



Modeling and Advanced Control of a PWR Nuclear Reactor Core with Temperature Effects and Xenon Consideration

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ABSTRACT

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The operation of nuclear power reactors (PWRs) in base load or load following mode is exclusively concerned with the continuous production of electricity. The reactors are only shut down for refueling and/or periodic maintenance. However, due to this economic reason, which prevents direct experimentation, modelling and simulation become imperative for the study and analysis of nuclear power plant performance. In this study, a PWR reactor core was modelled using the point-kinetic approach with MATLAB programming environment. To obtain a realistic representation of the reactor core behaviour, the developed mathematical model integrates neutronic and thermohydraulic sub-models, as well as negative feedback effects of temperature and xenon dynamics. The validation of the model was carried out by open-loop simulations, giving results that are consistent with previously published literature. To improve the stability and performance of power control, particularly during load-following operations PWRs, using both classical (PID) and advanced control strategy implemented in the validated model. With a PID controller, we observed a more prolonged transient regime, a higher power peak (121%), and a rapid fluctuation of total reactivity. In contrast, using Fuzzy Logic Controller (FLC), the results were significantly improved: the transient regime was shortened to 0.15 seconds, the power peak was reduced to 108%, and total reactivity became more stable. The FLC improved reactor control in terms of both stability and power tracking with reduced deviation between desired and controlled power.

1. INTRODUCTION

A nuclear reactor is a highly complex, nonlinear and time-dependent dynamic system. These inherent characteristics make it particularly challenging to control the power generated in the reactor core, a task that poses significant nuclear safety risks [1, 2]. Failure to respect nuclear safety regulations, in particular operating limits and conditions, could result in significant nuclear hazards. Therefore, the use of nuclear reactor core models is an indispensable prerequisite for the implementation of power control algorithms during load-following operation in nuclear power plants. This approach facilitates the simulation of reactor manoeuvrability in different scenarios without compromising safety [4, 5, 6]. Over the past decades, substantial efforts have been devoted to modeling and simulation, which have played a pivotal role in advancing nuclear technologies. This field of research

has predominantly focused on reactor core modeling, the development of advanced control strategies, the stability and performance analysis of power reactors in load-following mode. The literature offers numerous modeling and control methodologies for nuclear reactor cores, tailored to various objectives and requirements [7, 8, 9].

In reactor core modelling based on the point-kinetics approach, the core is simplified as a single point without consideration of spatial variations, with core parameters evolving only with time [3, 4]. This methodology has been widely applied to power control in nuclear power plants using advanced control strategies. In addition, it has been essential in analyzing core stability during transient power oscillations induced by xenon dynamics under load-following operation. For example, the feasibility of implementing second-order sliding mode control for reactor power control has been successfully demonstrated within this framework [10]. The approach has also been

adapted for the dynamic simulation of next fourth-generation high-temperature nuclear reactors, providing robust and reliable results [11]. In furthermore, the integration of point-kinetic equations with temperature feedback mechanisms in nuclear reactors has been effectively investigated using the MATLAB-Simulink platform [12, 13, 14].

In this study, the modelling of a pressurized water reactor (PWR) core was performed using the point-kinetics approach. The developed model was validated by comparing its simulation results with published benchmark data from the literature. This validation process focused on assessing deviations of main reactor parameters - such as power output and total reactivity - against their reference values. In the subsequent phase, the validated mathematical model was used to evaluate the performance of a PWR reactor operating in load-following mode. To achieve this, a proportional-integral-derivative (PID) controller, a control strategy widely used in industrial systems [15], was implemented in a closed-loop configuration to control the reactor core's thermal power output. For extension and comparison purposes, an advanced controller based on fuzzy logic was also developed and integrated into the same reactor core model [16]. The comparison of the performance of this controller with that of the conventional PID controller must be made in terms of reference load tracking, overshooting (undershooting) during transients, time to transient instability, etc. Dynamic load-following scenarios, including power manoeuvre simulations, were performed to evaluate the performance of the controllers. Temperature feedback and xenon dynamics were explicitly considered to ensure realistic simulations. The results demonstrated the effectiveness of both classical and advanced control strategies, with the fuzzy logic-based controller showing superior performance in terms of power tracking, stability, and responsiveness.

2. MATERIALS & METHODS

In order to simulate the physical and thermal-hydraulic processes in a nuclear reactor and to control the thermal power generated in its core, a comprehensive mathematical model was developed using the MATLAB programming environment. Among the various modelling approaches available, the point kinetic method was selected for its simplicity and efficiency, operating under the assumption that the reactor core parameters vary solely as a function of time. This approximation forms the basis for the development of the mathematical model, which is structured around six differential equations described below. These equations collectively govern critical aspects of the reactor's behaviour, including the evolution of the neutron population and, by extension, the thermal power, the concentration of delayed neutron precursors, the variations in coolant and fuel temperatures, the changes of the total reactivity and the dynamics of xenon poisoning in the reactor core.

It is worth noting that this model can be developed by considering either a single group of delayed neutrons or

six groups, as typically reported in the literature. In the present study, the model incorporates three groups of delayed neutrons, represented by the factors β_1 , β_2 and β_3 which correspond to the fractional contributions of each group (precursors) of delayed neutrons. While modeling the core using this approach is inherently more complex, it enables the development of a more accurate mathematical representation.

The resulting model, based on the differential equations (1, 2, 3, 4, 5, 6, and 7) provided below, offers a robust framework for simulating the dynamics of the reactor core and its associated physical phenomena. By incorporating these six groups of delayed neutrons, the model enhances the precision of the simulation and enables a comprehensive analysis of the reactor core's behavior under various operational scenarios.

$$\frac{dn_r}{dt} = \frac{\rho(t) - \beta}{\Lambda} n_r(t) + \sum_{i=1}^6 \frac{\beta_i}{\Lambda} c_{ri}(t), \quad i = 1, 2, \dots, 6 \quad (1)$$

$$\frac{dc_{ri}}{dt} = \lambda_i n_r(t) - \lambda_i c_{ri}(t), \quad i = 1, 2, \dots, 6 \quad (2)$$

$$\frac{dT_f}{dt} = \frac{f_f P_0}{\mu_f} n_r(t) - \frac{\Omega}{\mu_f} T_f + \frac{\Omega}{2\mu_f} T_{in} + \frac{\Omega}{2\mu_f} T_{out} \quad (3)$$

$$\frac{dT_c}{dt} = \frac{(1 - f_f) P_0}{\mu_c} n_r(t) + \frac{\Omega}{\mu_c} T_f - \frac{(2M + \Omega)}{2\mu_c} T_{out} + \frac{(2M - \Omega)}{2\mu_c} T_{in} \quad (4)$$

$$\frac{dX}{dt} = (\gamma_X \sum f - \sigma_X X) \Phi - \lambda_X X + \lambda_I I \quad (5)$$

$$\frac{dI}{dt} = \gamma_I \sum f \Phi - \lambda_I I \quad (6)$$

$$\rho(t) = \rho_{rod} + \rho_T - \rho_X \quad (7)$$

The expressions for the three reactivity components that are involved in the variation of the total reactivity in reactor core are provided in equations (8), (9), and (10).

$$\frac{d\rho_{rod}}{dt} = Z_r G_r \quad (8)$$

$$\rho_T = \alpha_c (T_f - T_{f_0}) + \alpha_f (T_c - T_{c_0}) \quad (9)$$

$$\rho_X = \frac{\sigma_X}{\nu \sum f} (X_0 - X) \quad (10)$$

Reactor power core, formulated by Equation (11), is expressed as a function of the initial power and the relative neutron density.

$$P(t) = P_0 n_r(t) \quad (11)$$

The constants and parameters used in the differential equations mentioned above is provided in nomenclature below.

3. POINT KINETICS REACTOR MODEL VALIDATION

To evaluate the reactor core model developed in Section 2 and illustrated in Figure 1, simulations involving reactivity insertions of 0.2β and 0.7β were conducted in the reactor core. The primary reactor parameters to be monitored are displayed as several outputs of the model. The sole input of the model corresponds to the control action, specifically the reactivity variation induced by the movement of the control rod, which is quantified by the variable Z_r , representing the velocity of the rod's displacement.

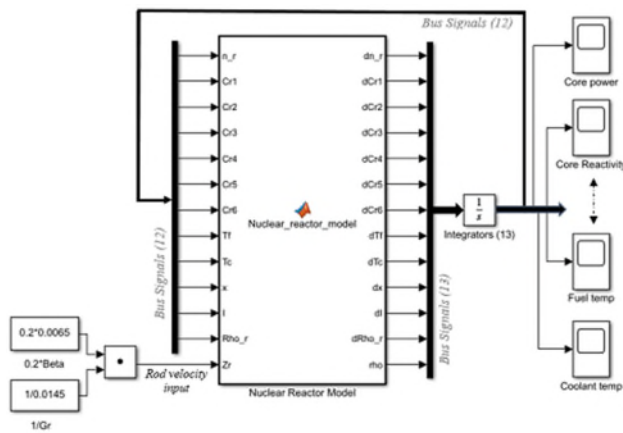


Figure. 1 Nuclear reactor core model in an open-loop configuration with reactivity insertion of 0.2β .

To simulate the insertion of reactivity in the model and analyze its response, it is necessary to define the model's initial conditions beforehand. This involves selecting a reactor type and inputting the constants and values of certain equilibrium parameters into the model. The values of these parameters and constants are provided in Table 2.

In addition, it is essential to compare the obtained results with reference data published in the literature for the same point kinetics reactor model to validate the mathematical model of the reactor core. Accordingly, the works of Nahrul Khair et al. and Mai Ismail et al. [12, 13] provide relevant results.

Table 1. Constants and parameters values at the initial steady state of the model

Constant and parameter designation	Value
Thermal power (P_0)	2500 MW
Core heights	400 cm
Core radius	200 cm
Total delayed neutron fraction (β)	0,0065
Delayed neutron fraction of first group neutron precursor (β_1)	0,00021

Delayed neutron fraction of second group neutron precursor (β_2)	0,00225
Delayed neutron fraction for third group neutron precursor (β_3)	0,00404
Delayed neutron fraction for forth group neutron precursor (β_4)	0,00256
Delayed neutron fraction for five group neutron precursor (β_5)	0,00074
Delayed neutron fraction for six group neutron precursor (β_6)	0,00027
Effective prompt neutron life time	2×10^{-5} s
Radioactive decay constant of first group neutron precursor (λ_1)	0,0124 s ⁻¹
Radioactive decay constant of second group neutron precursor (λ_2)	0,0269 s ⁻¹
Radioactive decay constant of third group neutron precursor (λ_3)	0.632 s ⁻¹
Radioactive decay constant of forth group neutron precursor (λ_4)	0,301 s ⁻¹
Radioactive decay constant of five group neutron precursor (λ_5)	1,140 s ⁻¹
Radioactive decay constant of six group neutron precursor (λ_6)	3,010 s ⁻¹
Total heat capacity of the fuel	26,3MW.s°C-1
Fraction of reactor power deposited in the fuel	0,92
Heat transfert coefficient between fuel and coolant	6.6 MW.s°C-1
Total heat capacity of coolant	71,8MW.s°C-1
Mass flow rate multiply by the heat capacity of the coolant	102MW.s°C-1
Xenon yield by fission	0,003
Iodine yield by fission	0.059
Xenon decay constant ;	$2,1 \times 10^{-5}$ s ⁻¹
Iodine decay constant;	$2,9 \times 10^{-5}$ s ⁻¹
Fuel temperature reactivity coefficient	$-3,24 \times 10^{-5}$ Δk.k-1.°C-1
Coolant temperature reactivity coefficient	-2.13×10^{-4} Δk.k-1.°C-1
Fuel average temperature at the initial condition	290 °C
Coolant average temperature at the initial condition	290 °C
Microscopic absorption cross-section of xenon	3.5×10^{-18} cm ²
Rod total worth reactivity	0.0145 Δk.k-1

4. CONTROL ALGORITHMS DESIGN

4.1 PID controller

The PID control strategy is the simplest to design and use in real-time industrial systems. Furthermore, the PI controller can be employed in this context due to its reduced responsiveness to comparatively swift alterations in state, resulting in a slower response of the system to the intended signal. This attribute assumes particular importance in the context of accident control and in

scenarios involving rapid power fluctuations. In comparison to the PI controller, the PID controller exhibits a reduced tendency to overshoot and a faster settling time. The PID controller follows a standard formulation that can be expressed in the time domain as follows:

$$\mu(t) = K_P e(t) + K_I \int_0^t e(\tau) d\tau + K_D \frac{de(t)}{dt} \quad (12)$$

Figure 2 illustrates the system for controlling nuclear reactors by means of PID control.

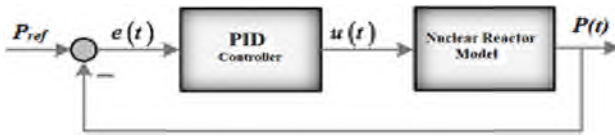


Figure. 2 Schematic diagram of nuclear reactor power control using PID.

4.2 Fuzzy Logic Controller design

For the implementation of fuzzy logic in the control of complex and highly non-linear pressurized water nuclear reactors, the design of a fuzzy controller is essential. The objective of the fuzzy controller design is to regulate the thermal power generated in the reactor core. In the extant literature, fuzzy controllers of the Mamdani type and others of the Sugeno type are encountered. In this study, the first type was implemented. The design of these two types of fuzzy controllers does not necessitate a mathematical model based on differential equations; rather, their design primarily relies on expert knowledge [18,19] and, in the case of this study, on the feedback and knowledge of operators and plant personnel with experience in nuclear reactors. The system of nuclear reactor power control by FLC is shown in Figure 3.

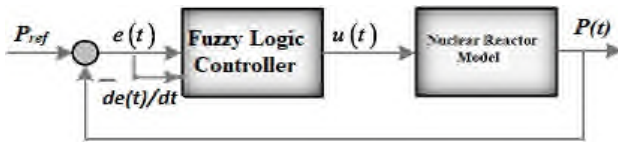


Figure. 3 Schematic diagram of nuclear reactor power control using FLC.

As illustrated in Figure 3, the FLC contains four components: the fuzzification interface, the fuzzy rule base, the fuzzy inference, and the defuzzification interface (see Figure 4). Operator experience indicates that the FLC receives two inputs: the error in the power demand (E_p) and the rate of change of the neutron density or power demand, which can be regarded as derivative feedback (dE_p).

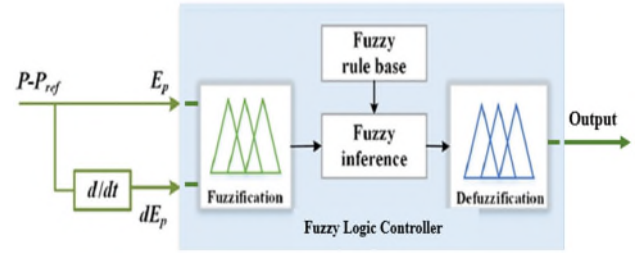


Figure. 4 General Structure of a Fuzzy Logic Controller

The design of a Mamdani-type fuzzy controller can be accomplished by employing one of MATLAB's applications, specifically the "Fuzzy Logic Designer." The FLC Input-Output Mapping is approached through the implementation of singleton fuzzification and centroid defuzzification methodologies. The utilization of these methodologies, in conjunction with the selection of membership functions, enables the expression of the input-output relationship of a controller in the following manner: employment of these methodologies, in conjunction with the selection of membership functions, facilitates the expression of the input-output relationship of a controller in the following manner:

$$\mu^* = \frac{\sum_{I=1}^{M_r} \hat{\mu}^I (\mu_{BI}(\hat{\mu}^I))}{\sum_{I=1}^M \mu_{BI}(\hat{\mu}^I)} \quad (13)$$

For each of the two inputs to the FLC, as illustrated in Figure 2, the membership functions are generated using triangular, trapezoidal, or Gaussian functions. In this study, Gaussian curves are employed to generate membership functions for both inputs to the FLC, as well as for its sole output. Accordingly, each entry is assigned a total of three fuzzy sets, and those assigned with the power error (E_p) are labeled NE (negative error), ZE (zero error), and PE (positive error). The fuzzy sets assigned to derivative error (dE_p) are NDE (negative derivative error), Z (zero derivative error), and PDE (positive derivative error). The control signal (output of FLC) is related to the reactivity, which can be altered by the insertion of rods into the reactor core. Consequently, the controller output determines the velocity of the control rod (Z_r). The output of the fuzzy logic controller (FLC) is associated with five fuzzy sets, which are designated as LN (low negative), SN (short negative), Z (zero), SP (short positive), and LP (low positive).

The membership functions are represented, respectively for the inputs E_p (E), dE_p (DE), and the output, in Figures 5, 6 and 7.

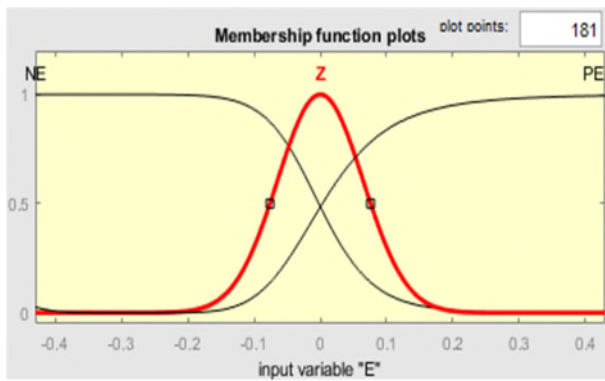


Figure. 5 Membership functions of the inputs “E”

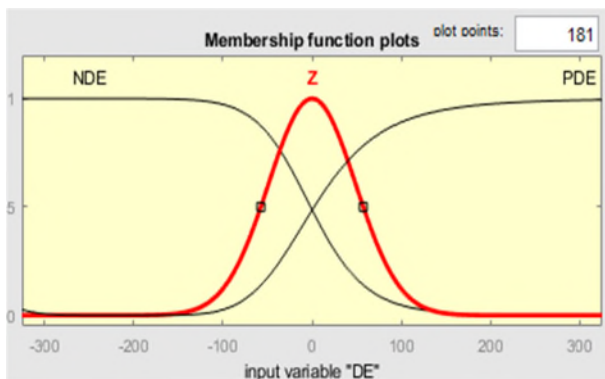


Figure. 6 Membership functions of the inputs “DE”

In accordance with the principles of decision-making, the FLC output, designated as a control action, undergoes modification. As illustrated in Table 2, the manipulation of this control action is governed by a set of fuzzy rules, which delineate the parameters of reactivity.

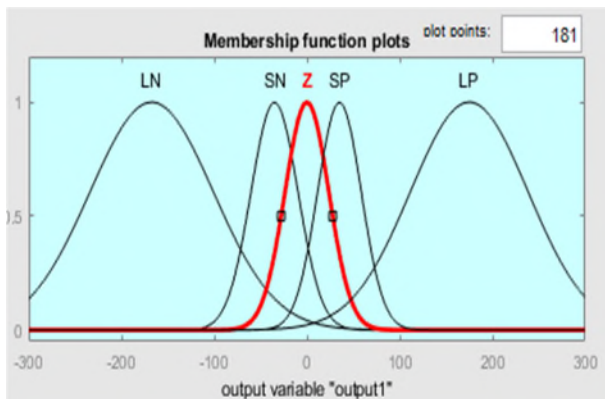


Figure. 7 Membership functions of the FLC controller output

Table 2. Rules for FLC decision making

$\begin{matrix} E \\ DE \end{matrix}$	NE	Z	PE
NDE	LN	SN	Z
Z	SN	Z	SP
PDE	Z	Z	LP

5. CONTROL ALGORITHMS IMPLEMENTATION

As shown in Figures 8 and 9, the implementation of the two PID and fuzzy controllers is illustrated. It is also useful to specify that the mathematical model developed in the present study, which has been tested and validated in an open loop, is separately coupled to two PID and fuzzy controllers. This allows the evaluation of their performance in load following mode operation.

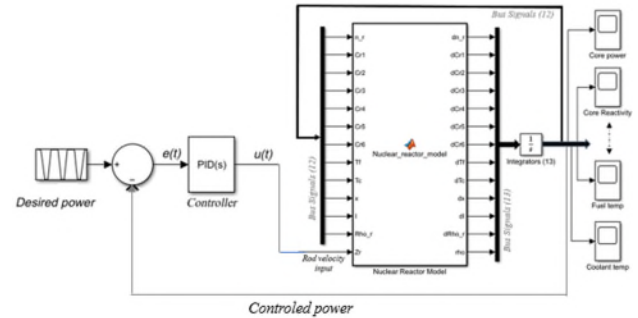


Figure. 8 Schematic implementation of nuclear core model power tracking in a closed-loop configuration with a PID controller

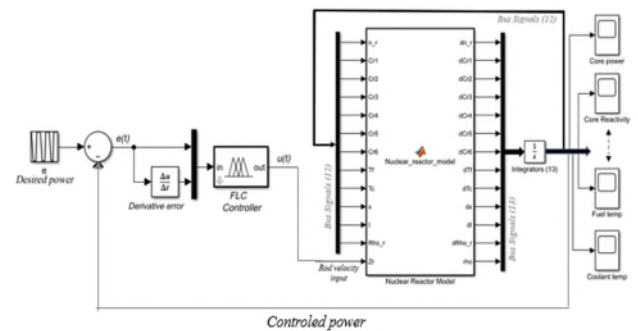


Figure. 9 Schematic implementation of nuclear core model power tracking in a closed-loop configuration with a FLC controller

The subsequent load-following scenario is illustrated in Figure 10.

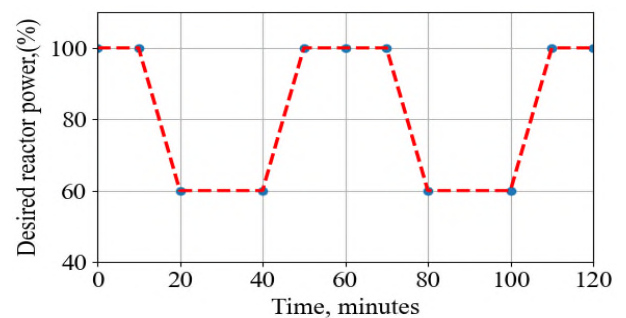


Figure.10 Load following scenario

6. SIMULATION RESULTS

6.1 simulation in an open-loop configuration

The effect of introducing reactivity at 0.2β and then 0.7β into the reactor core model on the power fluctuations is illustrated in Figures 11 and 12.

The following figures 13, 14, 15, 16, 17, and 18 illustrate the results for total reactivity, temperature effect on reactivity, coolant temperature, and xenon dynamics in the reactor core.

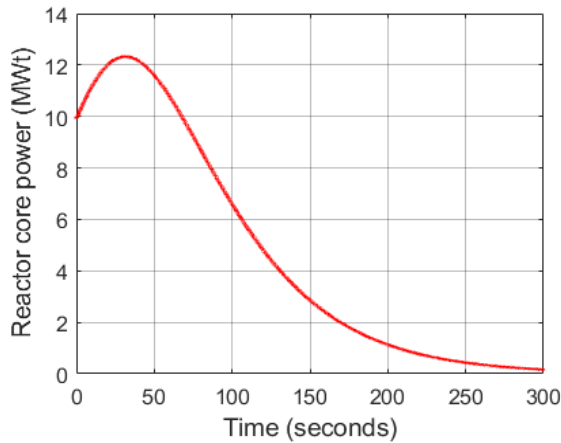


Figure.11 Reactor core power variation in response to 0.2β core reactivity insertion

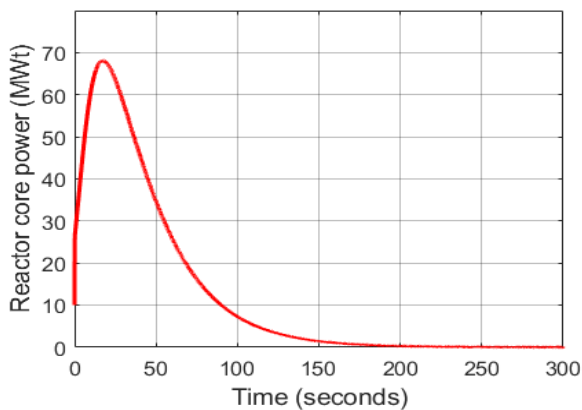


Figure.12 Reactor core power variation in response to 0.7β core reactivity insertion

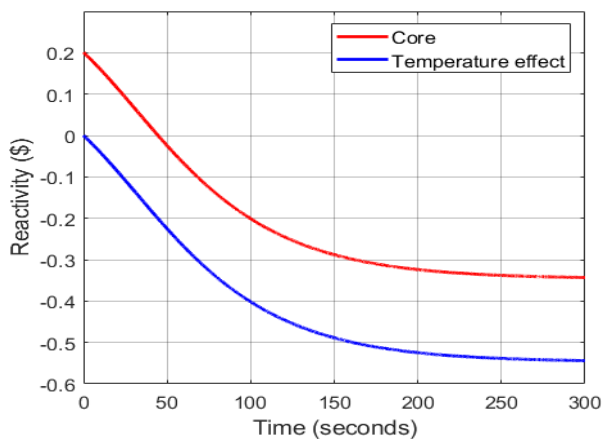


Figure.13 Total reactivity and temperature effect variations in response to 0.2β core reactivity insertion

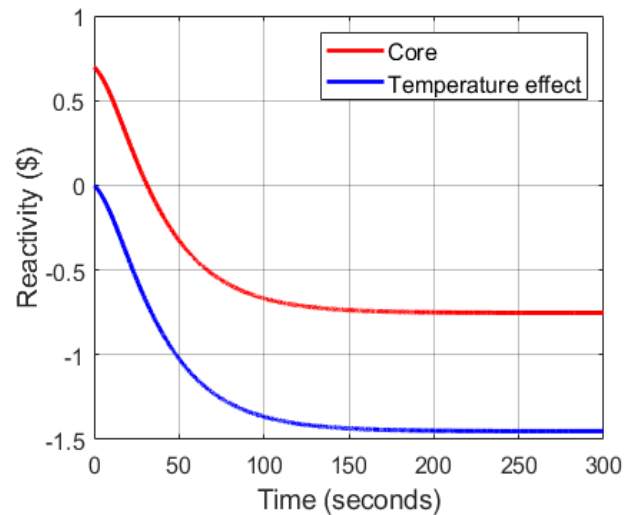


Figure.14 Total reactivity and temperature effect variations in response to reactivity insertion of 0.7β

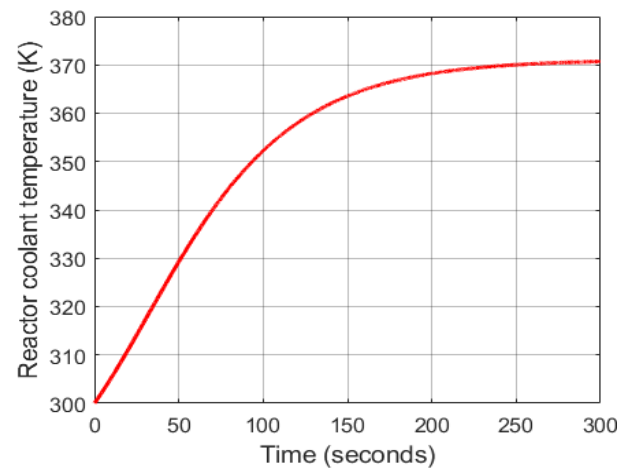


Figure.15 Coolant temperature variation in response to 0.2β core reactivity insertion

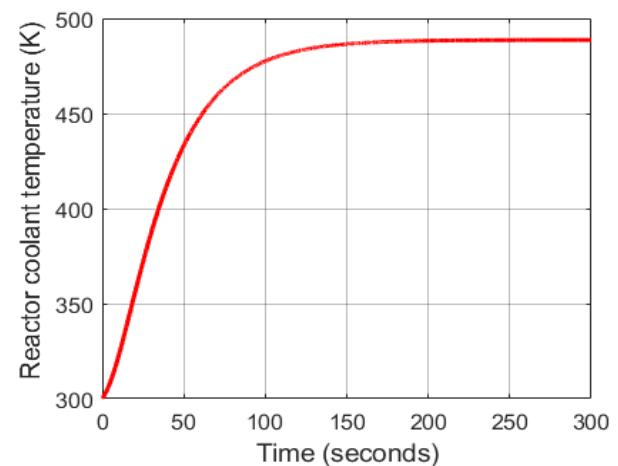


Figure.16 Coolant temperature variation in response to 0.7β core reactivity insertion

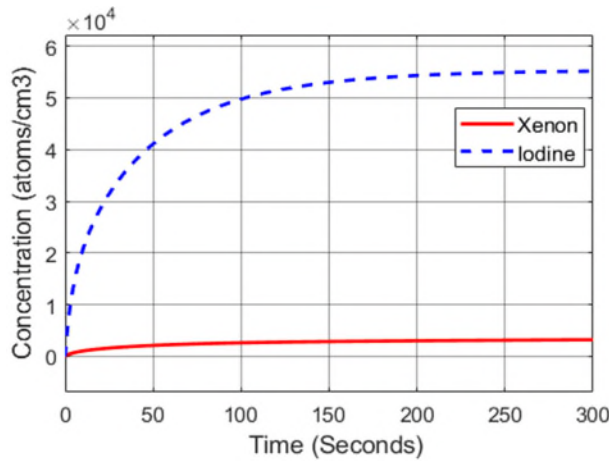


Figure.17 Xenon/Iodine dynamics in response to 0.7β core reactivity insertion

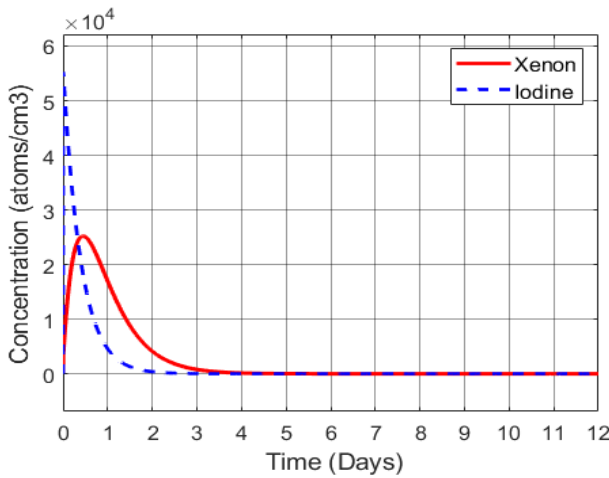


Figure.18 Xenon/Iodine dynamics in the reactor core during 12 days of operation in response to 0.7β reactivity insertion

In order to compare the simulation results shown in Figures 11, 12, 13, and 14 with the reference results [13], they are plotted in one figure at the same time for two reactor parameters (power and reactivity), see Figures 19 and 20.

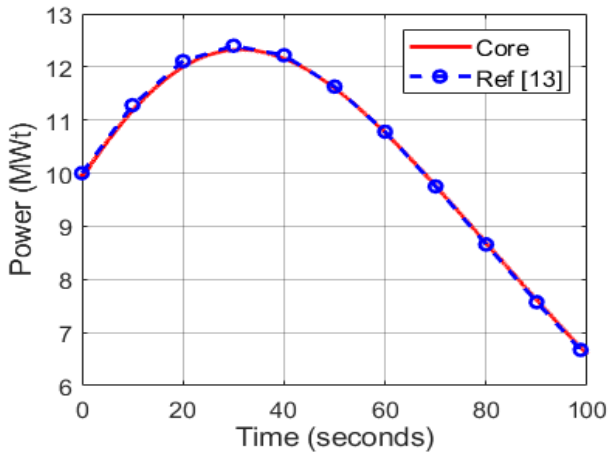


Figure.19 Reactor core power result by simulation in comparison with the same results in reference [13]

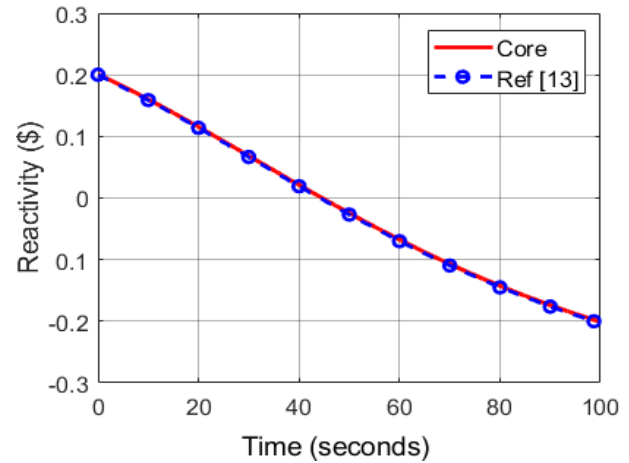


Figure.20 Reactor core total reactivity result by simulation in comparison with the same results in reference [13]

6.2 Simulation with the closed loop reactor core model

Figures 21, 22, 23, 24, 25 and 26 show the results of power control, total reactivity and temperature variation obtained by implementing PID and fuzzy controllers in the reactor core model.

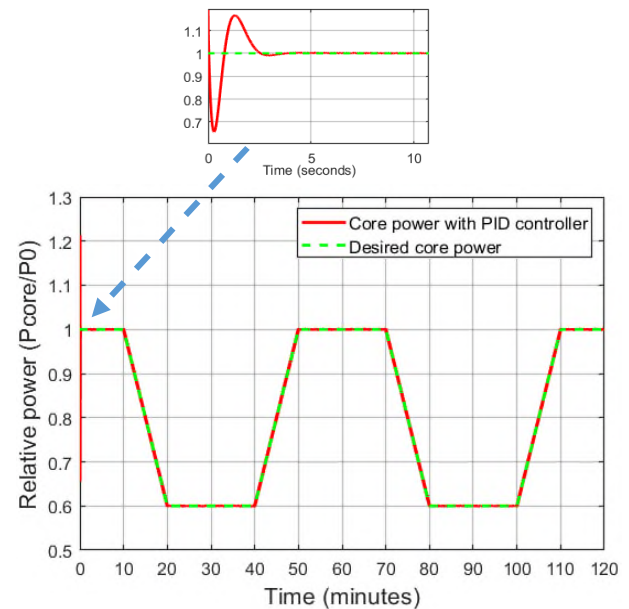


Figure.21 Core power control using PID in load-following reactor operation

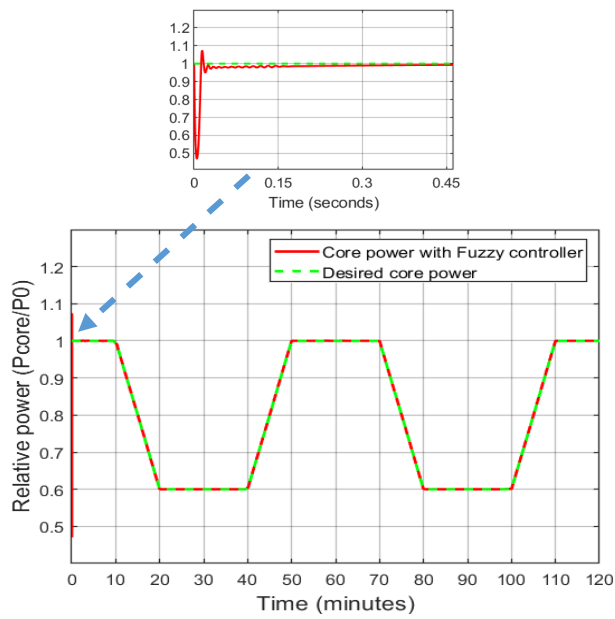


Figure.22 Core power control using FLC in load-following reactor operation

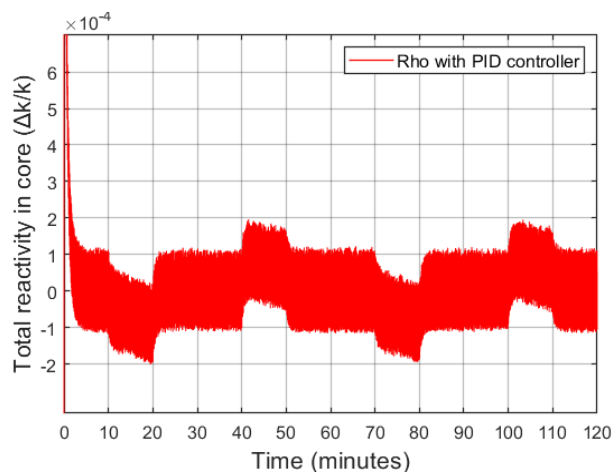


Figure.23 Total reactor reactivity variation using PID in load-following reactor operation

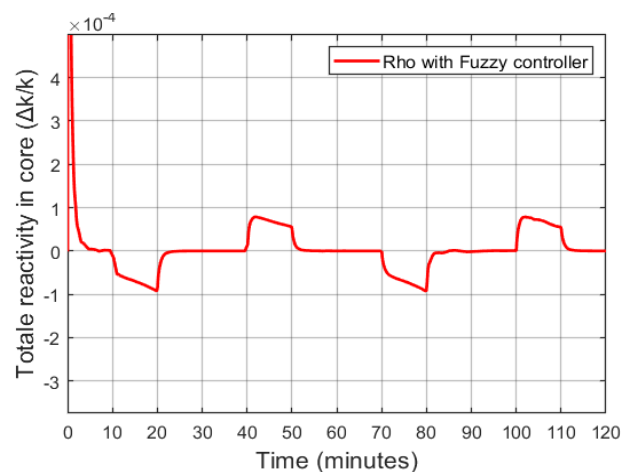


Figure.24 Total reactor reactivity variation using FLC in load-following reactor operation

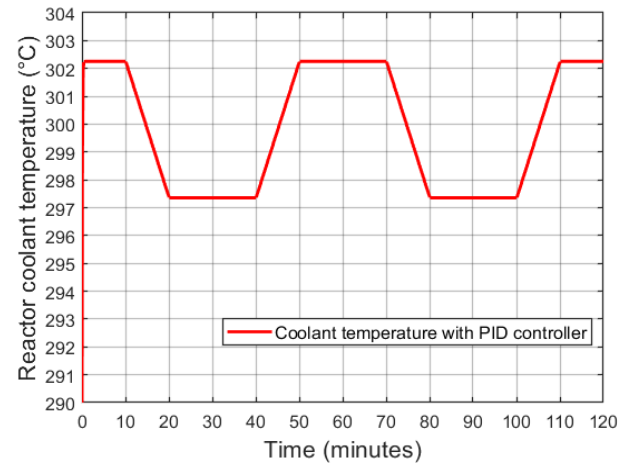


Figure.25 Coolant temperature variation using PID in load-following reactor operation

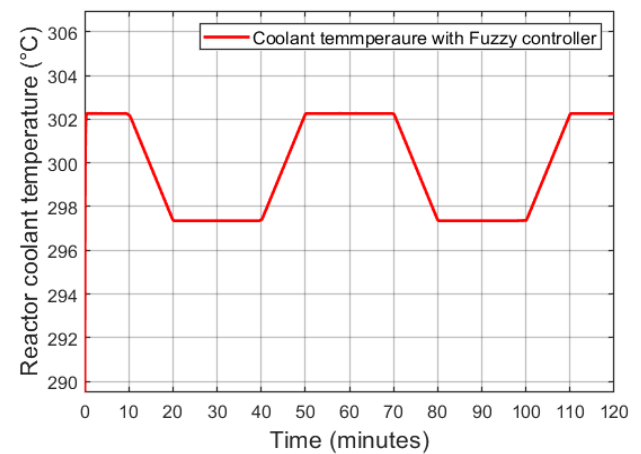


Figure.26 Coolant temperature variation using FLC in load-following reactor operation

For the analysis of the xenon dynamics in the developed reactor core model, the power control is simulated for five days. The result is shown in Figure 27.

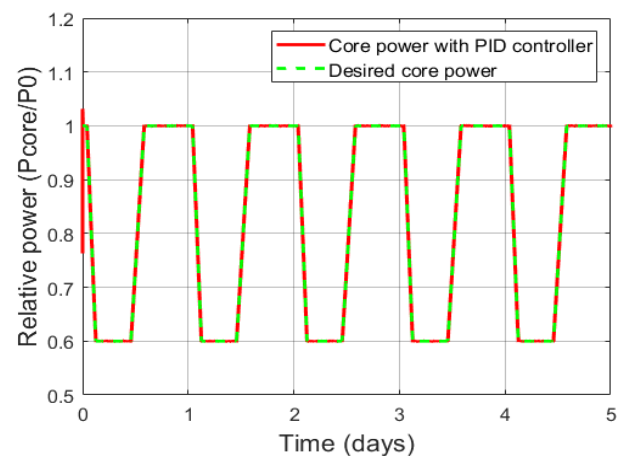


Figure.27 Core power control using PID in load-following reactor operation during 5 days

As a result, the xenon oscillations generated in the reactor core are shown in Figure 28.

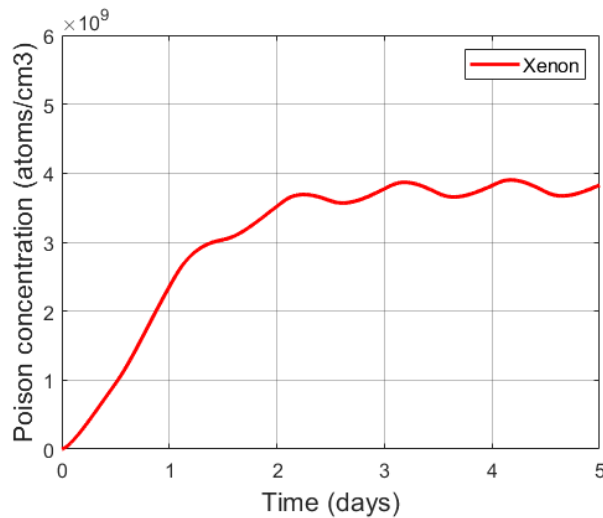


Figure.28 Xenon concentration variation in reactor core in load-following operation during 5 days

7. RESULTS ANALYSIS

The first observation of the variation curves of the reactor parameters, as shown in Figures 11, 12, 13 and 14, clearly indicates that the power and reactivity profiles are in agreement with the theory of the behavior of a nuclear reactor core perturbed by the introduction of external reactivity. Indeed, after the insertion of 0.2β reactivity, a power jump from 10 MWt to 12 MWt is recorded. The total reactivity is reduced to negative values under the effect of the negative temperature feedback from the moderator and the fuel. This effect is one of the safety conditions to be considered in the design of nuclear reactors.

As shown in Figure 17, the xenon concentration variation curve indicates that during the simulation duration (300 seconds), the insertion of 0.7β reactivity results in an increase in the xenon concentration that has not yet reached the saturation level. To observe the xenon dynamics, it is necessary to repeat the simulation with a duration of several days of operation. The result of this last simulation is shown in Figure 18. The figure reveals that xenon attains a maximum production at $t=50\,000$ seconds, approximately 13 hours after the start of reactor operation. After this maximum point, the xenon concentration undergoes a decrease and finally returns to the initial state of this xenon parameter. A comparison of the simulation and reference results, as illustrated by the curves of each reactor parameter in Figures 19 and 20, facilitates the verification of the difference between the two results. Consequently, the power and reactivity curves offer insight into a minor deviation between the simulation and reference results, as the curves are nearly superimposed. This demonstrates that the behavior of the modeled reactor core responds correctly to external reactivity insertions. This observation has enabled the validation of

the mathematical model of the nuclear reactor core developed.

In Figure 21, the two power curves (setpoint/model) offer insights into the efficacy of load-following. The model power demonstrates a high degree of proximity to the setpoint throughout the entire range of points. However, upon examination of the model's initial behavior, a notable transient is identified, persisting for several seconds before eventually converging towards the setpoint power. The transient's profile, depicted in Figure 21 above the power curve, highlights its transient nature. An analysis of the results presented in Figure 22 shows that the power control performed by the Fuzzy controller is accurate and of equivalent quality, as evidenced by the proximity of the two power curves. In comparison with the control performed by PID and shown in Figure 21, it is observed that the transient regime indicated above the power curve does not exceed one second. This result demonstrates the superior efficiency of the fuzzy controller in terms of load following control.

As the variation of the total reactivity parameter shown in Figure 23 confirms, the reactivity introduced by the control bar modifies the power in the core. Initially, reactivity is augmented to elevate the core power, and subsequently, it is reduced to zero in instances of power stabilization at either a nominal level of 100% or a minimum level of 60%. Ultimately, reactivity is decreased to decrease the core power. However, in the context of PID power control, and subsequent to a rigorous examination of the reactivity variation corresponding to the steady state of the model (second cycle of the scenario), it is evident that the impact of the PID controller's acceptable stability has influenced the reactivity variation by inducing a band of variation for this parameter throughout the duration of the simulated scenario. A further examination of the variation in reactivity during the second cycle of the scenario, as illustrated in Figure 24, reveals that the enhanced stability of the fuzzy controller results in a transformation of the reactivity variation into a thin line curve, as opposed to a band of values.

With a focus on the moderator and fuel temperature variations illustrated in Figure 25 and 26, the respective curves indicate that these temperatures align with the direction of power variation in the reactor core. Initially set at 290°C , the temperatures of the moderator and fuel oscillate within the specified limit values of 297°C and 302°C , respectively, and 500°C and 650°C , respectively. Therefore, the temperatures fluctuate within the same limits observed for power monitoring by PID and FLC controllers. This phenomenon can be attributed to the response time of temperature variations, which is inherently limited. As a result, the discernment of these fluctuations in particularly brief simulation time steps is limited.

The last observation concerning the xenon dynamics, shown in Figure 28, makes it possible to show the xenon oscillations that have reached a stationary regime after 3 days of reactor operation. The negative effect of these oscillations is generally suppressed by a special group of control rods.

8. CONCLUSION

In this study, a mathematical model of the nuclear reactor core is developed based on the reactor point kinetic approach. The analysis of the results obtained at the output of the tested model, in open loop, for two reactivity insertions of 0.2β and 0.7β , made it possible to note that the profiles of these parameters are correct and consistent with the theory dictated by the physics and thermohydraulics of nuclear reactors. With regard to the comparison of these results with other reference results, it was possible to validate the mathematical model before moving on to testing the closed-loop model. Therefore, a load following scenario was defined and fuzzy and PID controllers were designed and implemented in the validated mathematical model of the nuclear reactor core. The results of the power control, after analysis, showed that the fuzzy controller was more efficient than the controller in terms of sensitivity to xenon oscillations, which cause power oscillations. This better performance of the fuzzy controller is also seen in the reactivity variation curve, which shows a linear variation without oscillations, unlike that obtained by the PID, which shows a variation band. In order to follow up this work, it is planned to implement other power control strategies to study the performance of the control techniques in the face of the complexity constraints of the developed mathematical model and the poisoning in the core of the nuclear reactor.

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λ	Radioactive decay constant, s ⁻¹
μ_f	Total heat capacity of the fuel, MW.s.°C ⁻¹
μ_c	Total heat capacity of coolant, MW.s.°C ⁻¹
Ω	Heat transfert coefficient fuel/coolant, MWs/°C
γ_X	Xenon yield by fission;
γ_I	Iodine yield by fission;
λ_X	Xenon decay constant ;
λ_I	Iodine decay constant;
α_f	Fuel temperature reactivity coefficient, $\Delta k.k^{-1}.^{\circ}C^{-1}$
α_c	Coolant temp-reactivity coefficient, $\Delta k.k^{-1}.^{\circ}C^{-1}$
σ_X	Microscopic absorption of xenon, cm ²
Σ_f	Macroscopic fission cross-section of fuel, cm ⁻¹ .
τ	derivative time constant assumed to be fixed

NOMENCLATURE

C_{ri}	ith Group normalized precursor density,
G_r	Control rod total reactivity, pcm or $\Delta k.k^{-1}$
M	Flow rate by the coolant heat capacity, MW.s.°C ⁻¹
M_r	Number of fuzzy rules
P_0	Initial equilibrium (steady-state) power, MW
K_P	proportional gain
K_I	integral gain
K_D	derivative gain
T_{f0}	Fuel temperature at initial condition, °C ;
T_{c0}	Coolant temperature at initial condition, °C ;
T_f	Fuel average temperature , °C
T_{out}	Coolant outlet temperature, °C
T_{in}	Coolant inlet temperature, °C
$e(t)$	Error signal between setpoint and output signal
$u(t)$	Model input signal (control action).
f_f	Fraction of reactor power deposited in the fuel
n_r	Normalized neutron density, %
μ^*	FLC output
$\hat{\mu}^{-1}$	Center of the fuzzy set
μ_{B^i}	Degree with the Ith fuzzy rule is applicable
ρ_T	Total reactivity in reactor core, $\Delta K.K^{-1}$
β	Total delayed neutron fraction,
Λ	Effective prompt neutron life time, s