Evaluating the Transient Handling Capability of a Fuzzy Logic Controller for a Pressurized Heavy Water Reactor

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Abstract: Safe and reliable control of a nuclear reactor with sufficient accuracy has been a challenging task. The objective of this work is to evaluate and validate a Fuzzy Logic Controller (FLC) scheme for a Pressurized Heavy Water Reactor (PHWR) that not only provides a safe and reliable operation but also a fast, accurate and robust reactor control, especially under transient conditions. For evaluating an FLC, a 22^{nd} order Single-Input Single-Output (SISO) model of the PHWR has been selected. We consider Xenon and Iodine dynamics, fuel and coolant temperature feedbacks and delayed and photo neutron concentrations in the model. The Mamdani inference engine type FLC is selected here. Due to the very stringent requirement on control system to be rugged and safe in a nuclear power plant, the controller is simulated, evaluated and validated for the three practical case scenarios; (i) step power change, (ii) reactivity disturbance, and (iii) loss of grid scenario. The results show that the controller performs well in terms of safety, reliability and robustness.

Keywords: Fuzzy Logic Controller, Safety, Reliability, Pressurized Heavy Water Reactor, Transient Handling.

1. INTRODUCTION AND RELATED WORK

A Pressurized Heavy Water Reactor (PHWR) like any non-linear system, is an instance of a highly complex and unstable system. The design of a safe, reliable, and accurate nuclear reactor controller has been a continuously investigated research problem.

With classical control techniques, it is difficult to meet the performance requirements for the control of nuclear reactor (Cheng *et al.,* 2009). Moreover, for designing controller using linear control schemes, the nonlinear model has to be linearized around an operating point. The limitation with such a linearized system is that it can only predict the local behavior of the system around that point (Hassan, 2002). However, designing the controller using the FLC scheme does not require the model to be linearized which is one of the several advantages of the FLC. In addition, the FLC comes under the group of intelligent control schemes and an intelligent control is a good candidate for a nonlinear and time dependent system (Cheng *et al.,* 2009; Ismael and Yu, 2006).

Research on fuzzy logic-based control of a nuclear reactor started a few decades ago. (Na and Bien, 1995) proposed a fuzzy logic-based PWR steam generator water level control system. (Si-Fodel *et al.,* 1998) developed a fuzzy rule base for the control of a nuclear reactor. (Ruan, 2000) highlighted the safety aspects of nuclear power plants using FLC. Later, a comparative study of PID and fuzzy controller was reported by (Li and Ruan, 2000). In a more comprehensive study, the authors (Ruan *et al.,* 2005) compared the merits and demerits of fuzzy controller applications to nuclear reactor. Lately, researchers have proposed and implemented other aspects of FLC such as user interface and control (Benítez-Read, 2007; Zeng, 2007; Tonatiuh *et al.*, 2012).

The objective of this work is to evaluate the transient handling capability of the FLC for a 500 MWe PHWR. In this work, the focus is on three important practical case scenarios of reactor operation causing a transient situation i.e. step power change (increment or decrement), reactivity disturbances and loss of grid. The control of nuclear reactor is of great importance in terms of safety. Therefore, the controller for the reactor must be rugged and safe. That is why, in this work, the controller is evaluated for all possible practical case scenarios mentioned above.

A 22^{nd} order SISO model is considered here for evaluating the FLC for controlling the bulk power of the reactor especially under transient conditions. The power generated in PHWR may be controlled by controlling the reactivity. For fine control of reactivity, there is a liquid zone control (LZC) compartment in modern PHWR reactors. LZC is the primary mean for increasing or decreasing the reactor power by introducing or removing reactivity into the core, respectively. This is achieved by controlling the level of light water in the LZC (Rouben, 1999). In an earlier work (Fahad, 2012), the author considered a first order model of the LZC for designing the controllers. Though the model is quite simpler but it is deficient as it lacks the proper physical behavior of the LZC valve. In this work, this deficiency is compensated by considering the second order model of the LZC that is more close to the physical behavior as presented in the subsequent section. Moreover, in this work, a generic design of the FLC is presented, which is easier to implement, in order to show the effectiveness of the control scheme for the reactor control technology. It is also demonstrated here that the FLC with fast response can be designed by selecting the universe of discourse of the output's membership function larger than the required one and limiting the FLC output to the required signal bounds of the system under consideration.

The rest of the paper is organized as follows: in Section (2), a brief introduction of both PHWR and its SISO model is provided. In Section (3), the FLC for the PHWR is discussed. In Section (4), the results of the simulation performed in MATLAB and Simulink are reported. Section (5) gives discussion on these results. Finally, in Section 6, the conclusion and future recommendations are presented.

2. PHWR SISO MODEL

In a nuclear reactor, the neutrons, released instantaneously at the time of fission, are called prompt neutrons. There is a small group of neutrons that are released after the fission. They are due to decay of fission products and are known as delayed neutrons. In PHWR, there is another group of neutrons that are released due to the interaction of high energy gamma rays with deuterium nuclei and is known as photo-neutrons. A 6-group of delayed neutron and a 9-group of photo-neutron precursors are considered in this work. The dynamics of delayed and photo neutrons may be represented as (Duderstadt and Hamilton, 1976):

$$\frac{dC_{dj}(t)}{dt} = -\lambda_{dj}C_{dj}(t) + \frac{\beta_{dj}}{\Lambda}P(t) \tag{1}$$

$$\frac{dC_{pk}(t)}{dt} = -\lambda_{pk}C_{pk}(t) + \frac{\beta_{pk}}{\Lambda}P(t) \tag{2}$$

where P is the reactor power, C_{dj} and C_{pk} is the delayed and photo neutron precursors, respectively. λ_{dj} and λ_{pk} is the decay constant for the delayed and photo neutron precursors, respectively. Λ is the neutron generation time and β_{dj} and β_{pk} is the fractional yield of delayed and photo neutron precursors, respectively. The rate of change of power in PHWR can be defined by:

$$\frac{dP(t)}{dt} = \left[\frac{\rho(t)-\beta}{\Lambda}\right]P(t) + \sum_{j=1}^{m_d}\lambda_{dj}C_{dj}(t) + \sum_{k=1}^{m_p}\lambda_{pk}C_{pk}(t) \tag{3}$$

$$\beta = \sum_{j=1}^{m_d}\beta_{dj} + \sum_{k=1}^{m_p}\beta_{pk} \tag{4}$$

where ρ is the reactivity. The total reactivity ρ is given by:

$$\rho(t) = \rho_L(t) + \rho_{FB}(t) \tag{5}$$

where ρ_L is the reactivity due to the liquid zone compartment and ρ_{FB} is the feedback reactivity. The level of light water in the LZC is controlled via valve. The LZC valve can be modeled as:

$$\frac{dL(t)}{dt} = \frac{1}{\mathrm{T}}[L(t) + V(t)] \tag{6}$$

where $V(t)$ is the voltage signal produced by the FLC with saturator and L is the position of the valve. The liquid zone compartment can be modeled by (Talange, et al., 2006):

$$\frac{dH(t)}{dt} = -mL(t) \tag{7}$$

where $H(t)$ is the height (in percentage) of light water in the compartment and m is the constant. In this work, further non-linearity is added by restricting the LZC level between 0% and 100% in order to get more realistic behavior of LZC. The reactivity due to liquid zone can be expressed by (Talange, et al., 2006):

$$\rho_L(t) = -\mu_L[H(t) - H_0] \tag{8}$$

where µL is the reactivity coefficient for light water in the LZC.

The total feedback reactivity ρFB is composed of three elements:

$$\rho_{FB}(t) = \rho_F(t) + \rho_C(t) + \rho_X(t) \tag{9}$$

The fuel temperature reactivity ρ_F can be expressed as (Talange, et al., 2006) (Henryk Anglart, 2011):

$$\rho_F(t) = \mu_F[T_F(t) - T_{F0}] \tag{10}$$

$$\frac{dT_F(t)}{dt} = k_{F1}P(t) - k_{F2}[T_F(t) - T_C(t)] \tag{11}$$

The coolant temperature reactivity ρ_C can be expressed as (Talange, et al., 2006) (Henryk Anglart, 2011):

$$\rho_C(t) = \mu_C[T_C(t) - T_{C0}] \tag{12}$$

$$\frac{dT_C(t)}{dt} = k_{C1}[T_F(t) - T_C(t)] - k_{C2}[T_C(t) - T_{Cin}] \tag{13}$$

where μ_F and μ_C is the reactivity coefficient for fuel and coolant respectively, k_{F1}, k_{F2}, k_{C1} and k_{C2} are the constants and T_F and T_C are the fuel and coolant temperatures respectively.

There are various fission products in the reactor core that absorb the neutron population. Among them, Xenon-135 has the most substantial impact on reactor design and operation (Zeng, H., 2007). The reactivity due to Xenon ρ_X can be expressed as (Talange, et al., 2006) (Milton Ash, 1979):

$$\rho_X(t) = -\frac{\bar{\sigma}_X X(t)}{\Sigma_\mathrm{a}} \tag{14}$$

$$\frac{dX(t)}{dt} = \gamma_X\Sigma_\mathrm{f}\mathrm{P}(t) + \lambda_I I(t) - [\lambda_X + \bar{\sigma}_X\mathrm{P}(t)]X(t) \tag{15}$$

$$\frac{dI(t)}{dt} = \gamma_I\Sigma_\mathrm{f}\mathrm{P}(t) - \lambda_I I(t) \tag{16}$$

where, X is the Xenon and I is the iodine concentrations respectively while $\sum_\mathrm{a}$ and $\sum_\mathrm{f}$ are the thermal neutron absorption and fission cross sections, respectively. Similarly, γ_x and γ_I are the xenon and iodine yields, respectively. λ_x and λ_x are the xenon and iodine decay constants, respectively.

3. FUZZY LOGIC CONTROLLER

As mentioned earlier that PHWR is a nonlinear complex model and the FLC is usually found to be a good controller. Designing a Mamdani type FLC for the reactor involves the selection of membership functions for the input and outputs. In this work, triangular membership functions for both inputs and output are used. The reason for using the triangular membership functions is that they form an immediate solution to the optimization problems emerging in fuzzy modeling (Pedrycz, 1994).

There are two inputs to the FLC; error (E) and rate of error ($\dot{E}$). The membership functions for the error and rate of error are shown in Figure 1(a) and Figure 1(b), respectively. The universe of discourse for the input variables error is [-3 3] and rate of error is [-12 12]. The membership grades for the error can be expressed as:

$$\mu_{NL}^{E}(E)=\begin{cases}1, & P\le -3\\ \dfrac{-1.5-E}{1.5}, & -3\le E\le -1.5\\ 0, & otherwise\end{cases} \tag{17}$$

$$\mu_{NS}^{E}(E)=\begin{cases}\dfrac{3+E}{1.5}, & -3\le E\le -1.5\\ \dfrac{-E}{1.5}, & -1.5\le E\le 0\\ 0, & otherwise\end{cases} \tag{18}$$

$$\mu_{Z}^{E}(E)=\begin{cases}\dfrac{1.5+E}{1.5}, & -1.5\le E\le 0\\ \dfrac{1.5-E}{1.5}, & 0\le E\le 1.5\\ 0, & otherwise\end{cases} \tag{19}$$

$$\mu_{PS}^{E}(E)=\begin{cases}\dfrac{E}{1.5}, & 0\le E\le 1.5\\ \dfrac{3-E}{1.5}, & 1.5\le E\le 3\\ 0, & otherwise\end{cases} \tag{20}$$

$$\mu_{PL}^{E}(E)=\begin{cases}\dfrac{E-1.5}{1.5}, & 1.5\le E\le 3\\ 1, & E\ge 3\\ 0, & otherwise\end{cases} \tag{21}$$

The membership grades for the rate of error input can be expressed as:

$$\mu_{NL}^{\dot{E}}(\dot{E})=\begin{cases}1, & \dot{E}\le -12\\ \dfrac{-6-\dot{E}}{6}, & -12\le \dot{E}\le -6\\ 0, & otherwise\end{cases} \tag{22}$$

$$\mu_{NS}^{\dot{E}}(\dot{E})=\begin{cases}\dfrac{12+\dot{E}}{6}, & -12\le \dot{E}\le -6\\ \dfrac{-\dot{E}}{6}, & -6\le \dot{E}\le 0\\ 0, & otherwise\end{cases} \tag{23}$$

$$\mu_{Z}^{\dot{E}}(\dot{E})=\begin{cases}\dfrac{6+\dot{E}}{6}, & -6\le \dot{E}\le 0\\ \dfrac{6-\dot{E}}{6}, & 0\le \dot{E}\le 6\\ 0, & otherwise\end{cases} \tag{24}$$

$$\mu_{PS}^{\dot{E}}(\dot{E})=\begin{cases}\dfrac{\dot{E}}{6}, & 0\le \dot{E}\le 6\\ \dfrac{12-\dot{E}}{6}, & 6\le \dot{E}\le 12\\ 0, & otherwise\end{cases} \tag{25}$$

$$\mu_{PL}^{\dot{E}}(\dot{E})=\begin{cases}\dfrac{\dot{E}-6}{6}, & 6\le \dot{E}\le 12\\ 1, & \dot{E}\ge 12\\ 0, & otherwise\end{cases} \tag{26}$$

The membership function for the output is shown in Figure 1(c). The universe of discourse for the output is [-30 30]. The membership grades for the output variable can be expressed by:

$$\mu_{NL}^{Q}(Q)=\begin{cases}\dfrac{30+Q}{10}, & -30\le Q\le -20\\ \dfrac{-10-Q}{10}, & -20\le Q\le -10\\ 0, & otherwise\end{cases} \tag{27}$$

$$\mu_{NS}^{Q}(Q)=\begin{cases}\dfrac{20+Q}{10}, & -20\le Q\le -10\\ \dfrac{-Q}{10}, & -10\le Q\le 0\\ 0, & otherwise\end{cases} \tag{28}$$

$$\mu_{Z}^{Q}(Q)=\begin{cases}\dfrac{10+Q}{10}, & -10\le Q\le 0\\ \dfrac{10-Q}{10}, & 0\le Q\le 10\\ 0, & otherwise\end{cases} \tag{29}$$

$$\mu_{PS}^{Q}(Q)=\begin{cases}\dfrac{Q}{10}, & 0\le Q\le 10\\ \dfrac{20-Q}{10}, & 10\le Q\le 20\\ 0, & otherwise\end{cases} \tag{30}$$

$$\mu_{PL}^{Q}(Q)=\begin{cases}\dfrac{Q-10}{10}, & 10\le Q\le 20\\ \dfrac{30-Q}{10}, & 20\le Q\le 30\\ 0, & otherwise\end{cases} \tag{31}$$

The membership functions shown above are computed by considering the model dynamics of the PHWR. The membership functions are adjusted and tuned by performing the simulations in order to obtain the best results.

The FLC computes the output based on the value of the inputs and the associated rules and output membership functions. Several sets of rule-bases are available for the FLC. Most common are 9, 25, 49, 81 and 121 rules based rule-sets. But, increasing the rules beyond certain limits, are ineffective and inefficient because it only increases the complexity of the FLC demanding more memory and computation without improving the controller response (Seema Chopra *et al.,* 2005). For this work, 25 rule-base set is considered for the fuzzy inference as shown in Table 1 (Passino and Yurkovich, 1998).

Figure 2 shows the block diagram of the FLC based reactor power control system. The purpose of saturation block is to limit the output to ±5 volts. If we look at the membership function for the output variable, it ranges from -30 to 30 volts but in the reactor model, it is considered that the valve in the range of ±5 volts (Wallam, 2012). One way to resolve this difference is to select the universe of discourse [-5 5] volts for output membership function. But, it makes the control action too sluggish. Other way is to use the saturator to restrict the output to ±5 volts and design the membership function for voltage greater than ±5 volts without slowing the controller response and that has been done here. Figure 3(a) and 3(b) show the surface plot of the defined rules without saturator and with saturator, respectively. The saturator can be represented by:

$$V(Q) = \begin{cases} -5, & U \leq -5 \\ U, & -5 < U < 5 \\ 5, & U \geq 5 \end{cases} \tag{32}$$

Table 1. Rules for the FLC.

Output		Error NL	Error NS	Error Z	Error PS	Error PL
Error Rate	**NL**	NL	NL	NL	NS	Z
Error Rate	**NS**	NL	NL	NS	Z	PS
Error Rate	**Z**	NL	NS	Z	PS	PL
Error Rate	**PS**	NS	Z	PS	PL	PL
Error Rate	**PL**	Z	PS	PL	PL	PL

(NL: Negative Large, NS: Negative Small, Z: Zero, PS: Positive Small and PL: Positive Large)

4. SIMULATION AND RESULTS

The Fuzzy controller, discussed in Section 3, is applied for the PHWR reactor model presented in Section 2. All the simulation work is performed in MATLAB and Simulink.

First, simulations are performed for step changes applied to the desired power trajectory. In addition, the simulation for certain disturbances added to the reactor in the form of reactivity, is also performed and finally, a loss of grid transient is also simulated. The significance of doing all this is to evaluate if the controller is able to successfully bring the reactor to the demanded power and the reactor does not skip to super criticality or sub criticality state. Moreover, through these case scenarios, we can evaluate if the qualitative performance of the controller is good with safe operation of the reactor.

Figure 4(a) shows the response of the reactor for the step input. The controller shows almost no steady state error. However, the settling time is around 21 seconds. Figure 4(b), 4(c), 4(d), 4(e) and 4(f) show, respectively, the fuel temperature, coolant temperature, Xenon concentration, Iodine concentration and LZC water level variation for the same step input.

Figure 5(a) shows the reactivity disturbances of four signals with maximum values of 0.25 mk, 0.5 mk, 0.75 mk and 1.00 mk with the rates of ±0.025 mk/s, ±0.05 mk/s, ±0.075 mk/s and ±0.100 mk/s, respectively being introduced into the reactor core (Nafisah Khan, 2009). Figure 5(b) shows the reactor power variation due to the reactivity disturbances. The reactor power goes to 100.0184% at maximum and 99.94% at minimum before settling down to 100% for the reactivity disturbance signal of 0.25 mk. For the reactivity disturbance signal of 1.00 mk, the reactor power goes to 100.466% (max) and 98.739% (min) before settling down to 100%.

Figure 5(c), 5(d), 5(e), 5(f) and 5(g) respectively show the fuel temperature, coolant temperature, Xenon concentration, Iodine concentration and LZC water level variation for the reactivity disturbance signals.

The case of grid loss is also simulated (refer Fig 6(a)) when the reactor power decreases to 15% (operation at plant internal load or station load) from 100% full power. Results are shown in Figures 6(b-e).

5. DISCUSSIONS

5.1. Case (a): Step Power Change

In the first case (refer to Fig 4(a)), when a step change (initiating a decrement of 10% power) is introduced to the controller, we note a steady decrease in reactor power which takes about 21 seconds to reach to the steady state level which is adequate in terms of response time. Again for another decrement of 10% causes the same effect. Then, for an increment step of 10% in reactor power causes a follow up by the controller and same is the response for the second increment of 10%.

For both of the above step changes the performance of FLC is consistent, predictable and with acceptable response time. Regarding the reactor parameters, both the reactor fuel and coolant temperatures decrease and increase for desired power step decrements and increments, respectively (refer to Fig 4(b-c)). We may note that when the reactor power is restored back to 100% (initial value) both the reactor fuel and coolant temperature steadily return to the previous values in about 250 seconds. The behavior of both these parameters is as per reactor physics while the settling time is also reasonable.

We may also note that the reactivity changes caused by the step change as represented by concentration of both Xenon and Iodine and also the behavior of LZC (refer Fig 4(d-f)), are according to reactor physics which show a rise in Xenon concentration and then settling at a new value according to reactor dynamics. Similarly, the Iodine concentration and % value of LZC is as expected. Hence the FLC's overall response and performance is well suited for both increment and decrement for a step change simulated here.

In this case scenario, we may easily analyze the under and over shoots and fall and rise times of the response which ensure that the controller performance is good and acceptable as shown in figure 4.

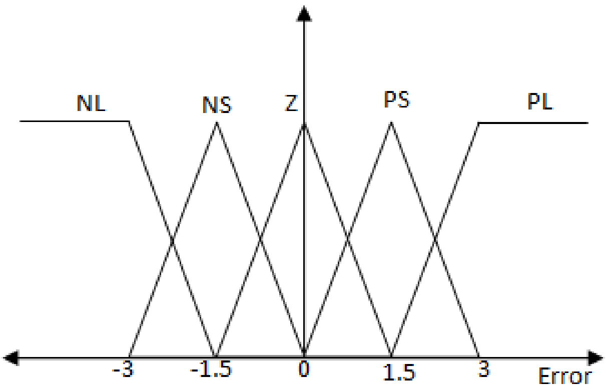

Fig. 1(a) Membership functions for the input variable, Error (E).

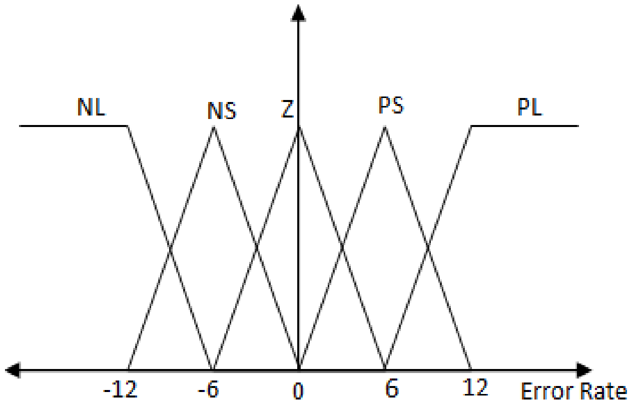

Fig. 1(b). Membership functions for the input variable, Error Rate (Ė).

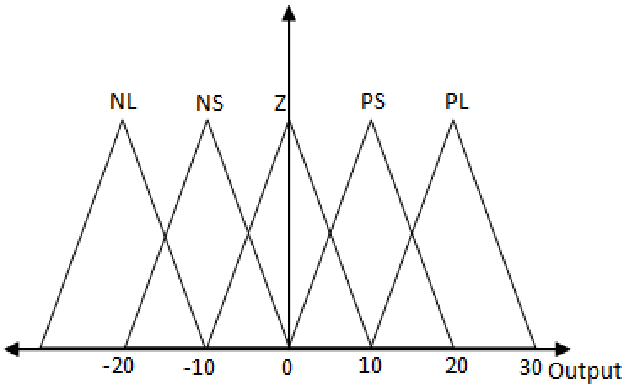

Fig. 1(c). Membership function for the output variable, Voltage.

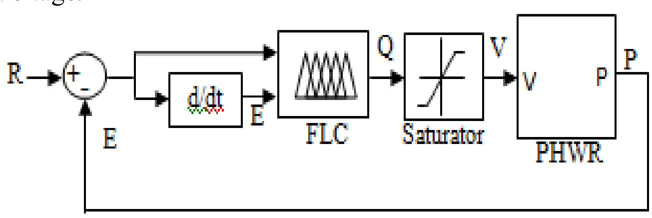

Fig. 2. FLC Based Reactor Control System.

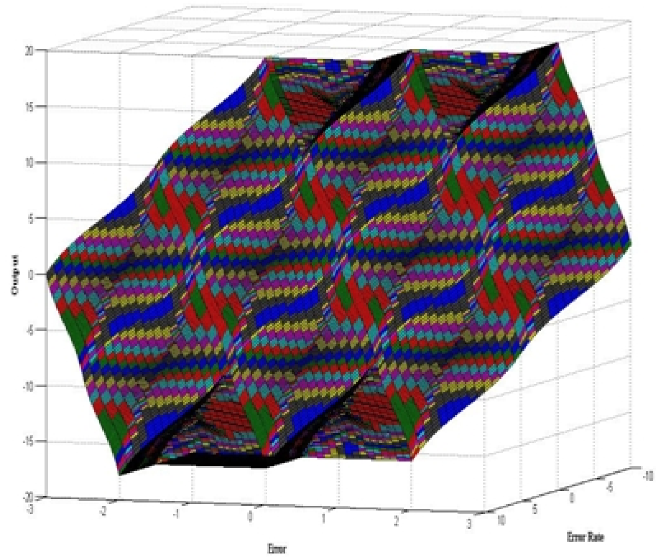

Fig. 3(a). Surface Plot without Saturator.

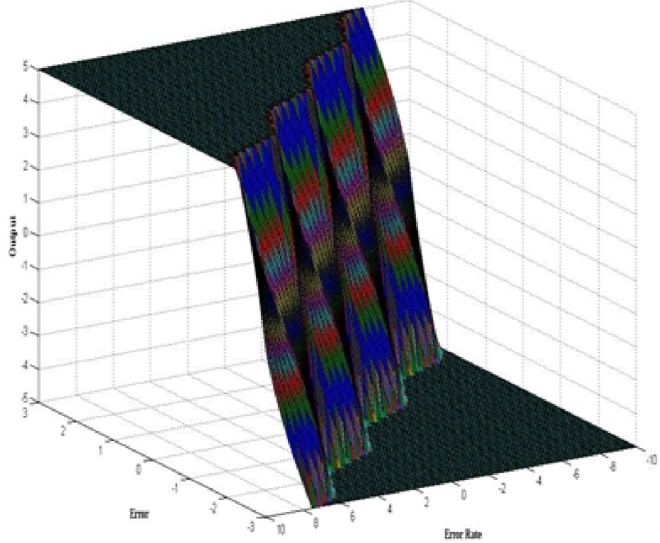

Fig. 3(b). Surface Plot with Saturator.

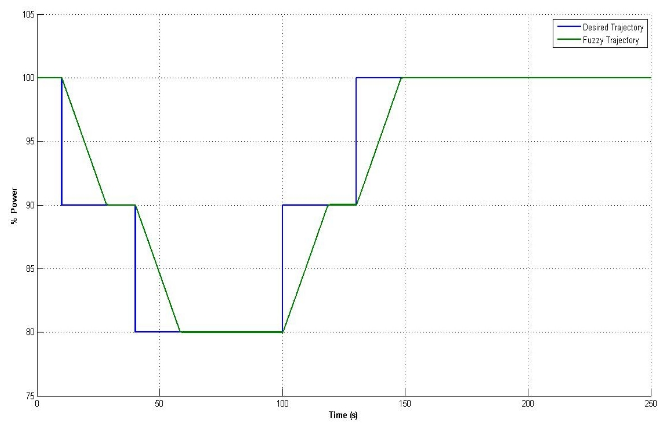

Fig. 4(a). Relative Reactor Power for Step Input.

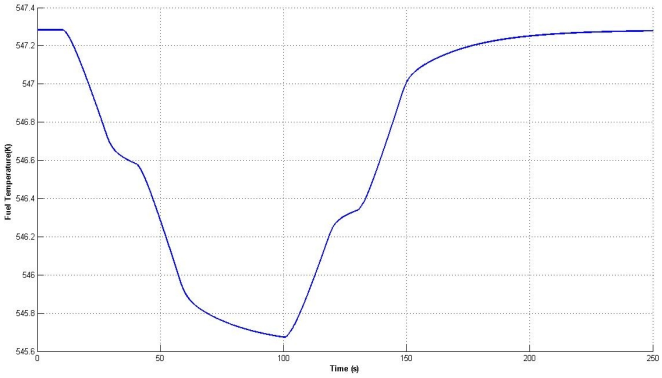

Fig. 4(b). Fuel Temperature variation for Step Input.

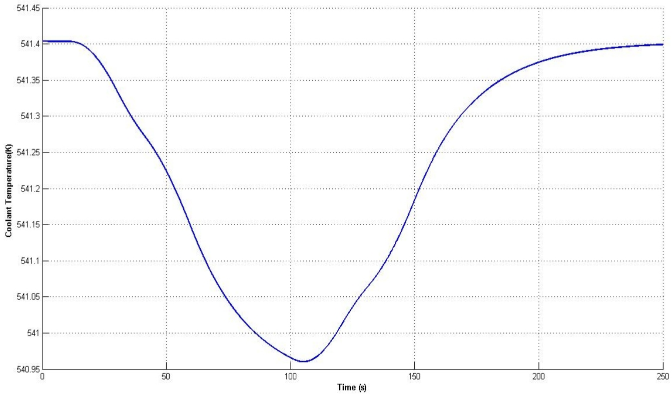

Fig. 4(c). Coolant Temperature variation for Step Input.

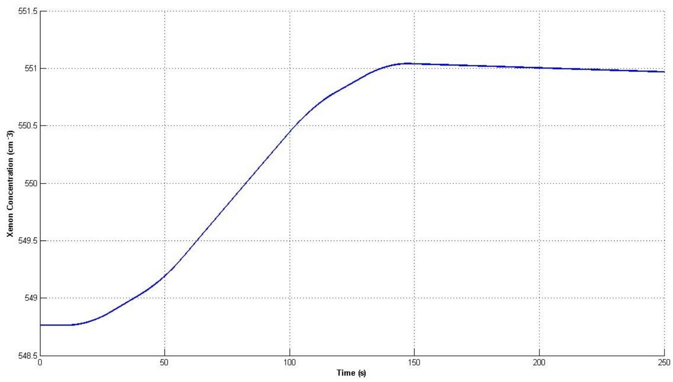

Fig. 4(d). Xenon variation for Step Input.

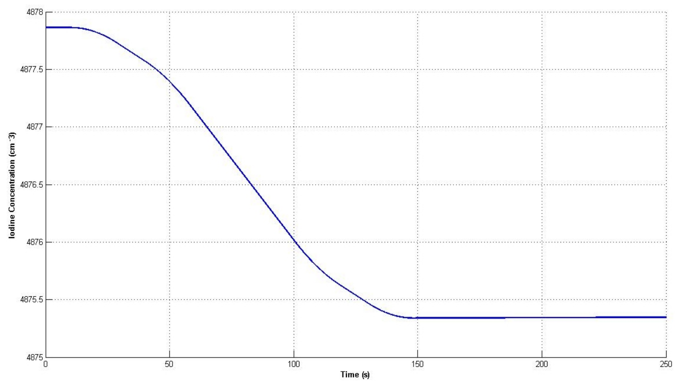

Fig. 4(e). Iodine variation for Step Input**.**

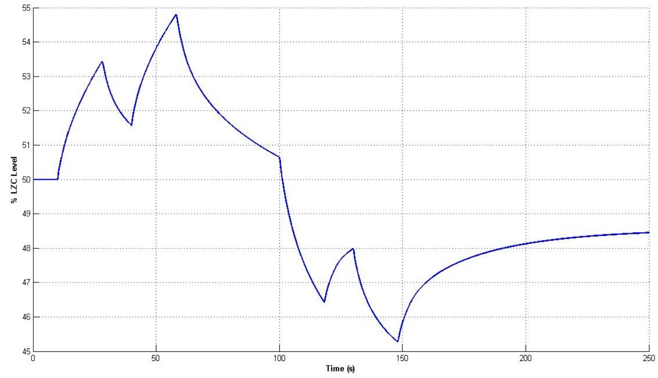

Fig. 4(f). LZC Level variation for the Step Input.

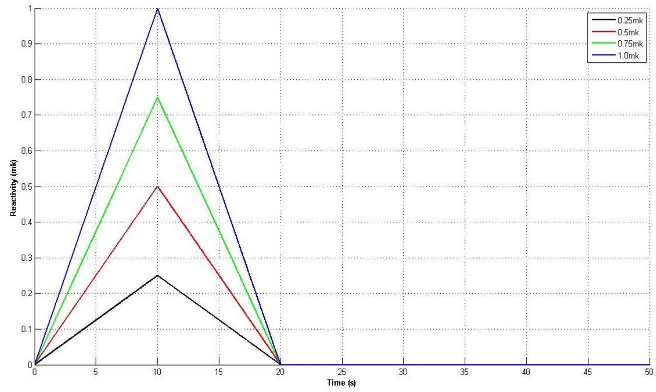

Fig. 5(a). Reactivity Disturbance Signals.

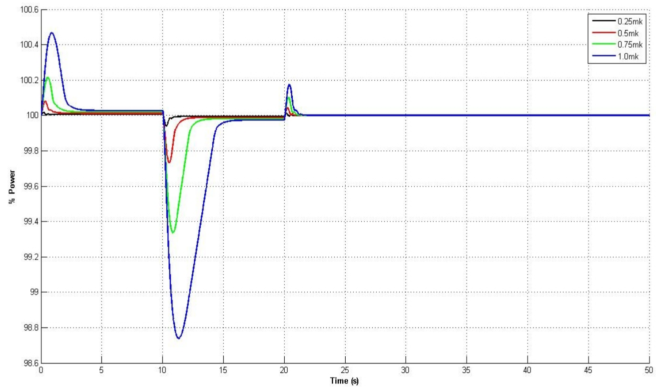

Fig. 5(b). Power variation for the Disturbances.

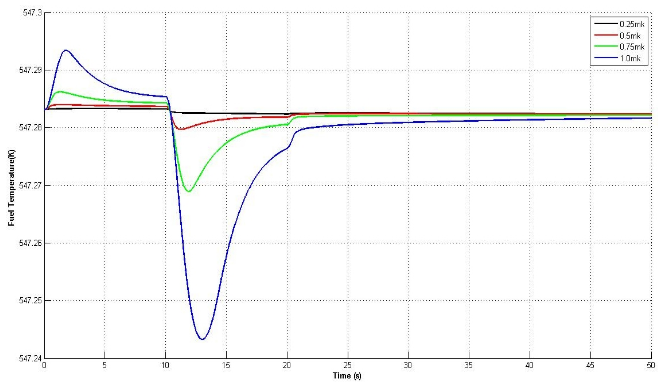

Fig. 5(c). Fuel Temperature variation for the Disturbances.

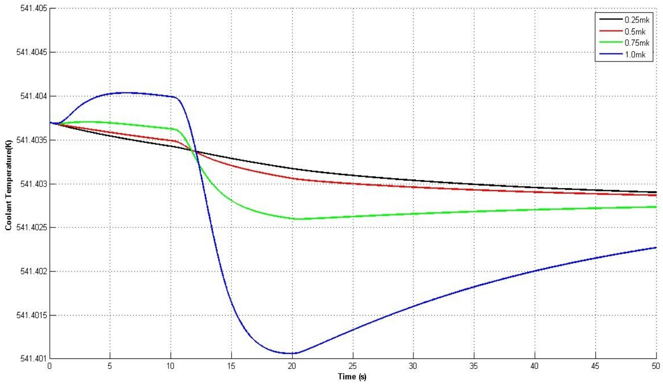

Fig. 5(d). Coolant Temperature variation for the Disturbances.

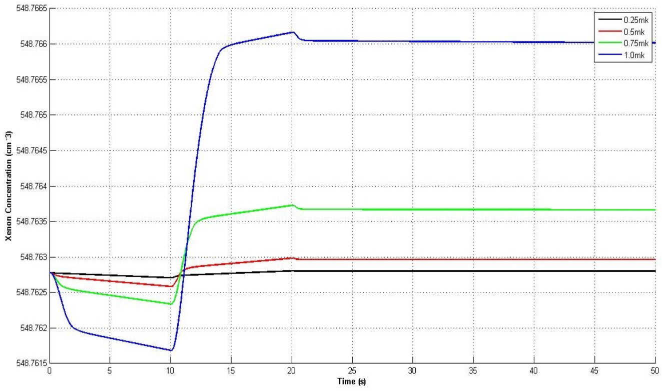

Fig. 5(e). Xenon variation for the Disturbances.

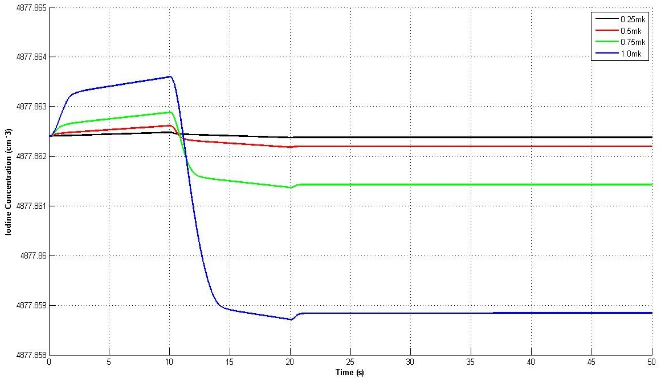

Fig. 5(f). Iodine variation for the Disturbances.

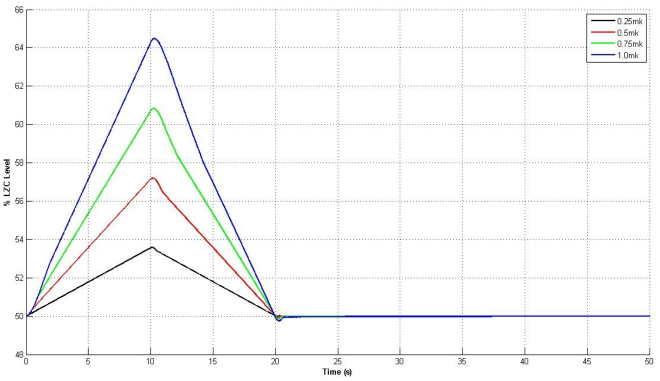

Fig. 5(g). LZC Level variation for the Disturbances.

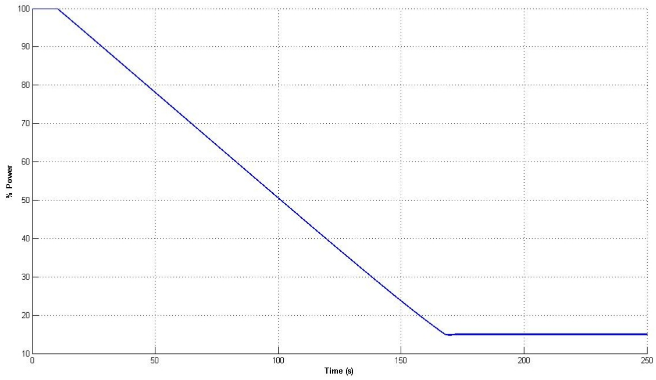

Fig. 6(a). Power variation for grid loss from 0 to 250 seconds.

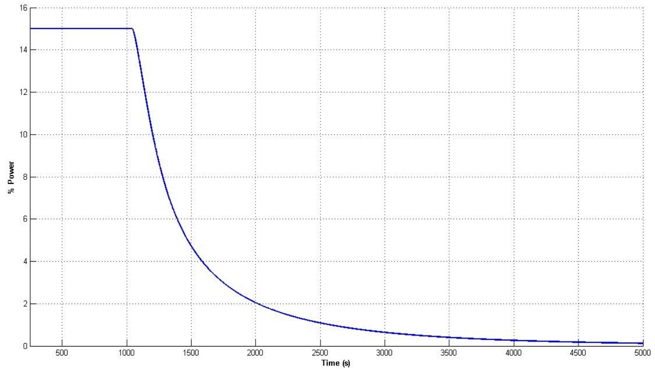

Fig. 6(b). Power variation for grid loss from 250 to 5000 seconds.

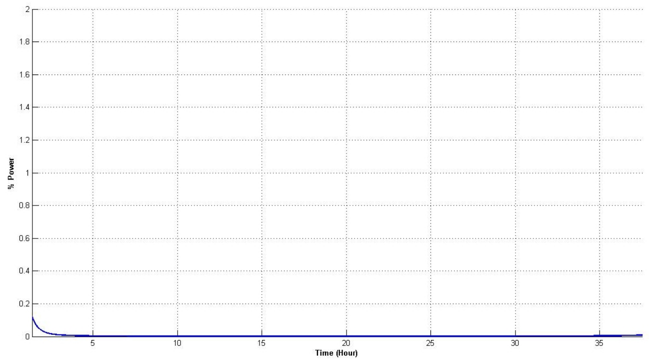

Fig. 6(c). Power variation for grid loss from 1.38 to 37.5 hours.

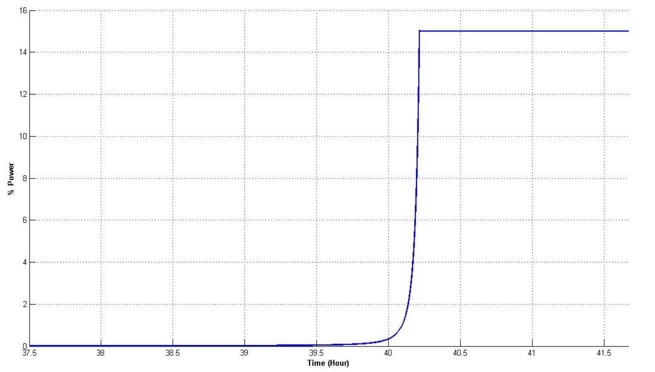

Fig. 6(d). Power variation for grid loss from 37.5 to 41.67 hours.

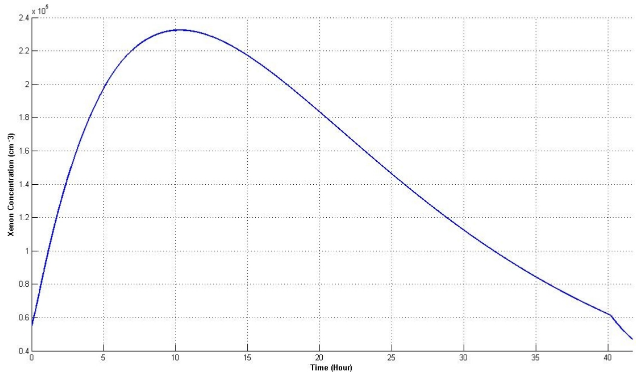

Fig. 7. Xenon concentration variation for grid loss.

5.2. Case (b): Reactivity Disturbance

We simulate the model using four different reactivity disturbance scenarios as shown in figure 5(a).

For a reactivity disturbance signal of maximum value of 0.25 mk with ±0.025 mk/s, the reactor power goes to 100.0184% (max) and 99.94% (min) before settling down to 100%. And with the maximum reactivity change of 1 mk with reactivity rate of ±0.100 mk/s, the reactor power varies from 100.466% (max) and 98.739% (min) before settling down to 100%. It may be noted that the reactor operation is within safe limits and it does not skip to super-criticality. The rest of the parameters, i.e. fuel and coolant temperatures, Xenon and Iodine concentrations and LZC, all show the expected behavior.

This scenario shows that the FLC rejects the disturbance with little effects on the reactor power. Thus, the FLC is proven to be safe and robust as it rejects the disturbances and does not push the reactor to super critical.

5.3. Case (c): Loss of Grid and Operation at Station Load

At t=10 second, the grid loss occurs and the reactor power dips to 15%. It takes about 165 seconds (approximately 2-3 minutes) and remains at this level for 1050 seconds (refer Fig 6(b)). The time of 165 seconds taken by the reactor to reach the station load is due to the limitations posed by maximum reactivity insertion rate of LZC, i.e. ±0.14 mk/s.

Obviously the reactor tends to shut down due to poisoning of Xenon after 1050 seconds and restarts after more than 40 hours of poison out time. The other parameters such as Xenon buildup and die out are as per reactor physics. The behavior of FLC is consistent for this case as well when several runs were performed for this case.

This scenario represents that the FLC is capable of bringing the reactor back to the 15% power after the poison out time without creating any instability.

6. CONCLUSION AND RECOMMENDATIONS

In this work, FLC is evaluated for its performance for a SISO model of the PHWR reactor. The controller is tested for the step change (increase or decrease), reactivity disturbances and loss of grid scenario. The results show that the performance of the generic type FLC is stable, fast, safe, accurate and robust which is reflected from the simulation results and discussions presented here.

This work may be extended by considering a multi-input multi-output (MIMO) model of the reactor. Furthermore, other non-linear control techniques such as neuro-fuzzy may also be used for designing the intelligent controller.

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