a PWR-1000 parameters (data available in the Presets category) [9, 10]. The next image shows a graphical model of the PWR-1000 dynamics. The model is active and you can interact with it by rotate in any direction as shown in Figure 2

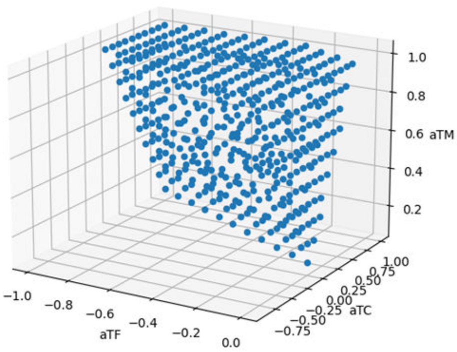

Figure 2: Boundaries of stability of the PWR-1000 model.

The application has the function of constructing a «custom point». You can get the model, which it shown below by setting values for the TCR in the appropriate area as shown in Figure 3.

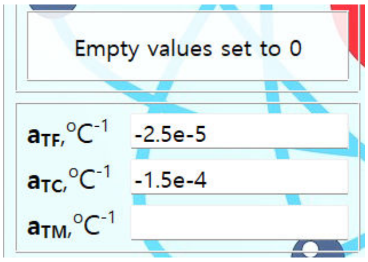

Figure 3: «Custom point».

Since the TCR value for the moderator has taken a zero value, and that it had went beyond the stability area-the «Custom point» had shown in red, and we also see a vector, who it heads to stable values. Rotating the model and watching at the values of the axes, we can conclude that the TCR values for fuel and coolant are included in the stability area, and the TCR value for the moderator should be increased as shown in Figure 4.

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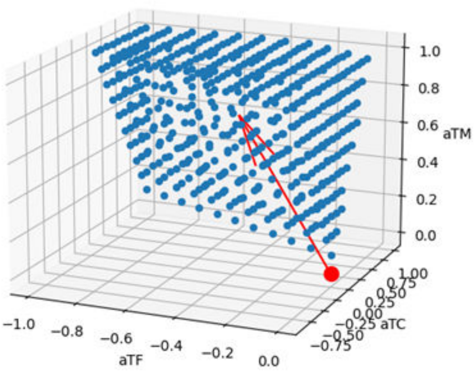

Figure 4: Directional vector.

Completing the described actions, we get this model shown in Figure 5-6.

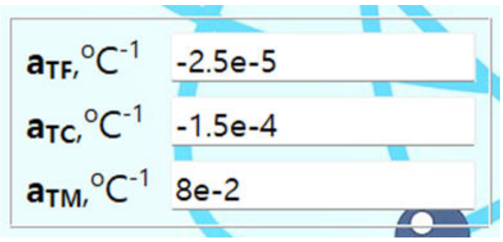

Figure 5: New «custom point».

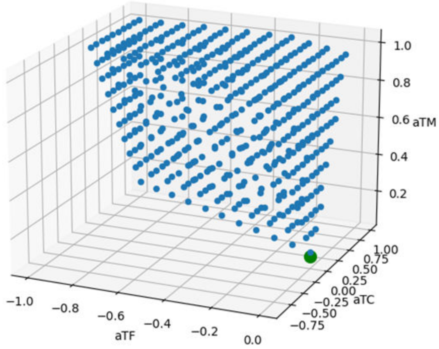

Figure 6: Stable parameters.

Conclusion

The model created in this project is dynamic and it can correct relatively fast by the new values of the core parameters. Also, if reactor power will change, then the fuel temperature will change fast enough, but not instantly. All this will help CPS of NPP to regulate the NR parameters to most optimal values from point of view the stability of values, and that it will help to synthesis the adaptive ARS.

Such an ARS will contain algorithms for optimal control of the all reactor, because it can evaluate a large number of different variants the TCR values, and it also have a function for checking the entered reactivity coefficients, which they are estimated by approximate methods for belonging to the stability region.

As a result, we obtain an ARS that it is adaptive to deviations in the parameters and it is do a monitoring of the TCR values.

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