SAFETY REGULATIONS AND FUZZY-LOGIC CONTROL TO NUCLEAR REACTORS

Da Ruan
Belgian Nuclear Research Centre (SCK•CEN)
Boeretang 200, B-2400 Mol, Belgium
E-mail: druan@sckcen.be

Summary

In this paper we report our on-going R&D project (1994-99) on fuzzy-logic control for controlling the reactor power of the Belgian Nuclear Reactor 1 (BR1) at the Belgian Nuclear Research Centre (SCK•CEN). We present our on-line experiment at BR1 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

Most nuclear engineers today are involved in the development of nuclear power installations, either stationary power plants for the generation of electricity or plants for the propulsion of mobile systems. The Chernobyl accident and its cross-border consequences have reminded us that nuclear safety remains a short-term priority, both at home and abroad, as nuclear technology has not reached the same maturity in all countries. The need for on-line reactor operator decision-support systems has become evident after the Three-Mile-Island accident in 1979. Since then, considerable attention has been paid by the engineering, scientific, economic, political communities and by society at large to prevent these types of event by using state-of-the-art artificial intelligence techniques. Nuclear engineering is different from many other engineering areas in the following respects: (1) an experimentation is only possible to a certain degree which does not provide a safe basis for stochastic models or the validity of the law of large numbers; (2) the consequences of misjudgement, wrong decisions or bad design can be such horrendous that one is hesitant to accept even a tiny probability for such an event to happen; (3) the waste disposal is one of the most difficult problems yet unsolved; (4) the abuse of nuclear material for criminal purposes can have unprecedented consequences, and (5) the public opinion with respect to nuclear energy and related issues is much more controversial and influential than in other engineering disciplines [9].

Among the available techniques, fuzzy logic control (FLC) has been recently applied to nuclear reactor control. Having acquired the accumulated skill of many operators, FLC can assist an operator in controlling a complex system. One of the advantages of FLC is to derive a conceptual model of the control operation, without the need to express the process in mathematical equations and to assist the human operator in interpreting and validating incoming plant variables and arriving at a proper control action.

Nuclear reactor control is one of the areas with a large potential for applications of intelligent systems including fuzzy logic, in which, however, the development is still in its infancy [1, 2, 3].

The significant influence of fuzzy logic control (FLC) in this field was illustrated by the response to FLINS'94 (the 1st international FLINS workshop on *Fuzzy Logic and Intelligent Technologies in Nuclear Science*, Mol, Belgium, September 14–16, 1994) [4], FLINS'96 (the 2nd international FLINS workshop on *Intelligent Systems and Soft Computing for Nuclear Science and Industry*, Mol, Belgium, September 25–27, 1996) [5], and FLINS'98 (the 3rd international FLINS workshop on *Fuzzy Logic and Intelligent Technologies for Nuclear Science and Industry*, Antwerp, Belgium, September 14–16, 1998) [6]. Despite many on-going research results on FLC to nuclear reactors, the real FLC applications at nuclear power plants (NPPs) with a license issued by the nuclear safety authority have not yet been fully realized in the entire world.

2 FLINS ACTIVITIES AT SCK•CEN

FLINS is an acronym for **F**uzzy **L**ogic and **I**ntelligent Technologies 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 [7, 8].

3 FUZZY CONTROL APPLICATIONS AT BR1

3.1 BR1 REACTOR

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

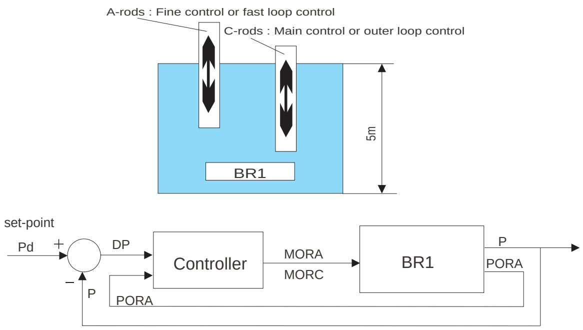


Figure 1: A-rods for the fine-tuning of reactivity, and C-rods mainly for the compensation of other reactivity effects.

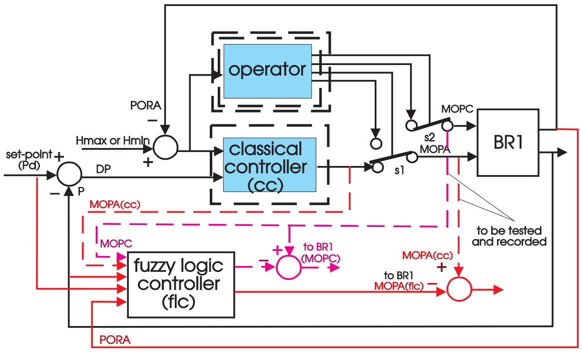


Figure 2: Safe testing environment for on-line experiments on the FLC during operation of the BR1 reactor.

3.2 FUZZY CONTROL CONFIGURATION

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

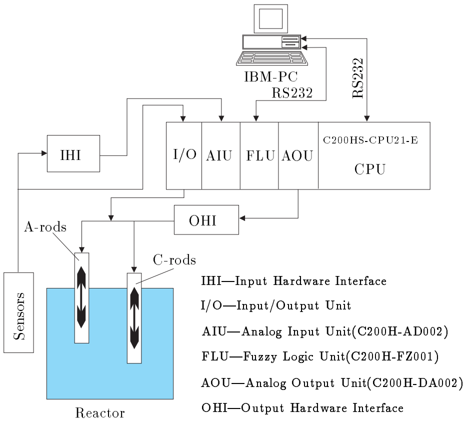


Figure 3: Fuzzy logic control configuration for BR1.

3.3 HARDWARE IMPLEMENTATION

The controller platform selected to implement our fuzzy controller is the Sysmac C200HS programmable logic controller (PLC) of OMRON (Figure 4). Among the reasons to choose this professional platform are the demand to meet the real-time requirements of the reactor and its proven robustness in an industrial environment. The latter reason is induced by the safety requirements of nuclear reactor. An additional advantage is that our fuzzy controller can be directly mapped onto the fuzzy inference unit, based on the OMRON FP3000 processor. 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.

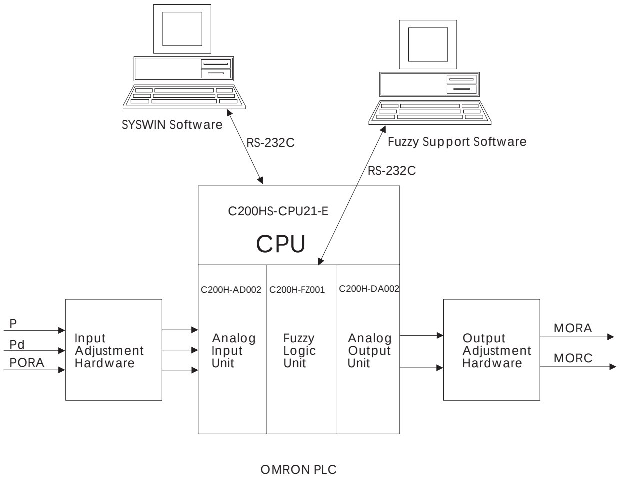


Figure 4: Hardware implementation of the PLC-based FLC.

3.4 FUZZY KNOWLEDGE BASE

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	MOPC	MOPA	MOPC	MOPA	MOPC
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

4 BR1 AS A TEST BED FOR APPLYING FUZZY LOGIC

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 5 recorded that experiment.

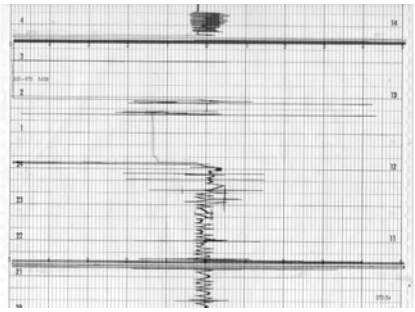
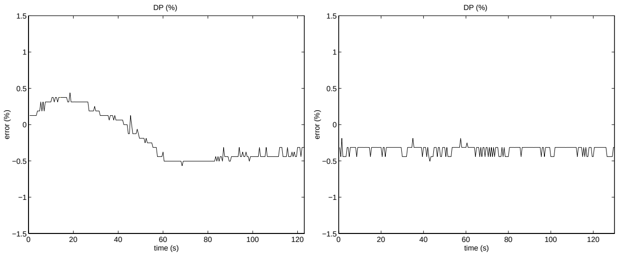


Figure 5: The first fuzzy control on-line experiment at BR1 (September 1998).

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 of course the most essential property the FLC must have.

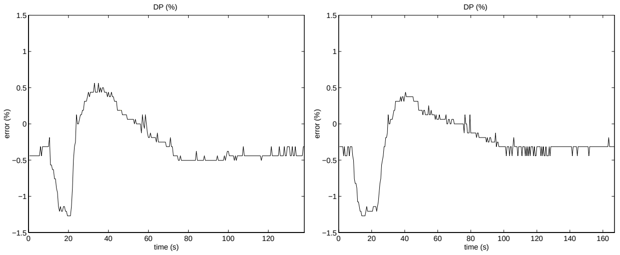
The second part of this experiment was to show that FLC can handle a (manually invoked) disturbance of C-rods (resulting in a sudden power change). For every experiment, we show how classical control (CC) and FLC behave. We have carried out over ten tests so far. Among them, we illustrate two cases in Figure 6: (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.



(a) DP for CC

(b) DP for FLC



(c) DP for CC

(d) DP for FLC

Figure 6: The error DP up to 400 kW at its stability (a) and (b), and with a disturbance (c) and (d), respectively.

5 CONCLUDING REMARKS

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 [2].

In this paper, we present a real on-going project with on-line experiments on fuzzy logic application to the BR1 reactor as a test bed. We aim to be of benefit to the existing control systems by applying fuzzy logic as an additional tool for both the safety and economic aspects in nuclear power plants (NPPs). However, the licensing aspect of this technology as nuclear technology remains more challenging and time consuming.

To extend our working licence, we are currently designing an automatic “start-up” and “shutdown” with fuzzy logic during an operation of BR1. The further on-line experiments will concentrate on the transition period of the reactor operation. The final goal of this research is to obtain a license for designing or using fuzzy logic based approach in NPPs.

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