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Design of Fault Tolerant Control System for Steam Generator Using Fuzzy Logic

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Abstract

A controller and sensor fault tolerant system for a steam generator is designed with fuzzy logic. A structure of the proposed fault tolerant redundant system is composed of a supervisor and two fuzzy weighting modulators. A supervisor alternatively checks a controller and a sensor induced performances to identify which part, a controller or a sensor, is faulty. In order to analyze controller induced performance both an error and a change in error of the system output are chosen as fuzzy variables. The fuzzy logic for a sensor induced performance uses two variables : a deviation between two sensor outputs and its frequency. Fuzzy weighting modulator generates an output signal compensated for faulty input signal. Simulations show that the proposed fault tolerant control scheme for a steam generator regulates well water level by suppressing fault effect of either controllers or sensors. Therefore through duplicating sensors and controllers with the proposed fault tolerant scheme, both a reliability of a steam generator control and sensor system and that of a power plant increase even more.

I. INTRODUCTION

We cannot emphasize safety of a nuclear power plant too much. A lot of efforts have been performed to increase safety by upgrading reliability of systems, particularly safety related systems. In order to achieve high reliability, critical systems or components are designed with redundant structure. The mechanical components such as pumps and valves are main targets to be duplicated since a failure probability of mechanical components is largely higher than that of control system. However, in order to make overall systems even more reliable, a redundancy concept should be applied to corresponding control systems including sensors. Among safety related systems in the plant a steam generator including relevant control systems plays a role in safety as well as operation. By reviewing operating experiences

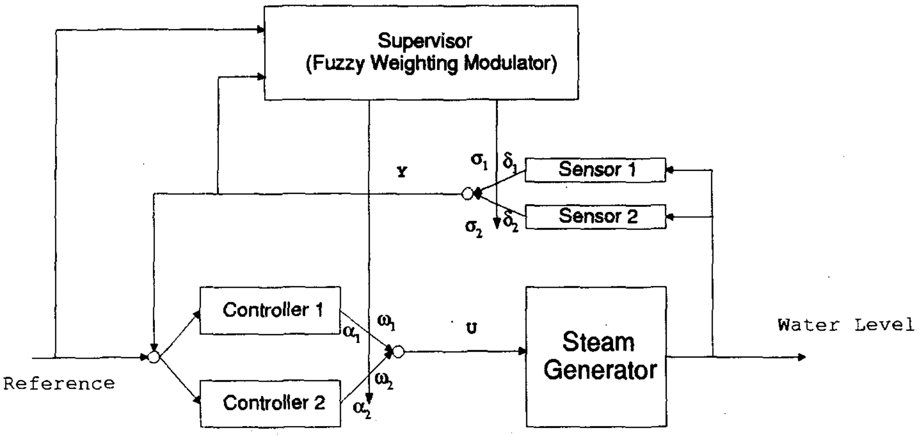

Fig. 1. Fault tolerant redundant system structure.

an advertent reactor trip is caused by malfunction of a steam generator. The current steam generator water level controller design is single while multi-sensors are installed to measure a steam generator water level and an auctioneered signal from multi-signals is used for control. For further reliable power plant it is necessary to duplicate a control system and to adopt an new diagnosis mechanism for a sensor and controller fault. That is, where one of controllers and/or sensors is out of order, the remaining controller and/or sensor takes a control action, resulting in maintaining better performance of a system. In this study we propose a design method of a controller and sensor fault tolerant system with redundant structure using fuzzy logic and apply it to a steam generator control system. The proposed fault tolerant scheme has an advantage over some existing schemes such as analytical redundancy in the terms of the following facts : 1) handling a sensor fault detection as well as a controller, 2) no transfer switching action between component/system and 3) easy design without an exact mathematical plant model.

II. STRUCTURE OF FAULT TOLERANT REDUNDANT SYSTEM

As shown in Fig. 1, the structure of the proposed fault tolerant redundant system is composed of a supervisor and two fuzzy weighting modulators. In normal state, the primary controller (C1) and sensor (S1) are in operation and the secondary or backup controller (C2) and sensor (S2) are in standby. The supervisor alternatively checks a controller and a sensor induced performance to find out which part, a controller or a sensor, is faulty. And then, it traces changes in a system performance and finally sets up strategies of action. Fig. 2 shows actions taken by the supervisor. The fuzzy weighting modulator dedicated to controllers decides weighting values (α_1 and α_2) for each controller, and finally makes uncontaminated input signal with the combination of two weighted controller outputs. The fuzzy

Before one step		At present		Supervisor Control Action	Status			
CIP	SIP	CIP	SIP		C_1	C_2	S_1	S_2
Good	Good	Good	Good	No Action (System Success)	S	S	S	S
Good	Bad	Good	Good	Stop Changing Sensor Weighting	S	S	S	F
Good	Bad	Good	Good	Begin Changing Sensor Weighting	S	S	F	S
Good	Worst	Good	Worst	No Action (System Fault)	S	S	F	F
Bad	Good	Worse	Good	Stop Changing Controller Weighting	S	F	S	S
Bad	Bad	Worse	Worse	Stop Changing Controller and Sensor Weighting	S	F	S	F
Bad	Bad	Worse	Good	Stop Changing Controller and Begin Changing Sensor weighting	S	F	F	S
Bad	Worst	Bad	Worst	No Action (System Fault)	S	F	F	F
Bad	Good	Good	Good	Begin Changing Controller Weighting	F	S	S	S
Bad	Bad	Good	Worse	Begin Changing Controller and Stop Changing Sensor weightin	F	S	S	F
Bad	Bad	Good	Good	Begin Changing Controller and Sensor Weighting	F	S	F	S
Bad	Worst	Good	Worst	No Action (System Fault)	F	S	F	F
Worst	Good	Worst	Good	No Action (System Fault)	F	F	S	S
Worst	Bad	Worst	Worse	No Action (System Fault)	F	F	S	F
Worst	Bad	Worst	Good	No Action (System Fault)	F	F	F	S
Worst	Worst	Worst	Worst	No Action (System Fault)	F	F	F	F

Remark 1. Initially C1 and S1 in operation and no fault
2. Supervisor alternatively checks the controller and the sensor induced performances ,
CIP : Controller induced performance,
SIP : Sensor induced performance
3. S : Success, F : Failure

Fig. 2. Supervisor Control Strategies.

weighting modulator for sensors performs also the similar function as that for controllers. The weighting values for controllers and sensors are as follows:

$$U = \alpha_1 \times \omega_1 + \alpha_2 \times \omega_2$$

$$Y = \sigma_1 \times \delta_1 + \sigma_2 \times \delta_2$$

where U is modulated controller output and Y is modulated sensor output, α_1 is output of controller 1, α_2 output of controller 2, α_1 weighting value of controller 1, α_2 weighting value of controller 2 and σ_1 is weighting value of sensor 1, σ_2 weighting value of sensor 2, δ_1 output of sensor 1, and δ_2 output of sensor 2. At normal state ω_1 and σ_1 are 1 and ω_2 and σ_2 are 0.

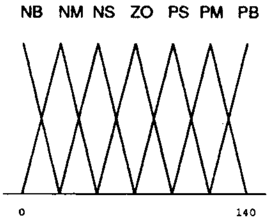

Fig. 3. Fuzzy variable of the error and the change in error.

CE \ E	NL	NM	NS	ZO	PS	PM	PL
NL	NB	NM	NM	NM	NM	PM	PB
NM	NM	NS	ZO	ZO	ZO	PB	PM
NS	NS	ZO	PS	PS	PS	PB	PS
ZO	ZO	PS	PM	PB	PM	PS	ZO
PS	PS	PB	PS	PS	PS	ZO	NS
PM	PM	PB	ZO	ZO	ZO	NS	NM
PL	PB	PM	NM	NM	NM	NM	NB

Fig. 4. Failure detection and weighting fuzzy rule.

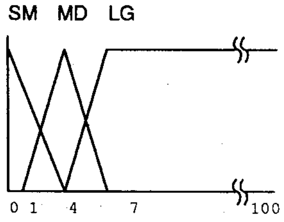

Fig. 5. Fuzzy variable of the deviation between two sensors.

III. Fuzzy Logic System

A. Fuzzy Logic for Fault Controller Redundant System

If a deviation of the plant output from the expected trajectory occurs in a well designed controlled system, its cause can be considered as some faults in controllers or sensors. The supervisor identifies which part, controllers or sensors and if the cause of output deviation stems from controllers, fuzzy modulating mechanism starts to function with the performance decision table can be used as measuring tool for fault degree. The error and the change in error of the system output are chosen as fuzzy variables to present a fault degree. Fuzzy variables are divided into seven fuzzy sets : NB, NS, NM, ZO, PS, PM, and PB, which are shown in Fig. 3. NB is completely faulty state whereas PB is faultless state. Performance decision fuzzy rule can be described as follows. In case of a controller being faultless, the error and the change in error lie on the diagonal region and the system performance is high, namely, PB. In addition, where the error is positive and the change in error is negative, the error will go to zero eventually, it means that the performance is PB. Finally, the degree of the fault can be measured by the distance between the diagonal and the current system state. Performance decision fuzzy rule for determining a fault of the controller is illustrated in Fig. 4.

Weighting modulator initially sets the weighting value of the primary controller to be one and the secondary controller to be zero. In the normal state, faultless condition, only the primary controller participates in control action and the output of performance fuzzy table gives PM which represents the system is in a good condition. Where a fault occurs in primary controller, the fuzzy rule detects an ill condition using fuzzy variables of the error and the change in error, it decreases a weighting of the primary controller and increases that of secondary controller. The modification action of weighting of the controller output is in progress until the trajectory of the error and the change in error goes back into the faultless region.

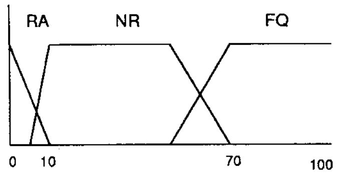

Fig. 6. Fuzzy variable of frequency of deviation.

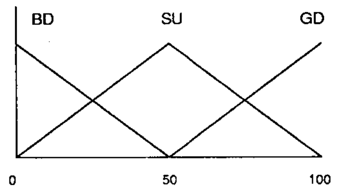

Fig. 7. Fuzzy output variables.

		Deviation		
		SM	MD	LG
Frequency	RA	SU	SU	SU
	ME	SU	SU	BD
	FQ	GD	BD	BD

Fig. 8. Fuzzy rule for sensor failure detection.

B. Fuzzy Logic for Fault Sensor Redundant System

The fuzzy logic for a sensor fault detection uses two fuzzy logic variables : one is the deviation between two sensor outputs and the other is the frequency of a deviation. The relative deviation between two sensor outputs may be calculated as follows:

$$d = \frac{|\delta_1 - \delta_2|}{\delta_1 + \delta_2}$$

where d is the deviation and δ_1 is the output of sensor 1 and δ_2 is output of sensor 2. The possible value for d varies from zero when the two sensors are in good agreement, to one when it is in completely abnormal state or in saturated state. This deviation is then converted into a fuzzy value by using the predefined deviation intervals of small(SM), medium(MD), and large(LG). These fuzzy variables are shown in Fig. 5. Another fuzzy variable considered in detecting the faulty sensor is the frequency of a deviation observed in the fixed time interval. Fig. 6 illustrates a fuzzy variable of the frequency of a deviation which are divided into three ranges, rare(RA), normal(NR), and frequent (FQ). The output fuzzy variables of a sensor fault are bad(BD), suspect(SU), and good(GD), shown in Fig. 7. BD means sensor is faulty, SU in suspect, and GD valid. The fuzzy rule for detecting sensor fault detection is shown in Fig. 8.

IV. SIMULATION AND RESULTS

The proposed fault tolerant control scheme is simulated for demonstrating the capability of detecting fault and mitigating fault situation. We use the Irving's steam generator model for simulations and the

TABLE I

STEAM GENERATOR DYNAMIC PARAMETERS WITH RESPECTIVE TO OPERATING POWER.

Variable	$q_v(kg/s)$	$p(\%)$	G_1	G_2	τ_2	τ	T	G_3
Value	1435	100	0.058	0.47	3.4	28.6	11.7	0.105

equation is as follows:

$$\begin{aligned} \dot{x}_1(t) &= G_1(q_e(t) - q_v(t)) \\ \dot{x}_2(t) &= -\tau_2^{-1}x_2(t) - \frac{G_2}{\tau_2}(q_e(t) - q_v(t)) \\ \dot{x}_3(t) &= -2\tau^{-1}x_3(t) + x_4(t) + G_3 q_e(t) \\ \dot{x}_4(t) &= -(\tau_2^{-2} + 4\pi T^{-2})x_3(t) \\ y(t) &= x_1(t) + x_2(t) + x_3(t) \end{aligned} \tag{1}$$

where p is the operating power, $y(t)$ the steam generator water level, $q_e(t)$ the feedwater flow, and $q_v(t)$ the steam generator flow which are deviations from initial state, respectively. As shown in Fig. 1 the controllers and sensors are duplicated and H_∞ controller is used as a basic controller because it guarantees disturbance attenuation. Fig. 9 shows the output signal where the primary sensor has a fault of which the profile is the staggered manner with deviation by 70% at $50sec$, whereas the secondary sensor performs well. The sensor fault detection fuzzy rule successfully identifies the ill condition of sensor output. The weighting of the primary sensor reduces from 1 to 0.01 and finally to zero as the degree of the sensor fault increases. The output signal is almost the same as the reference value. Fig. 10 shows the system response with the step fault of the primary controller. The fuzzy weighting modulator well tracks the reference value by suppressing fault effects. In case of the ramp failure of the primary controller, Fig. 11 illustrates the system response that the controller output increases gradually. As in the previous case, the fuzzy weighting mechanism gives a good weight modulating capability with which the control action is successfully taken over to the secondary sensor.

V. CONCLUSIONS

In the study, a failure detection and mitigation scheme is proposed for controllers or sensors by using fuzzy logic. The supervisor control strategies and two failure detection fuzzy rules for a controller and a sensor are presented. The fuzzy failure detection rule and mitigating faults in a controller and a sensor fworks well even if a mathematical model is not involved. The simulation results show that the fault tolerant control system can maintain its own control capability while suppressing a faulty signal.

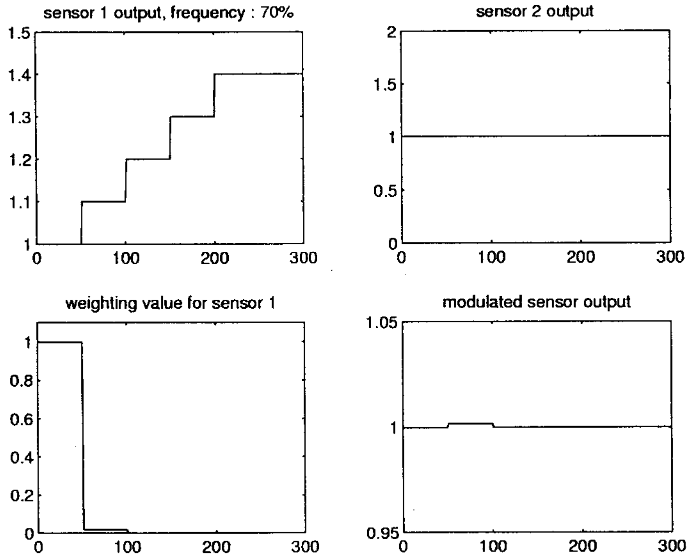

Fig. 9. Sensor failure and modulated sensor output.

Through duplicating sensor and controller with this proposed fault tolerant scheme, system reliability can be increased much more.

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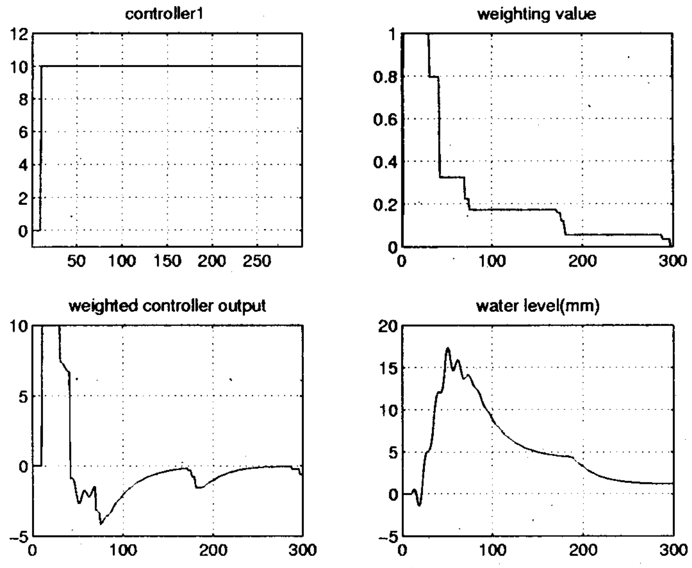

Fig. 10. Controller step failure and the response of steam generator water level.

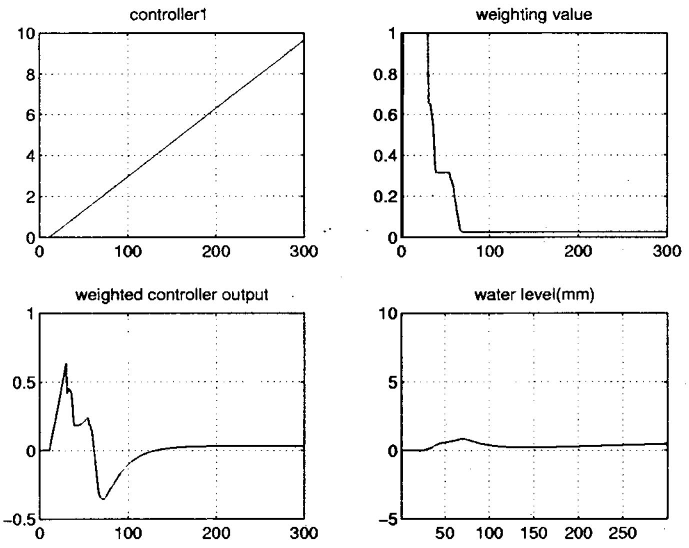

Fig. 11. Controller ramp failure and the response of steam generator water level