

Safety Regulations and Fuzzy-logic Control to Nuclear Reactors

D. Ruan

Belgian Nuclear Research Centre (SCK•CEN)

Boeretang 200, B-2400 Mol, Belgium

druan@sckcen.be

Abstract

We present an R&D project on fuzzy-logic control applications to the Belgian Nuclear Reactor 1 (BR1) at the Belgian Nuclear Research Centre (SCK•CEN). The project started in 1995 and aimed at investigating the added value of fuzzy logic control for nuclear reactors. We first review some relevant literature on fuzzy logic control in nuclear reactors, then present the state-of-the-art of the BR1 project, with an understanding of the safety requirements for this real fuzzy-logic control application in nuclear reactors.

Keywords: Nuclear reactors, Nuclear engineering, FLINS, BR1 reactor, Fuzzy logic control.

1 Introduction

Nuclear reactor control is one of the nuclear areas with a large potential for applications of fuzzy logic. However, as pointed out in [23], the nuclear power industry puts special demands on plant safety, surpassing all other industries in its safety culture. The regulatory environment in which nuclear power plants operate reflects these needs, and also the demands of the public for high levels of assurance about safety and regulatory compliance. This culture is not one that encourages innovation in control systems and philosophy, yet nowhere are there greater potential benefits from high reliability systems, automated fault recognition and rationally supported decision-making. A demonstration of the use of intelligent control in an actual plant is a vital step in prototyping the next generation of nuclear power plants. These demonstrations must prove not only the ability to safely survive major disturbances, but also the ability to operate efficiently and reliably in normal operation and to recover smoothly from the minor events that will occur on a regular basis, without challenge to future operations.

Fuzzy logic applications in nuclear reactors present a tremendous challenge due to its strict nuclear safety regulation. The fields of nuclear engineering and fuzzy logic have nevertheless matured considerably during the last decade [18, 19, 20]. We list here part of references from the literature concerning nuclear engineering

applications of fuzzy logic: A fuzzy-logic approach to HTR nuclear power plant model control [4], to a rule-based system for process control [2], to a nuclear reactor control [7, 17, 9, 12, 14, 21], to nuclear reactor system dynamics [15], to a PWR-type nuclear power plant [1, 8], to a site selection for nuclear plants [6], to control of steam generator water-level in PWR [13, 16, 5], to nuclear technology [22], and to the redundant sensor validation [10].

2 Fuzzy Control Applications at BR1

FLINS is an acronym for **F**uzzy **L**ogic and **I**ntelligent **T**echnologies in **N**uclear **S**cience. The main task for FLINS for the coming years is to solve many intricate problems pertaining to the nuclear environment by using modern technologies as additional tools and to bridge a gap between novel technologies and the industrial nuclear world. Specific prototyping of fuzzy logic control of the BR1 research reactor has been chosen as FLINS' first priority. The accumulated knowledge at BR1 during this time has lead to the best calibration conditions for applying FLC for nuclear reactor control [21].

The mathematical model presently used for the BR1 graphite-moderated research reactor actually is the point kinetics model. It can be described by a non-linear system with a set of differential equations with six delayed neutron groups [3]:

$$\frac{dn}{dt} = \frac{\rho - \beta}{\Lambda} n + \sum_{i=1}^6 \lambda_i c_i$$

$$\frac{dc_i}{dt} = \frac{\beta_i}{\Lambda} n - \lambda_i c_i, i = 1, \dots, 6$$

Where

n is the neutron density at rated power (%);

c_i is the i th group precursor concentration;

β_i is the i th group delayed neutron fraction;

β is the total delayed neutron fraction;

λ_i is the i th group delayed neutron decay constant (s^{-1});

Λ is the neutron generation time (s);

ρ is the reactivity due to the control rod ($\Delta k/k$). (Note: Reactivity is defined as the difference between the effective multiplication factor and unity divided by the effective multiplication factor).

The neutron density is related to the power level, and depends on the reactivity of the reactor and the number of delayed neutrons. The control requirements of BR1 are to keep the reactivity ρ near zero or to exhibit a certain transient behaviour for a required power transient. At the required steady-state conditions, if ρ is different from zero, the controller inserts or withdraws the regulating rods to return ρ to zero. However, since ρ is not easily measurable, we use input signals such as the difference of power (DP) (difference between the actual and the desired power) and the reactor period (T). In steady state, T remains infinitely large.

Basically, the controller reads DP as input. This input signal is electronically transformed into an analogue command signal. Its sign and magnitude command the selection of the direction and speed of A-rods (the rods for fine-tuning the reactivity). The controller is efficiently limited by a certain delay due to neutronics and the thermal behaviour of the reactor. Whereas the fuzzy logic control (FLC) no longer requires an explicit model of the reactor, it can take into account the knowledge of the operators for controlling the reactor. Figure 1 is a simplified version of the BR1 controller.

Figure 1: A-rods for the fine-tuning of reactivity, and C-rods mainly for the compensation of other reactivity effects.

Figure 2 shows the testing environment schematically. In addition the control initially focuses exclusively on the movement of A-rods, thereby mimicking the classical controller. The full rule base controlling both A- and C-rods simultaneously, thereby eliminating the manual movement of C-rods by the operator, is of course the ultimate goal of this work.

Figure 2: Safe testing environment for FLC on-line experiments at BR1.

The hardware configuration of fuzzy-logic control scheme for BR1 is shown in Figure 3.

Figure 3: Fuzzy control configuration for BR1.

In the experience of the author it is wise to rely on certified, proven industrial hardware instead of developing *ad hoc* software when developing a controller for use in an environment that presents a potential high risk if control breaks down. It also makes it easier to exchange rule bases, because it is the responsibility of the PLC manufacturer to provide state-of-the-art tools that work in modern operating system environments. In taking this strategy, it is straightforward to extrapolate the present results to similar industrial reactors without having to repeat all safety tests.

The kernel of FLC is a fuzzy knowledge base in fuzzy control applications. Our current aim is to control the reactor in steady-state operation. According to observations and experience, if the difference between the real and the desired power (DP) is larger than 0.2 % but smaller than 0.8 %, A-rods do not insert as far; by contrast, if DP is larger than 0.8 %, A-rods insert further. For a negative value of DP, A-rods withdraw to an extent depending on the magnitude of the DP perturbation. This rule base remains true for as long as A-rods have enough space to move. However, when A-rods reach their insertion or withdrawal limit, they start to move in the opposite direction to return to their initial position. In the meantime, C-rods are controlled to equilibrate the reactivity by slow insertion or withdrawal. This sequence of actions can be modelled in the more sophisticated rule base presented in Table 1.

Table 1: Rule base of FLC with two inputs and two outputs

PORA	IL		NIL		AC		NWL		WL	
DP	MOPA	MOPC	MOPA	MOPC	MOPA	MOC	MOPA	MOC	MOPA	MOC
NL	WB	NA	WB	NA	WB	NA	WS	WS	NA	WB
NM	WM	NA	WM	NA	WM	NA	WS	WS	NA	WS
NS	WS	NA	WS	NA	WS	NA	WS	NA	NA	WS
NZ	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
PS	NA	IS	IS	NA	IS	NA	IS	NA	IS	NA
PM	NA	IS	IS	IS	IM	NA	IM	NA	IM	NA
PB	NA	IB	IS	IS	IB	NA	IB	NA	IB	NA

3 BR1 as a Test Bed for Applying Fuzzy Logic

To build a controller for BR1 in the steady-state operation, two inputs are selected in our current study: DP, and POR (the current position of the control rod: PORA is for A-rods, and PORC for C-rods, respectively). DP is the power mismatch between the actual power and the desired power. In the steady-state operation, DP is free to vary within 0.2 %. It is expressed by 7 linguistic values from -2 to 2 %: Negative Large (NL), Negative Medium (NM), Negative Small (NS), Near Zero (NZ), Positive Small (PS), Positive Medium (PM), and Positive Large (PL). The rod position is expressed by 5 linguistic values from 0 to 4 *m*: Insertion Limit (IL), Near Insertion Limit (NIL), Around Centre (AC), Near Withdrawal Limit (NWL), and Withdrawal Limit (WL).

Two outputs in terms of MOPA (Motion of Position for A-rods) and MOPC (Motion of Position for C-rods) are set up regarding the speeds of the A- and C-rods, respectively. MOPA is expressed by 7 singletons from -100 to 100 *mm/s*: Insertion Big (IB), Insertion Medium (IM), Insertion Small (IS), No Access (NA), Withdraw Small (WS), Withdraw Medium (WM), and Withdraw Big (WB). In the same way, 5 singletons are used to represent MOPC (from -35 to 35 *mm/s*). Although the definition of MOPA and MOPC are similar, their effects on the resulting reactivity are not the same. Generally, the amount of reactivity controlled by the C-rods is 8 times larger than that of A-rods. Figures 4 and 5 are membership functions presently used for this BR1 project.

At our current stage, we aim at realizing a real on-line control at BR1. This is very important for us to be sure that everything, including both hardware and software, can work properly. Afterwards we are confident of carrying out some basic experiments at BR1. We briefly outline the plan of our early experiments at BR1. Given a desired power of BR1, we ask the FLC system to control the reactor's power output at this desired value while we turn the FLC system on. To ensure the maximum reactor safety during FLC experiments, we design an automatic switch between an FLC experimental operation and a normal control (NC) operation ¹. The switch can only be automatically connected with either FLC or NC in order

¹a normal control (NC) has the same meaning as a classical control (CC) in this paper, i.e., this is the current control at BR1.

Figure 4: Membership functions for DP and PORA.

Figure 5: Membership functions for MOPA and MOPC.

to at least keep the NC operation of BR1. Figure 6 illustrates the electrical circuit connection of FLC and NC.

As shown in Figure 7, we require an extra support software for our safety design of FLC at BR1.

The software environment of PLC guarantees to the realization of the programme. After turning the power on, the PLC will always first read each input signal from the A/D unit, i.e., P, Pd, T, PORA, and PORC. Then the PLC checks each signal with its corresponding alarm boundary. If any of the above-mentioned parameters is outside the alarm boundary, the FLC will stop running and NC will automatically take over. Otherwise, the FLC will proceed with outputs of motion of the A-rods (MOA) and that of the C-rods (Mc) to control the A-rods, and

Figure 6: Electrical circuit connection of FLC and NC.

Figure 7: Extra support software for safety design of FLC at BR1.

C-rods, respectively.

4 Fuzzy Logic Control On-line at BR1

By July 1998, we obtained a permission to carry on our FLC on-line test at the BR1 reactor. The very first on-line experiment was successfully carried out in September 1998. Figure 8 recorded that experiment.

We had a dual aim for this on-line experiment. First of all we wanted to show that the FLC is able to keep the reactor stable for different power levels. This is

Figure 8: The first fuzzy control on-line experiment at BR1 (September 1998).

of course the most essential property the FLC must have. The second part of this experiment was to show that FLC can handle a (manually invoked) disturbance of C-rods (resulting in a sudden power change). For every experiment, we show how classical control (CC) and FLC behave. We have carried out over ten tests so far. Among them, we illustrate two cases in Figure 9: (1) Test FLC up to 400 kW at its stability, and (2) Test FLC up to 400 kW with a disturbance.

With these experiments, we showed that FLC is as good as CC in the stable situation and in the compensation of a small disturbance. Though the results reported here are very limited and preliminary, they have clearly demonstrated that it is feasible to apply fuzzy control in the nuclear reactor domain. Moreover, it should be understood that these results are obtained under an issued permission from the nuclear safety authority, which is different from other academic study.

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Figure 9: The error DP up to 400 kW at its stability (a) and (b), and with a disturbance (c) and (d), respectively.

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