RESEARCH ARTICLE

Regulation of Differential Pressure in Liquid Zone Control System using Fuzzy Logic Control Scheme

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1. Introduction

Nuclear reactor control is one of the areas with a huge potential for application of intelligent systems including fuzzy logic, in which, however, the development is still in its infancy, despite its success in other domains. Fuzzy logic control provides a formal methodology for representing, manipulating and implementing a human's heuristic knowledge about how to control a system. Despite many on–going research activities on fuzzy logic controller in nuclear reactors, on-line applications of fuzzy logic controllers in nuclear power plants with a license issued by the nuclear safety authorities are rare [1].

The operation of large Pressurized Heavy Water Reactors (PHWRs) *e.g.*, the 540 *MWe* PHWR with flattened radial and axial flux distributions coupled with xenon poisoning effect [2] leads to complex operational and control problems. The Liquid Zone Control System (LZCS) is provided in large PHWRs, for continuous fine control of the reactor power level and power distribution. The LZCS is a complex hydropneumatic system, in which maintaining the differential pressure between gas outlet header and delay tank is an important function, from the point of view of reactivity control. In the existing systems in India, a conventional PI controller is employed. In this paper, fuzzy control scheme has been proposed for maintaining the pressure difference between gas outlet header and delay tank, close to a specified setpoint.

2. Overview of LZCS

The LZCS consists of six vertically oriented tubes running interstitially between the calandria tubes from the top to the bottom of the core, as shown schematically in Fig.1. The two central tubes are divided into three compartments each, by appropriately placed bulkheads and the outer four tubes are divided into two compartments each, to give a total of 14 individually controllable compartments in the reactor. These compartments

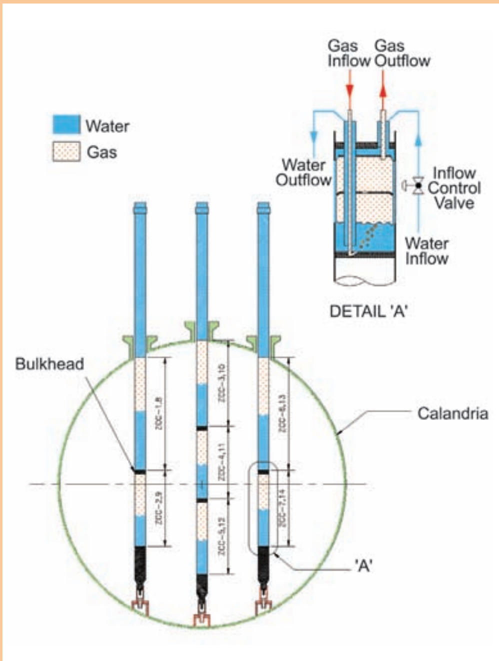

Fig.1: General arrangement of liquid zone control assemblies in a large PHWR

are called Zone Control Compartments (ZCCs). The level of water in each compartment can be individually controlled, by varying the inflow rate while outflow is maintained at a constant rate [3]. The water level in each compartment is varied individually for spatial control and in unison with other compartments for bulk power control [4].

A simplified flowsheet of the LZCS is shown in Fig.2. The water level in each ZCC is measured and gas is maintained under continuous circulation by a bubbler arrangement. For maintaining the water outflow rate at a constant value, the differential pressure between the ZCCs and the delay tank should be kept constant. As all the ZCCs are directly connected to the gas outlet header, at equilibrium, the pressure in the ZCCs is approximately equal to the pressure in the gas outlet header. The differential pressure between the gas outlet header and the delay tank is sensed by a ΔP instrument and maintained constant by means of a feed–bleed arrangement, consisting of a set of feed control valves, a set of bleed control valves and a feed and bleed controller.

Feed control valves are located between gas storage tank and gas outlet header, and bleed control valves are located between gas outlet header and delay tank. The feed and bleed controller generates the control signals for feed control valves and bleed control valves, based on the difference between the measured value and set value of differential pressure storage tank to flow into the gas outlet header, so that the pressure in gas outlet header increases and consequently the differential pressure between gas outlet header and delay tank is restored. On the other hand, if the differential pressure is larger than the set value, then bleed control valves are opened and gas flows out from gas outlet header to the

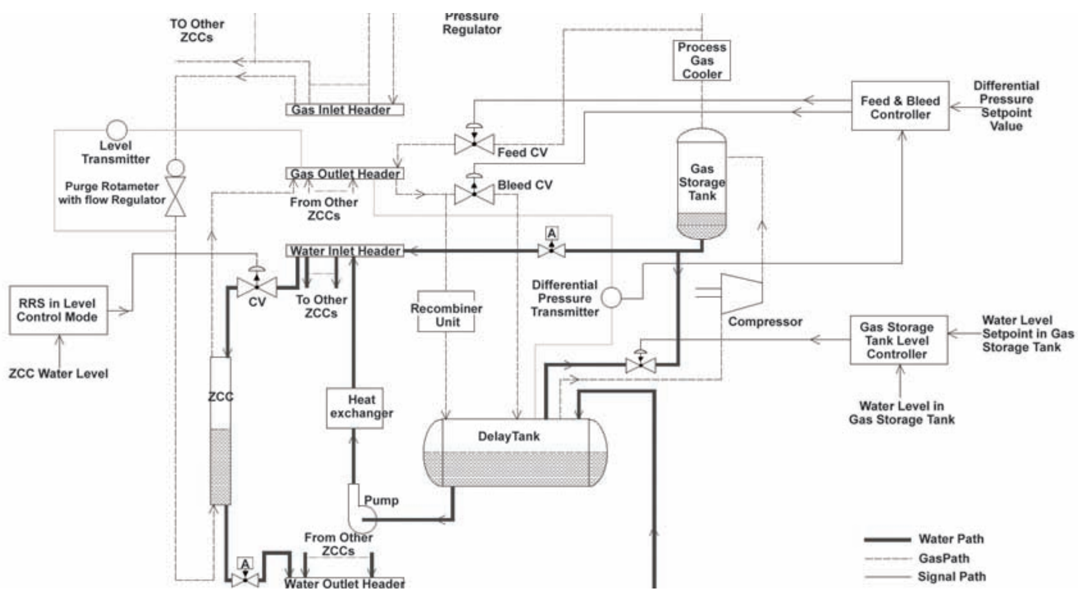

Fig.2: Simplified flow sheet of LZCS

delay tank, thus decreasing the differential pressure between gas outlet header and delay tank, towards the set value.

For understanding the behaviour of the LZCS before its installation in large PHWR units in India, a full scale test setup of LZCS was installed at the Reactor Control Division. Process fluids in the test setup are water and air. The control system of LZCS test setup is a PC-based system having a data acquisition module, a controller module, and an operator interface module.

3. PI type feed and bleed control system

A Proportional plus Integral (PI) controller is used, for control of differential pressure between gas outlet header and delay tank in CANDU reactors and in PHWR units in several countries. The PI controller accepts the sensor signal corresponding to differential pressure between gas outlet header and delay tank as input and generates control signals for the feed and bleed control valves, depending upon its deviation from the set differential pressure. Let ΔP and e be respectively the differential pressure and differential pressure error, defined as:

$$\Delta P = P_{GO} - P_{DT} \quad Kg/cm^2$$
$$e = \Delta P_S - \Delta P \quad Kg/cm^2 \qquad (1)$$

where ΔP_S , P_{GO} and P_{DT} denote respectively the set value of differential pressure between gas outlet header and delay tank, gas outlet header pressure and delay tank pressure. Then from e, the PI controller generates

$$I_C = K_P \times e + \frac{K_P}{T_I} \int edt + 12 \quad mA \; ; 4 \le I_C \le 20 \, mA$$

where K_P is the proportional gain and T_I is the integral time constant of the controller. Control signals for feed and bleed control valves are derived by split ranging PI controller output I_C .

4. Fuzzy logic controller for regulation of differential pressure in LZCS

A fuzzy logic controller can be employed in lieu of the PI-type feed and bleed controller, introduced in Section 3 to control the differential pressure between gas outlet header and delay tank in LZCS. The fuzzy logic controller, as shown in Fig.3, has four major parts: Fuzzification, Rule Base, Inference Engine and Defuzzification. The input to fuzzy logic controller is *e*, defined earlier by (1). The output of fuzzy logic controller is *L* (% *open*), based on which the control signals for feed and bleed control valves are derived.

The fuzzification module converts the crisp variables into linguistic variables (fuzzy sets), as defined by their membership functions. According to observation and experience, when $e \ge -2\%$, then feed control valves opened fully and if $e \le -2\%$ then bleed control valves opened fully. The symmetric triangles with equal base and 50% overlap with neighbouring membership functions are used, to convert *e* into seven linguistic terms: NL (Negative large), NM (Negative medium), NS (Negative small), Z (Zero), PS (Positive small), PM (Positive medium) and PL (Positive Large) as shown in Fig.4. The seven triangles are used to express *L* in the seven linguistic terms: BL (Bleed large), BM (Bleed medium), BS (Bleed small), Z (Zero), FS (Feed small), FM (Feed medium) and FL (Feed Large) as shown in Fig. 5. The universe of discourse for output is between gas outlet header and delay tank. Feed control valves are opened if this differential pressure is less than the set value, allowing gas from gas chosen in the range from "134 to 134 so that controller uses the full output range.

The following seven *if-then* rules are used, to control the differential pressure between gas outlet header and delay tank:

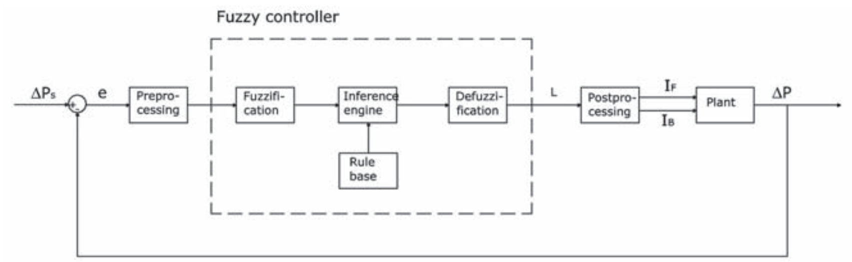

Fig.3: Fuzzy logic controller for feed and bleed control valves

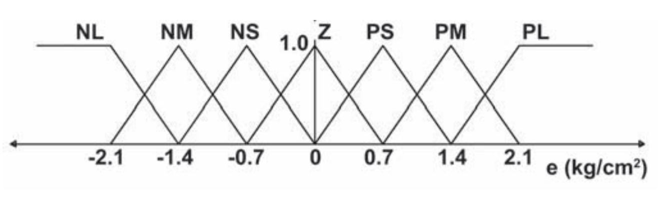

Fig.4: Membership functions for error

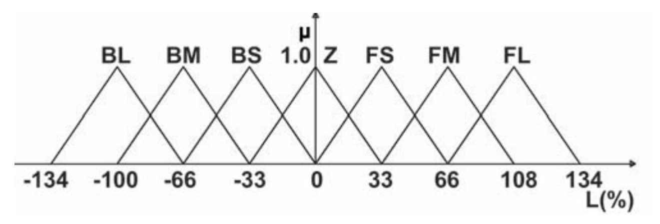

Fig.5: Membership functions for % opening of valve

1. *if* e is NL, *then L* is BL.
2. *if* e is NM, *then L* is BM.
3. *if* e is NS, *then L* is BS.
4. *if* e is Z, *then L* is Z.
5. *if* e is PS, *then L* is FS.
6. *if* e is PM, *then L* is FM.
7. *if* e is PL, *then L* is FL.

The Mamdani implication [5] with union aggregation is used to infer the output contribution from each rule and the centroid technique is employed, for performing defuzzification operation. Finally, the control signals for feed control valves (I_F) and bleed control valves (I_B) are derived from L in the postprocessing block.

5. Validation of fuzzy logic controller

On-line tests for evaluation of fuzzy logic controller proposed in Section 4 were performed on the test setup of LZCS. The experiments were conducted with transients involving step change in the set point of differential pressure and variations in average ZCC water level.

The responses of the system with PI controller and fuzzy logic controller for reduction in differential pressure setpoint from 4.5 Kg/cm^2 to 2.5 Kg/cm^2 in step manner, are shown in Fig.6. This experiment was being conducted with only air circuit in operation and water circuit was kept isolated to avoid undesired entry of water into pneumatic lines. With PI controller differential pressure settled with a little undershoot but with fuzzy logic controller differential pressure settled to final value without any undershoot. The fuzzy logic controller performs better than the conventional PI controller.

The performances of the PI and fuzzy logic controllers during simultaneous filling of all ZCCs (such that the average ZCC level rises from 30% FL to 70% FL nearly in a ramp manner) are illustrated in Fig.7. As the average ZCC water level starts rising, the pressure inside the ZCCs also starts increasing

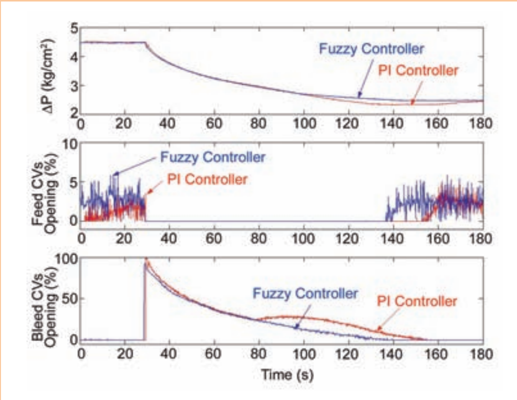

Fig.6: Response of PI and Fuzzy controllers to step change in set differential pressure from 4.5 kg/cm^2 to 2.5 kg/cm^2

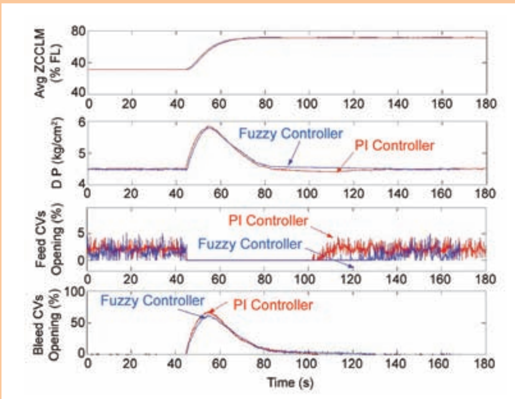

Fig.7: Response of PI and Fuzzy controllers during ramping up of average ZCC water level from 3% FL to 70% FL

and consequently the differential pressure between gas outlet header and delay tank is also increased. It is evident from Fig.7 that the differential pressure increased from 4.5 Kg/cm^2 to 5.85 Kg/cm^2 when PI controller is applied and it is increased to 5.78 Kg/cm^2 when fuzzy logic controller is applied for the same transient. Hence overshoot with fuzzy logic controller is smaller than that with PI controller. The settling time with fuzzy logic controller was also smaller than that with PI controller as seen from Fig.7. Therefore fuzzy logic controller performs better than PI controller.

The fuzzy logic controller was also validated for compressor on-off cycle, step rising in set differential pressure and simultaneous draining of all ZCCs in a controlled manner.

6. Conclusions

The fuzzy logic controller has been validated by performing a variety of experiments on LZCS test setup. In comparison to the existing PI controller, the fuzzy logic controller's performance is superior in all cases considered. Specifically, with fuzzy logic controller:

1. There is no overshoot during all setpoint change transients.
2. Settling time is shorter or almost equal to that with the PI controller for all transients.
3. The feed and bleed control valves operation is comparatively smoother.

Research involved in this project included a real test case and is a step forward in future fuzzy logic controller applications in nuclear power plants.

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