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Fuzzy Power Controller Design for Purdue University Research Reactor-1

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***Abstract*—**The Purdue University Research Reactor-1 (PUR-1) is a 10 kWth pool-type research reactor located at Purdue University's West Lafayette campus. The reactor was recently upgraded to use entirely digital instrumentation and control systems. However, currently, there is no automated control system to regulate the power in the reactor. We propose a fuzzy logic controller as a form of digital twin to complement the existing digital instrumentation system to monitor and stabilize power control using existing experimental data. This work assesses the feasibility of a power controller based on a Fuzzy Rule-Based System (FRBS) by modelling and simulation with a MATLAB algorithm. The controller uses power error and reactor period as inputs and generates reactivity insertion as output. The reactivity insertion is then converted to control rod height using a logistic function based on information from the recorded experimental reactor control rod data. To test the capability of the proposed fuzzy controller, a point-kinetic reactor model is utilized based on the actual PUR-1 operation conditions and a Monte Carlo N-Particle simulation result of the core to numerically compute the neutronics parameters of reactor behavior. The Point Kinetic Equation (PKE) was employed to model dynamic characteristics of the research reactor since it explains the interactions between the spatial and time varying input and output variables efficiently. The controller is demonstrated computationally using various cases: startup, power maneuver, and shutdown. From the test results, it can be proved that the implemented fuzzy controller can satisfactorily regulate the reactor power to follow demand power without compromising nuclear safety measures.

***Keywords*—**Fuzzy logic controller, power controller, reactivity, research reactor.

I. Introduction

NUCLEAR power plants and research reactors are complex, time variant, constrained systems where state variables vary with operating power levels which may affect the systems performance [1]. In view of this, reactor systems and equipment must be monitored and controlled with a robust control system to guarantee compliance with nuclear safety requirements. Purdue University's Reactor number 1 also known as PUR-1 is the first and maiden nuclear reactor in the state of Indiana. The reactor is designed to and currently operates at 10 kWth.

PUR-1 is also the first reactor in the United States that uses entirely digital instrumentation and control systems. During reactor operation, it is possible to have some oscillations in the power level due to reactivity feedback, especially when there is a change in the power demand set by the operator. As a result, it is important to adjust the control rod position to maintain the power level in compliance to regulatory safety limits. The present digital system of PUR-1 makes it feasible to implement a fuzzy controller using the period and power change rate as inputs and reactivity as output to determine the appropriate control rod position required to regulate the power level.

Some of the benefits of a fuzzy logic controller comprise power stabilization, ensuring automatic increase and decrease in power, automatic reactor start-up, covering a wide range of conditions, overcoming non-linearity for better system response, and being able to assist operators to make better and more informed decisions. These benefits informed and motivated the implementation of a fuzzy controller to be integrated into the digital control system of PUR-1. Fuzzy controllers have been incorporated in the use of automatic controls for Light Water Reactors (LWRs) and research reactors such as the TRIGA reactor at the National Nuclear Center of Mexico [2].

In this study, a fuzzy logic controller was developed using the knowledge of operator actions during manual reactor operations as well as the non-linearities introduced by slow control rod drive mechanisms. The kernel fuzzy rule based inferenced system ensures smooth transitions between different power levels and stability within the safety margins of reactor operation.

II. PUR-1 Research Reactor

The Purdue University's research reactor was built by Lockheed Nuclear Corporation in 1962 and is mostly used for reactor physics and materials research. The reactor core is approximately 2 ft^3 in volume and is fueled by 190, 19.75% enriched, U2Si3-Al fuel plates clad in Al- 6061. The active core region consists of 16 fuel assemblies containing up to 14 fuel plates each and is surrounded by 20 graphite reflector assemblies. The core sits on an aluminum grid plate at the bottom of a 17 ft deep, 6400-gallon pool of water which acts as a coolant, moderator, and shielding for the reactor. A large amount of water between the core and the surface allows for people to directly observe the operation of the reactor [3]. The reactor is controlled using two borated stainless steel control rods, known as Shim-Safety 1 (SS1) and Shim-Safety 2 (SS2), and one air-filled stainless-steel regulating rod known as the RR rod. Currently, control of each control rod and the core power level is performed manually by the operator without any

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assistance from automated controllers. Four power detectors optimized for different power range are used to record the reactor power from startup to full power. The neutron flux is measured using vertical in-core neutron detectors placed within the reactor core. Since the reactor's upgrade to an all-digital system, the recorded power information is obtained from the Neutron Measurement System (NMS).

Monitored data such as coolant temperature, control rod positions, power change rates, etc., are collected and stored in real-time allowing for future analysis of the data. A high fidelity MCNP (Monte Carlo N-Particle Code) model of the PUR-1 reactor was utilized to determine key parameters of the reactor such as the six-group delayed neutron fractions and mean generation time to tailor our PKE model to PUR-1 [4]. An image of PUR-1 and an XY plane cross-section of the PUR-1 MCNP geometry can be seen in Figs 1 and 2.

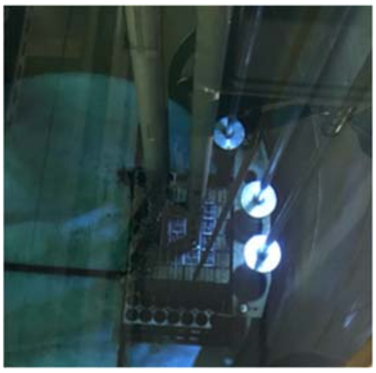


Fig. 1 PUR-1 pool type reactor core

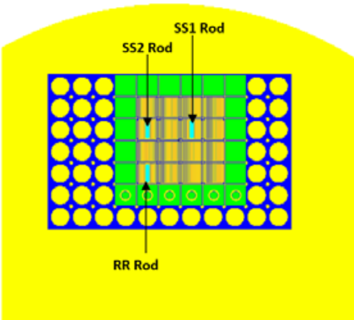


Fig. 2 MCNP core geometry with control rod locations

III. Methodology

A. Numerical Implementation Using MATLAB

We begin by modelling the dynamic behavior of the nuclear reactor system by the point kinetic model in space and time. The PKE using the exact parameters specific to PUR-1 reactor conditions are examined and discretized to develop a better understanding of how different physical parameters behave under varying types of transients. The PKE is shown as:

$$\dot{P}(t) = \frac{(\rho(t)-\beta(t))}{\Lambda(t)} P(t) + \frac{1}{\Lambda_0} \sum_k \lambda_k \zeta_k(t) + \frac{1}{\Lambda(t)} s(t) \quad (1)$$

$$\dot{\zeta}_k(t) = -\lambda_k \zeta_k(t) + \frac{\Lambda_0}{\Lambda(t)} \beta_k(t) P(t), k = 1{:}K \quad (2)$$

and are discretized using the theta method coupled with the exponential transform method to reduce the stiffness of the equation. Table I describes the meaning of parameters used in this section. The theta method is used for the flux level equation and can be altered to represent the explicit, implicit, and Crank-Nicolson (C-N) methods when $\theta = 0$, 1, and 1/2. This project only uses the C-N method since it exhibits second-order quadratic convergence which yields a more accurate solution for small-time step size. The precursors are analytically integrated over each time step with a linear approximation of the fission rate during each time step. These are the critical reasons why the PKE needs a small timestep to avoid oscillations in the solution [5].

A program was developed in MATLAB which numerically solved the PKE. The program can handle any number of delay groups as well as ramp reactivity. The β, λ, and Λ values were provided from PUR-1 data and are shown in Table I.

TABLE I
VARIABLES USED IN PKE

$\dot{P}(t)$	Unnormalized power/flux level
Δt	Time-discretization time step
$\zeta_k(t)$	*k*th precursor density
β_k	*k*th delayed fraction
Λ	Neutron generation time
λ_k	*k*th group decay constant
S_d	Delayed source term
θ	User-input parameter for finite differencing
ρ_{im}	Imposed reactivity
γ_d	Doppler feedback constant

TABLE II
SIX DELAYED GROUP PARAMETERS

Group	λ	β (%)
1	0.0128	0.02584
2	0.0318	0.15200
3	0.119	0.13080
4	0.3181	0.30704
5	1.4027	0.11020
6	3.9286	0.02584

The temporal integration method is applied to the flux level equation (denoted as R) per time step (denoted by n and n-1):

$$\frac{1}{v}[\phi^n(x) - \phi^{n-1}(x)] = \int_{t_{n-1}}^{t_n} R(\phi, x, t)\, dx \approx \Delta t_n(\theta R^n + (1-\theta)R^{n-1}) \quad (3)$$

The thread value $\theta[0,1]$ allows the equations to range from fully explicit all the way to fully implicit. We approximate the flux between the time-steps as a linear change seen as:

$$\frac{1}{v}[\phi_n(x) - \phi_{n-1}(x)] \approx \Delta t_n \left[\frac{1}{v}\frac{\phi_n(x)-\phi_{n-1}(x)}{\Delta t_n}\right] \quad (4)$$

Having enough information to solve for the flux level (and power) at each time-step from this discretization scheme, we restate that a small Δt was needed to avoid oscillations in the solution, somewhere on the order of $\sim 10^{-5}$ s. Having such fine time-steps made the calculations very expensive. Additionally, a reasonably sized Λ ensures computational stability especially with respect to the explicit method when $\theta < 0.5$. Thus, the exponential transform method was introduced. This method transforms the equations by multiplying each term by an exponent term, such as:

$$y(t) = \tilde{y}(t)e^{\alpha t} \tag{5}$$

which transforms to

$$\frac{d\tilde{y}(t)}{dt} = -(\lambda + \alpha)\tilde{y}(t) \tag{6}$$

This establishes a shift of $|\lambda+\alpha|$. If the alpha parameter is close in value to negative λ, this allows the PKE stiffness to soften, allowing for a wider range of time-steps to be applied.

Applying the same methods to the precursor equation results in k+1 equations and k+1 unknowns. Since the precursors only depend on power and happen to be independent of each other, we can bypass introducing finite differencing error to the precursor equations. However, we do introduce a small error by approximating the fission rate as linear between time-steps:

$$G(\tilde{t}) \equiv \frac{\Lambda_0}{\Lambda(\tilde{t})}\beta_k^{eff}(\tilde{t})p(\tilde{t})e^{-\alpha\tilde{t}} \approx G^n w + G^{n-1}(1-w) \tag{7}$$

This is a sufficient approximation given that the time steps do not get too large. $G(\tilde{t})$ is used for the order of precursor integration when approximating the fission rate. It can be linear like in (7) or quadratic (not shown). The parameter w is a fixed value between 0 and 1 to approximate the linear dependence between the current and previous timesteps. We can then directly solve for the flux from (7) at each time step. We use the transformation parameter α^n to solve for the precursors' concentrations at t_{n-1}. From there, we use it to calculate the delayed source $\hat{S}_d$ and S_d at t_n and t_{n-1}. We use this new information to calculate the flux level at t_n. We accept this value if the transformed solution is closer to linear than the original solution. Otherwise, we redo the previous steps for $\alpha_n = 0$. We do this for every time step which allows us to collect the necessary info, flux level, and precursor over the analyzed period. We can update the period at any time from (9) below and pass it along with the power to the fuzzy controller.

$$\rho = \frac{\Lambda}{T_t} + \sum_k \frac{\beta_k}{1+\lambda_k T_t} \tag{8}$$

where the reactor period (T) is defined as:

$$T = \frac{1}{\omega} \tag{9}$$

The reactivity output-input to the PKE is a ramp reactivity from the Control Rod (CR) system's algorithm developed in this work, which limits the rate of reactivity insertion or addition. To account for feedback, the doppler and all the coolant temperature feedback are accounted for by ρ (reactivity). All the rest are considered by ρ_{im}(impulse reactivity), which is a constant value that is read-in by the reactor. We typically solve for the second part in (10) which accounts for the feedback reactivity.

$$\rho(t) = \rho_{im}(t) + \gamma_d \int_0^t (H(t') - P_0)\exp\left(\lambda_H(t'-t)\right)dt' \tag{10}$$

However, we only consider the impulse since it is easier to obtain. Thus, the input reactivity from the FRBS is impulse reactivity from the CRs. The approximated reactivity and temperature feedback coefficient λ_H was 1.0 seconds as well as the doppler coefficient γ given as $\left(-\frac{1.2\$}{fp}\right)$ as indicated in the PUR-1 CR experimental data used in this work.

B. Fuzzy Controller System

The control loop of the power control system using the FRBS for PUR-1 is shown in Fig. 3. This fuzzy controller couples the FRBS and the PKE model as represented in the control loop shown in Fig. 3. The implemented FRBS is a Mamdani-type fuzzy system, which has the following stages:

- Fuzzification of inputs using fuzzy sets
- Rule evaluation using the inference system
- Aggregation of consequent rules
- Defuzzification using Center of Gravity (COG) method

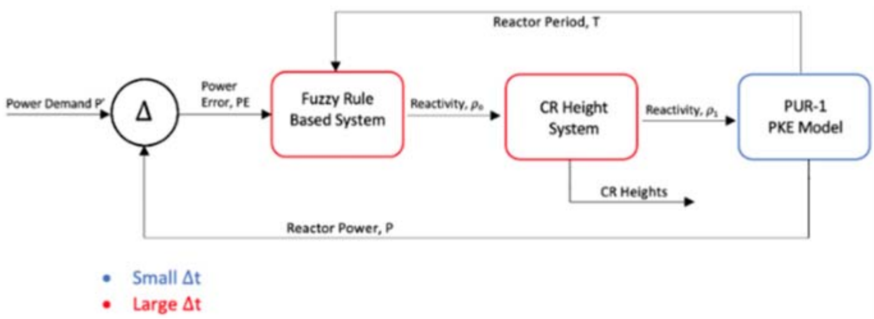


Fig. 3 Fuzzy Logic Control Loop

In this work the crisp input variables for the fuzzy system are Power Error, Reactor Period. Reactivity is the output control signal which can be changed by inserting (insertion) or withdrawing CRs from the reactor core. The fuzzy rule-based inference system is developed based on expert's understanding of the nuclear research reactor operation associated with membership functions. These fuzzy rules are used to manipulate the output reactivity control signal to the desired response. The Max-Min inference system is used in this work where the firing strength was determined by the maximum intensity of the control output reactivity fuzzy set. Aggregation is done by the Max function by the union of fuzzy sets that represents the output of the rules into a single fuzzy set used to decide the value of the final output. Defuzzification is done by combining the fuzzy set from the aggregation process into a single scalar crisp quantity for the reactivity control variable using the COG method as [6], [7]:

$$\rho = \frac{\int_x \mu_A(x)xdx}{\int_x \mu_A(x)dx} \tag{11}$$

where $\mu_A(x)$ represents the aggregated membership function, x is the fuzzy set of the output variables.

C. Fuzzy Sets Description

For the fuzzy controller design, two inputs fuzzy sets are used to obtain one output control signal. The fuzzy sets can be described as follows:

- Input 1: Power Error (Measured - Demand Power, in %)
- Input 2: Reactor Period (T, in seconds)
- Output: Reactivity Insertion (ρ, in $)

Fuzzy sets for the error in reactor power are presented in Fig. 4. The fuzzy sets consist of five membership functions defined using trapezoidal and triangular plots. The zero error is defined as EZ to represent the ideal condition of the reactor when the measured power is quite close to the power demand.

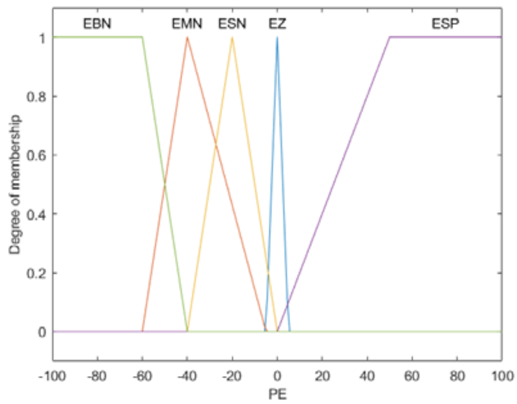


Fig. 4 Fuzzy sets for power error: EBN (Error Big Negative); EMN (Error Medium Negative); ESN (Error Small Negative); EZ (Error Zero); ESP (Error Small Positive)

The EZ membership function ranges from -5% to 5% error with a peak in the 0% error. As many as five membership functions are used for the reactor period fuzzy sets as shown in Fig. 5. Since the reactor period represents how fast the reactor power changes as a response to the reactivity insertion, the fuzzy sets are used to control this rate. For example, in the critical and little critical periods, a positive reactivity insertion should be avoided at any cost. At this level, the reactor power can increase dramatically in just a few seconds.

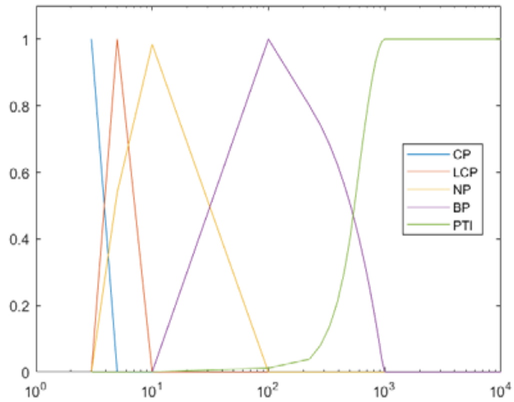


Fig. 5 Fuzzy sets for reactor period: CP (Critical Period); LCP (Little Critical Period); NP (Normal Period); BP (Big Period), and PTI (Period Tends to Infinity)

For the reactivity control signal output, six different membership functions are used for the fuzzy sets as shown in Fig. 6. The values range from -0.4$ to 0.4$ to avoid the reactor period being very small and unsafe for reactor operation. The reactivity insertion impacts the reactor period directly.

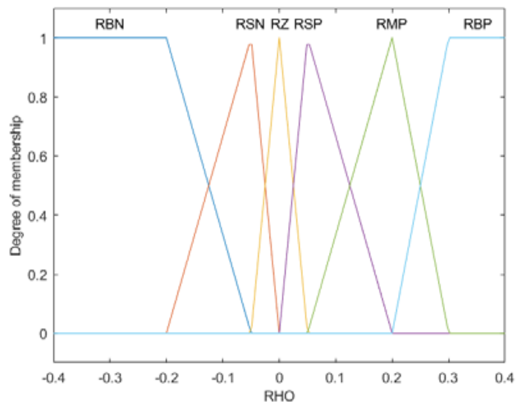


Fig. 6 Fuzzy sets for reactivity insertion (in $): RBN (Reactivity Big Negative); RSN (Reactivity Small Negative); RZ (Reactivity Zero); RSP (Reactivity Small Positive); RMP (Reactivity Medium Positive); RBP (Reactivity Big Positive)

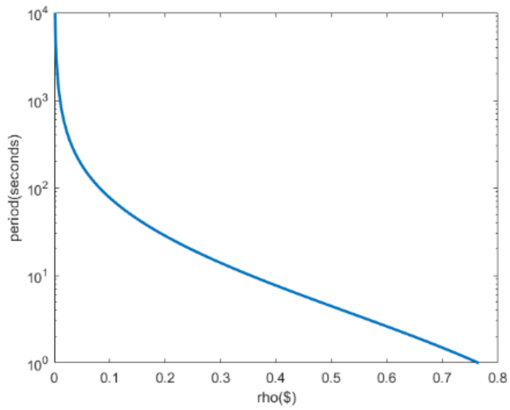


Fig. 7 Period versus reactivity insertion using reactivity equations

The relationship between reactivity and period is presented in Fig. 7. In this figure, the period tends to go infinitely large for small reactivity.

The 0.4$ limit is chosen for the reactivity insertion limit because the period in this value will be around 10 seconds, which is just a little bit above the critical period.

Since there are five membership functions of power error and period fuzzy sets respectively, the fuzzy rules consist of 25 conditions (5x5). It can be observed in Fig. 8 that the fuzzy rules include all the input fuzzy sets defined.

Power Error Fuzzy Sets	Period Fuzzy Sets: CP	LCP	NP	BP	PTI
EBN	RZ	RZ	RSP	RMP	RBP
EMN	RZ	RZ	RSP	RSP	RMP
ESN	RZ	RZ	RZ	RSP	RSP
EZ	RSN	RZ	RZ	RZ	RZ
ESP	RBN	RSN	RSN	RSN	RSN

Fig. 8 Fuzzy rules with given input and output fuzzy sets

As explained previously, there is no positive reactivity insertion in the critical period and little critical period. On the other hand, if the period is going to be infinitely large, a bigger reactivity insertion applies.

D. CR System

The FRBS controller proposed in this work to control the PUR-1 power is similar to what is currently done during manual operation. Experimental data recorded from several startups, shutdowns, and power level changes were analyzed to determine the maximum power change rate utilized in actual operation along with the typical CR movement procedures used to achieve startup and shut down. All of these parameters are recorded by PUR-1's digital system and are easily plotted to observe patterns. One of the greatest real-world limiting factors for operation is the conservative nature of changing the power level. During normal operations, a power change rate of 2 %/s is rarely exceeded which means going from zero to full power can take up to 15-20 minutes. Due to this, the maximum reactivity the FRBS can call for is limited to about 180 pcm which is the amount of reactivity needed to initiate a roughly 2 %/s power change rate. Additionally, the SS1 and SS2 rods are typically not used for power level changes so all power changes are performed using the RR rod. These operating procedures can be seen in the PUR-1 experimental data for a simple power up from zero to near full power seen in Figs. 9 and 10.

To convert the reactivity requested by the FRBS to CR positions or heights it is necessary to know the rod worth curves for all three rods. All three CRs for PUR-1 have a maximum movement of 62.5 cm. From experimentation, the integral rod worth curves for SS1 and SS2 are known. However, only the integral rod worth of the RR rod is unknown [8]. To determine the reactivity worth of any given rod movement each rod worth curve was fit to a linear logistic function described below which was then used to determine the change in rod position for a given change in reactivity.

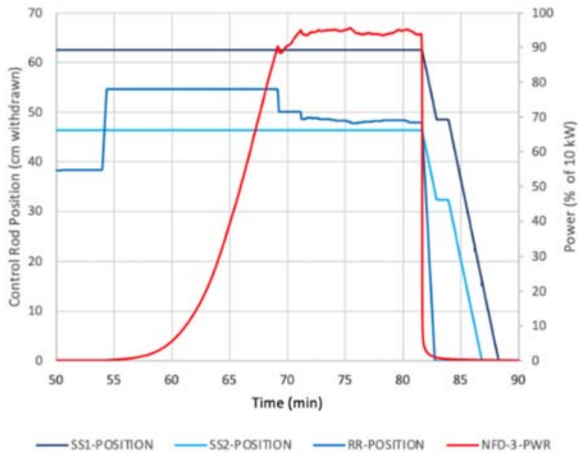


Fig. 9 Experimental CR positions versus power

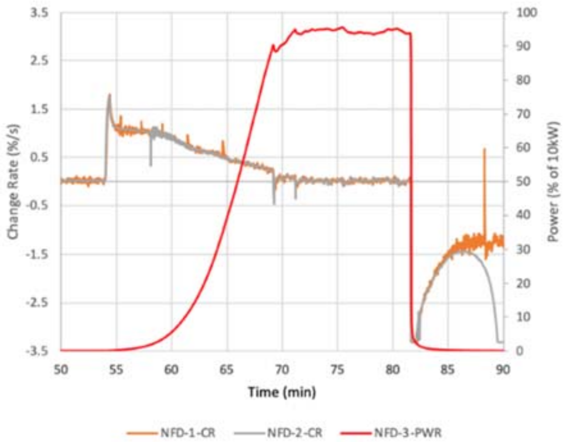


Fig. 10 Experimental power change rate versus power

The CR worth is the change in reactivity caused by rod motion. Insertion of the most negative reactivity is the location in the reactor core at maximum flux value. Reactivity efficiencies of CRs need to be quantified to ensure the power level regulation to satisfy nuclear safety conditions. This can be obtained by calibrating CRs where calibrated positions or heights can help determine the excess reactivity of the core. Fig. 11 shows the flow chart algorithm used in the MATLAB code for the FRBS automatic CR system.

The CR experimental data for PUR-1 used in validating this work follow the integral rod worth characteristics given ρ(s) as the reactivity worth at a position s and ρ(H) be the total reactivity worth of fully inserted rod of total height H of the reactor core related as [9]:

$$\rho(s) = \frac{H \cdot \rho(H)}{\pi}\left[\frac{\pi s}{2H} - \frac{\sin}{4}\left(\frac{2\pi s}{H}\right)\right] \qquad (12)$$

The total reactivity ρ_t located at the maximum height is given by:

$$\rho_t = \frac{H \cdot \rho(H)}{2} \qquad (13)$$

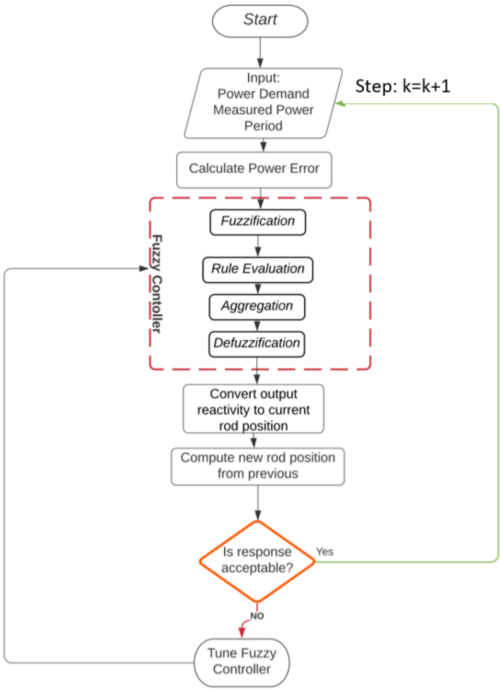


Fig. 11 Automatic CR System Algorithm

Reactivity at a particular rod position is approximately:

$$\frac{\rho(s)}{\rho_t} = \left[\frac{s}{H} - \frac{1}{2\pi}\sin\left(\frac{2\pi s}{H}\right)\right] \quad (14)$$

In an ideal system, the reactivity change called for by the FRBS would be able to be applied to the core instantly, but this would require an instantaneous movement of the CRs. In Purdue's research reactor, the amount of reactivity that can be added or removed in a given period without initiating a scram is limited by the rate at which the CRs can be moved. The SS1 and SS2 rods have a maximum speed of 4.4 in/min while the RR rod has a maximum speed of 17.7 in/min. This actual limit is used to adjust the reactivity requested by the FRBS through the CR system. Each time step the CR system takes the reactivity requested by the FRBS and determines how much reactivity can be added based on the maximum speed of the CRs. If the CRs can be moved, the amount required to fulfill this reactivity worth is output from the CR system to the PKE model along with the updated new position of the CR. If the reactivity requested is not achievable in one timestep then the CR system outputs the maximum amount of reactivity change, achievable for that time step, to the PKE model, and the CRs are then moved the maximum amount each subsequent timestep until either the FRBS calls for a different reactivity or the original reactivity amount called for is achieved. The CR position adjustments in the CR system follows the summarized algorithm where $\bar{s}_{new}$ is the updated rod height based on the previous rod position indicated by as $\bar{s}_{old}$ The change in CR position and reactivity is denoted as $\Delta\bar{s}$ and $\Delta\rho(s)$ respectively:

$$\bar{s}_{\text{new}} = \bar{s}_{\text{old}} + \Delta\bar{s} \quad (15)$$

$$\Delta s(i) = \begin{Bmatrix} \min(\Delta\bar{s})\,, if\ \Delta\rho(s) < 0 \\ \max(\Delta\bar{s})\,, if\ \Delta\rho(s) > 0 \end{Bmatrix} \quad (16)$$

IV. Results

To demonstrate the capability of the designed fuzzy controller, some operational tests were conducted using our developed MATLAB code and the results are discussed in this section.

A. CR Height

In the CR system, only the RR rod is moved to initiate changes in reactivity. If the RR rod reaches its maximum amount of movement and has not yet achieved the desired reactivity, the SS1 rod moves a preset amount to allow the RR rod to reset allowing for additional room for changes in reactivity. Comparison between measured and fuzzy simulated output by adjusting the CR system positions to achieve requested reactivities can be seen in Fig. 12.

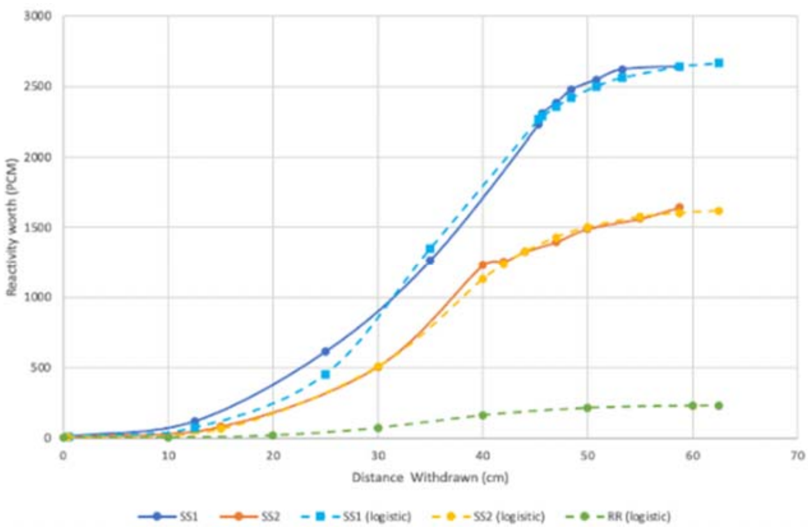


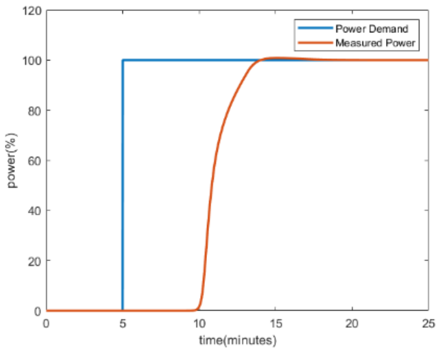
Fig. 12 Measured rod worth (Smooth lines) and Fuzzy Simulated (logistic) rod worth curves

B. Automatic Operation Test Cases

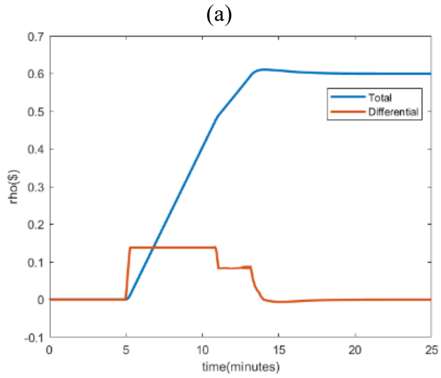
The operational test cases include the start-up operation, power maneuver, and shutdown. These three tests are important to the reactor operation and cover all the necessary parts of the power controller, to increase, decrease and maintain the reactor power.

C. Reactor Start-up

The plots of power and reactivity insertion evolution for each minute of the startup process are presented in Fig. 13. This case illustrates the reactor startup in PUR-1 going from zero power to full reactor power. The demanded power was set to 100% at five minutes time stamps. Currently, when this process is conducted, the PUR-1 reactor operator will need to manually adjust the CR position to give a positive reactivity insertion. The fuzzy controller developed in this work is capable of adjusting the measured power to follow the power demand automatically as shown in Fig. 13 (a).



(a)



(b)

Fig. 13 Power (a) and reactivity insertion, (b) during reactor startup

In Figs. 13 (a) and (b), the reactivity insertion for each time step is given during reactor start up. Initially, a positive reactivity insertion is given to increase the reactor power. After reaching the demanded power, the reactivity insertion is decreased eventually back to 0.0$ to further stabilize the constant power. The CR height evolution is presented in Fig. 14. It can be observed that, this follows a similar shape with the reactivity insertion and the power experimental plot shown in Fig. 9 earlier. On a side note, only the RR (regulating rod) CR moved in this case, resulting in sufficiently slow, but safe power changes. To provide positive reactivity insertion, the CR is raised from 30 cm to approximately 42 cm of height. After the power level reached the demanded power, the CR is returned gradually to its initial position.

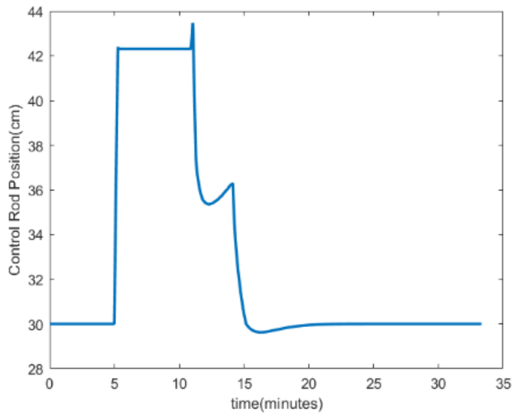
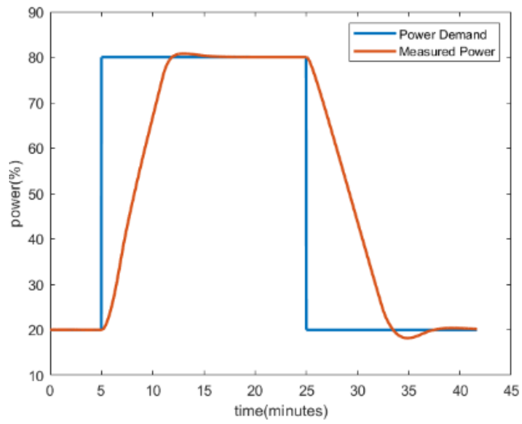


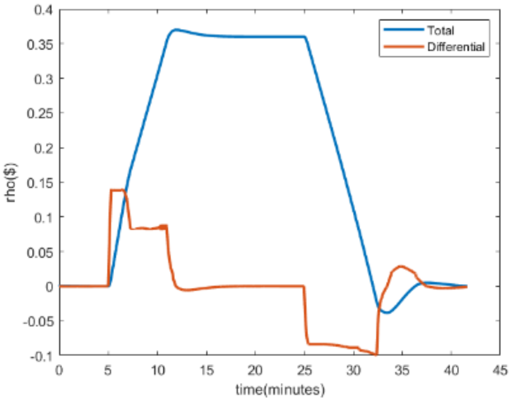
Fig. 14 CR height profile during reactor startup

D. Power Maneuver

The next cases to test are related to the power maneuver. The power maneuver scheme used for this purpose is the power maneuver from 20% to 80% then back to 20%. These results are used to assess the capability of fuzzy controllers to follow the power demand change on time. To demonstrate the flexibility of the fuzzy controller to fulfill the demanded power, another test is presented in Fig. 15. In this case, after five minutes of reactor operation at low power (20%), the power is demanded to increase to high power (80%). After around 20 minutes, the power is set to decrease again to 20% power. In less than 10 minutes, the reactor can achieve the power demand for increasing or decreasing power. In the plot, we can also see that there is an overshoot and undershoot in the power level. However, the fuzzy controller can fix this quickly to maintain the reactor power to the demanded power.



(a)



(b)

Fig. 15 Power evolution (a) and reactivity insertion (b) in the case of power maneuver from 20% to 80%, then back to 20%

E. Shut Down

For the final test, a demonstration for reactor shutdown is conducted as shown in Fig. 15. It can be observed that the reactor can reach zero power level in around 15 minutes from the full power. With the fuzzy controller, there is no need to manually adjust the power level using CRs. Instead, the fuzzy controller will automatically and slowly reduce the power level until zero power is achieved and the reactor can be shut down safely.

V. Conclusion

The main contribution of our work is to propose a feasible digital twin in the form of a fuzzy controller to complement the existing digital instrumentation control system of the PUR-1 research reactor for power stabilization. This would aid in monitoring the life cycle of the reactor and fuel elements through the analysis of big data which would tackle nuclear safety, security, and safeguards concerns.

In this paper, we have been able to prove that a fuzzy controller can be used to provide a way to control the power output of a research reactor using modelling and simulation techniques with our MATLAB algorithm. The important consideration of the proposed Fuzzy logic controller as an integration to the existing digital system is to maintain a fail-safe condition during the automatic operation of the reactor to prevent possible operator errors to ultimately adhere to nuclear safety limits. We have also been able to prove that the PUR-1 reactor can be accurately represented by a PKE model coupled with an FRBS. A simple set of rules, based upon the expert knowledge of reactor operation, can achieve power control in place of an operator. The fuzzy controller has guaranteed smooth transitions during possible transients with inherent stability encountered during operation of the research reactor under study. This proves that the proposed system should be able to eventually replace the manual control system after the fuzzy parameters have been tuned based on the heuristic membership functions in the inference system. This work can be further extended to experimentally test the fuzzy controller in the PUR-1 research reactor at Purdue University.

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