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Fault Simulation and Fuzzy Controller for High Pressure Heater in Thermal Power Plant

S. Srinivasan [1*], **P. Kanagasabapathy**[1], **K. Chitra**[1], **R. Pugazhendi** [2] and **N. Selvaganesan** [3]

[1]Department of Instrumentation Engineering, MIT Campus, Anna University, Chromepet, Chennai – 600044, India.
[2]Assistant Executive Engineer, Control & Instrumentation, 210 MW North Chennai Thermal Power Station, TNEB.
[3]Department of Electrical and Electronics Engineering, Pondicherry Engineering College, Pondicherry – 605014, India.

[*]Corresponding author: srini@mitindia.edu (S. Srinivasan), Tel: 91 44 22230850, Fax: 91 44 22232403

Abstract: This paper presents fault simulation and design of fuzzy logic controller for a high pressure heater in a thermal power plant. An analytical model for the system has been presented in the nonlinear state space form based on fundamental physical laws. The mathematical model is validated with the real time plant data. A fuzzy controller is developed, which performs like a classical proportional plus integral controller, giving the level reference variation based on error in condensate level inside a heater and its change. The state variables are estimated for the normal and faulty condition using the model which is simulated using the plant data. The performances of both controllers are evaluated and the faults are simulated using Matlab simulink.

Keywords: High pressure heater, Fuzzy logic controller, Fault simulation, Model, Valve failure

1. INTRODUCTION

Prompt detection and diagnosis of faults in industrial systems are essential to minimize production loss and to increase the safety of the operator and equipment. Many approaches have been developed and significant distinctions between the various approaches can be seen in the model free method and model based method. For the model free techniques the fault detection scheme uses only input/output data or some pre-processed form of them are taken into account [1-3]. Model based fault diagnosis concepts have increasingly gained attention over the last decade due to the demand for uninterrupted operation and higher safety and reliability standards. Moreover the mathematical model of the system allows evaluating a measurement of the analytical redundancy between the nominal plant and the plant when a fault occurs [4-7].

Work has already been done in developing the model of a high pressure heater [8-12]. A more realistic model can provide a faster and better way of designing controllers. The biggest challenge is due to the high degree of non-linearity present in the system. T.Parisini [8-9] has extensively worked on developing the model of a high pressure heater based on the physical principles.

This paper deals with fault simulation and design of fuzzy controller for a High Pressure (HP) heater using a nonlinear mathematical model. The performance of the Fuzzy Logic Controller (FLC) is compared with a conventional Proportional plus Integral (PI) controller. The faults such as input drain water valve failure, input steam valve failure, leakage in feed water tubes and sensor fault are simulated. The rest of the paper is divided into four sections. The HP heater modeling is explained in Section 2. The fuzzy controller design is dealt with in Section 3. Section 4 deals with the simulation of faults using FLC. Finally, conclusions are made in Section 5.

2. HP HEATER

HP heaters are employed to increase the overall efficiency of the regenerative cycle of thermal power plants by heating the feed water, coming from the feed pump and flow through the heaters and goes into the boiler, by the extracted spill over steam from suitable stages of the turbine. The closed type HP feed water heaters are vertically mounted and known as shell and tube heat exchangers. This is because bleed steam is condensed on the shell side, whereas the feed water which acts like circulating condensed water is heated on the tube side. These heaters are located on the discharge side of the boiler feed pump and use highly superheated steam for heating the feed water. The heaters are therefore subjected to very high pressure and temperature. Figure 1 shows the regeneration process in a thermal power plant. Figure 2 shows the temperature path length diagram of the three zones in the closed type vertical HP feed-water heater. They are the *de-superheating zone* (point 1 to 2) where the superheated steam cools down until it reaches the saturated steam condition. The *condensing zone* (point 2 to 3) is where the latent heat of vaporization removed and condensed to a saturated liquid (Vapor liquid transition) and *Sub-cooling zone* (point 3 to 4) where the condensed steam is cooled below its saturation temperature and exchanges heat with the feed water along with drain coming from stream heaters [13]. Points 5 to 8 represents the counter flow direction of the feed water where the temperature raises from T_1 to T_2. The feed water flows through the tubes and passes through a drain cooling section, a condensing section and finally to the de-superheating section. The schematic diagram of the heat exchanger with three different zones is shown in Figure 3.

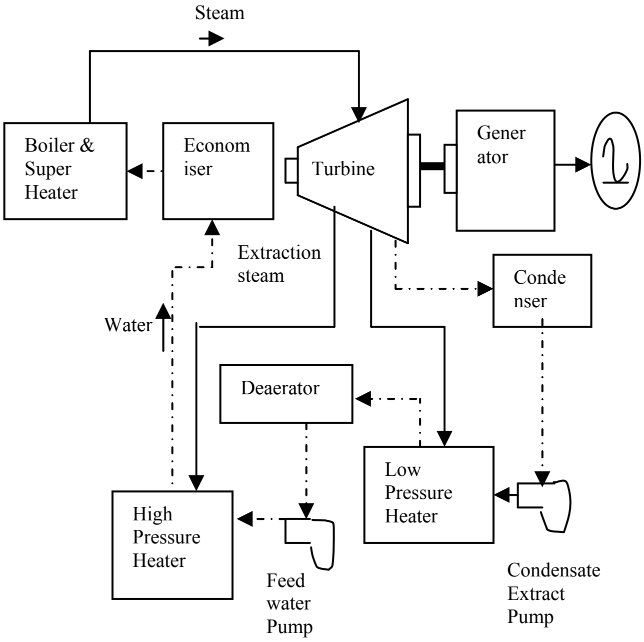


Figure 1. The scheme of regeneration process

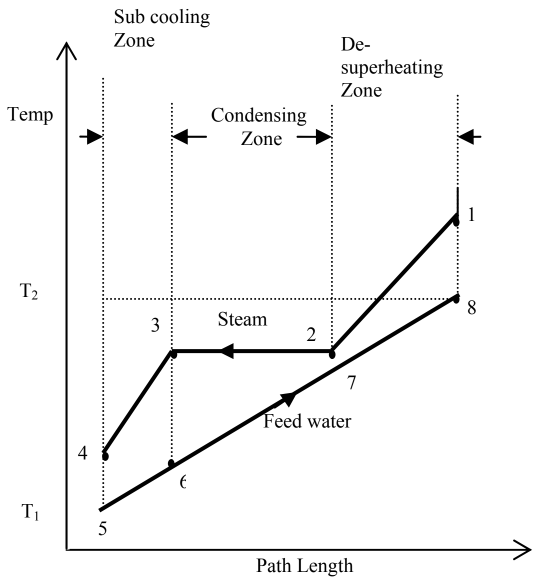


Figure 2. Temperature-Path length diagram for three zone closed type vertical high pressure feed water heater.

2.1 Modeling of the HP Heater

The model of the heater has been obtained by physical approach. The equations describing the heater have been derived from the mass, energy and momentum conservation laws. In particular, it has been analysed for i) the behaviour of the fluid inside the hollow by using the equations for the conservations of the mass of drain water, the mass of water and steam and the energy of sub-cooled water ii) the behaviour of the fluid in the tube bundle by using the equations for the heat exchange in the de-superheating, drainage and condensation areas and the equations for the loss of pressure in the tube bundles due to metal friction.

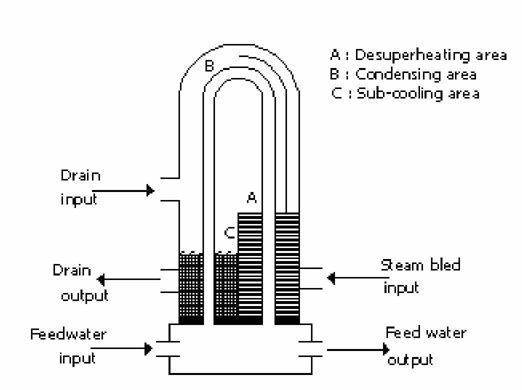


Figure 3. The schematic diagram of the heat exchanger

The non-linear state equations can be derived to define the behaviour of the thermodynamic coordinates of the thermo-transformation in a heater and can be described by the following equations [8]

$$\frac{dX_L}{dt} = \frac{W_{idr} + W_{con} - W_{odr} - W_{ev}}{\rho_{odr} A_h} \qquad (1)$$

$$\frac{dX_p}{dt} = \frac{W_{tur} + W_{idr} - W_{odr} - (\rho_{odr} - \rho_{sst}) A_h \frac{dX_L}{dt}}{(V_h - A_h X_L)\frac{d\rho_{sst}}{dX_p}} \qquad (2)$$

$$\frac{dH_1}{dt} = \frac{1}{m_w}(W_{idr}(h_{idr} - H_1) + W_{con}(h_{sw} - H_1) - W_{ev}(h_{sst} - H_1) + A_h X_L \frac{dX_L}{dt} - Q_c) \qquad (3)$$

$$\frac{dH_2}{dt} = \frac{W_{fw}(H_3 - H_2) + Q_A}{L_A m_{me}} \qquad (4)$$

$$\frac{dH_3}{dt} = \frac{W_{fw}(H_4 - H_3) + Q_B}{L_B m_{me}} \qquad (5)$$

$$\frac{dH_4}{dt} = \frac{W_{fw}(h_{fw} - H_4) + Q_c}{X_L m_{me}} \qquad (6)$$

$$\frac{dS_e}{dt} = \frac{1}{\tau_1}(X_L - O_1 - S_e) \qquad (7)$$

The state variables are X_L: Liquid level in the heater in mm, X_p: Pressure in the hollow of the heater Kg/cm^2, H_1 : Specific enthalpy of output drain KJ/Kg, H_2 : Specific enthalpy of output feed- water KJ/Kg, H_3 : Specific enthalpy of feed- water in condensing area KJ/Kg, H_4 : Specific enthalpy of feed- water in sub-cooling area KJ/Kg, S_e : State of the liquid level sensor in mm, τ_1 : Time constant of liquid level sensor and O_1 **:** Offset of sensor. The input variables are W_{idr} : input drain water flow, W_{tur} : steam flow from turbine, W_{fw} : feed water flow and W_{odr} : output water drain flow. The output variable is the condensate level in the heater. The nominal values and the physical parameters of an HP heater are given in the Appendix.

3. DESIGN OF A FUZZY LOGIC CONTROLLER

The typical block diagram of the FLC is shown in Figure 4. The fuzzy controller contain "*fuzzifiers*", "*knowledge base*", "*decision making logic*" and "*defuzzifiers*" [14 - 17]. The operations performed by a fuzzy logic controller are follows.

The input variables used for the FLC are the error e(k), which is the difference between the desired level of condensate and the measured value of condensate level and the change in Error Δe(k), which is calculated by the difference between the error at the present instant e(k) and the error at the previous instant e(k-1), The output variable is the change in output Δe(k) and the output of the FLC is given by

$$u(k) = u(k-1) + \Delta u(k) \quad (8)$$

The Universe Of Discourse (UOD) for error is set to be between -100 mm to 100 mm, for Change in error is -3mm to 3 mm while for change in output is -50mm to 50 mm. The *Linguistic Variables* for the fuzzy input and output variables, namely Error, Change in Error and Change in Output, are divided into seven linguistic (fuzzy) variables namely NL (Negative Large), NM (Negative Medium), NS (Negative Small), Z (Zero), PS (Positive Small), PM (Positive Medium), and PL (Positive Large). The membership functions are of symmetric triangular shape with equal base and 50% overlap. The rules that tie the input and output variables are given in Table 1. The max-min implication technique is used for decision making and the 'center of area' method is used as a defuzzifier which generates the center of gravity of the final fuzzy control space. Figure 5 represents the surface area of the designed fuzzy controller.

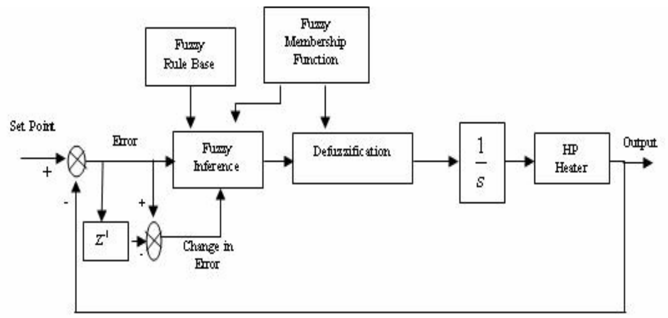


Figure 4. Block diagram of the FLC System.

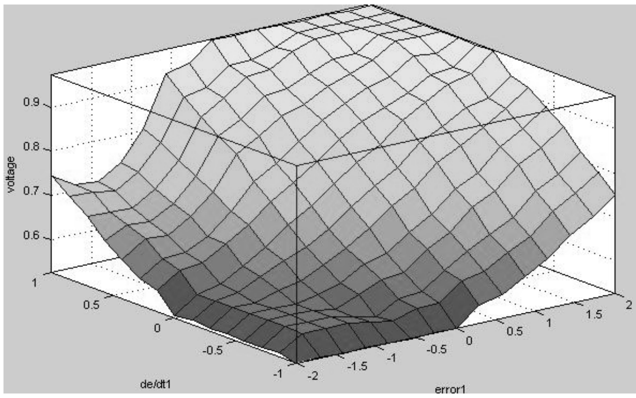


Figure 5. Surface area of the FLC.

Table 1. Rule database

e / Δe	NL	NM	NS	Z	PS	PM	PL
NL	NL	NL	NL	NL	NM	NS	Z
NM	NL	NL	NL	NM	NS	Z	PS
NS	NL	NL	NM	NS	Z	PS	PM
Z	NL	NM	NS	Z	PS	PM	PL
PS	NM	NS	Z	PS	PM	PL	PL
PM	NS	Z	PS	PM	PL	PL	PL
PL	Z	PS	PM	PL	PL	PL	PL

4. RESULTS AND DISCUSSION

4.1 FLC Simulation

The controller performance of the HP heater is simulated using Matlab / Simulink package with change in the reference level and load disturbance. The performance of the designed FLC is compared with that of conventional PI controller. The real time PI controller parameters are K_p = 2.5, and K_i = 83.33. The quantitative criteria for measuring the performance are chosen as Integral Absolute Error (IAE) and Integral of Time weighted Absolute Error (ITAE). IAE accounts mainly for errors at the beginning of the response and to a lower degree for the steady state deviation. ITAE not only accounts for the error at the beginning but also emphasises the steady state.

4.1.1 Servo Response

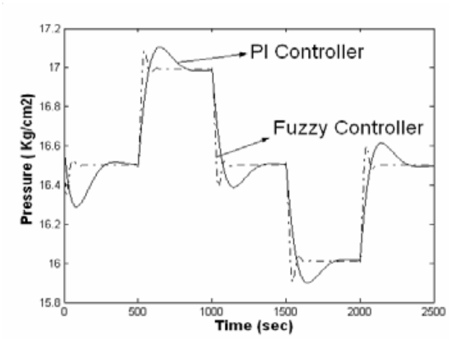
The set point is initially varied from 350 mm to 360mm at t =1000. The response of both pressure and level for PI controller and FLC can be depicted as shown in Figure 6.

4.1.2 Regulatory Response

The mathematical model is validated in order to perform exactly with the same behavior of the measurable variables in the plant under steady state operating condition. A disturbance of 0.3 % opening of input water valve to the HP heater is made, which is actually the output drain water of the previous HP heater. This causes a rise on the condensate level inside the tested heater to 352 mm from its set point value of 350 mm. The simulation is also applied to the mathematical model by opening 0.3% of the input water valve at t = 1000 sec. The simulated result shown in Figure 7 thus proves that the model obtained is very accurate and suitable for use in testing fault diagnosis techniques. The performance of PI and FLC controller, in terms of pressure and level in the heater, for the load disturbances is shown in Figure 7. The above simulation results demonstrate the comparable steady state performance. The performance indexes are summarized in Table 2. From the table it can be seen that the servo and regulatory response of the FLC achieves a better transient and steady state performance than PI controller.

Table 2. IAE and ITAE for HP heater

Controller Type	Servo		Regulatory	
	IAE	ITAE	IAE	ITAE
PI	2.399	1395	1.946	894.6
FLC	0.6694	383.1	0.3336	35.53



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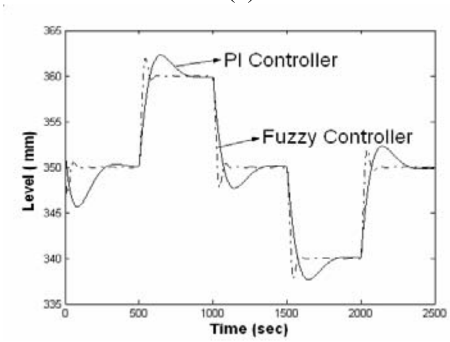

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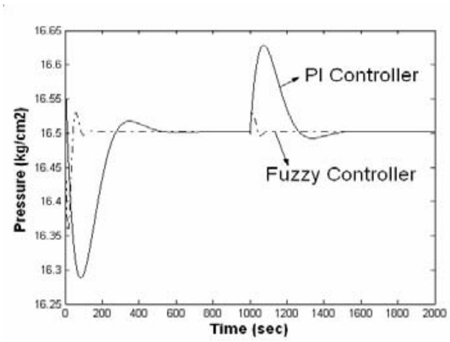
Figure 6. Servo response of controllers



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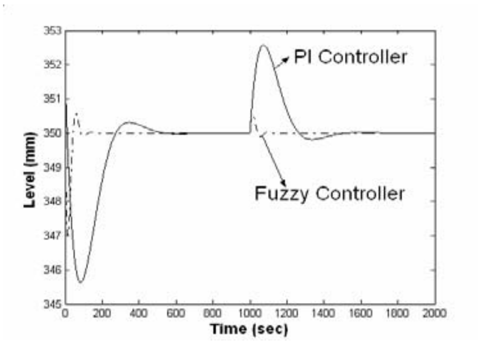

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Figure 7. Regulatory response of controllers

4.2 Faults Simulation

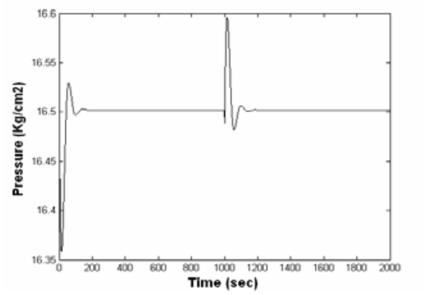
The faults simulated are input steam valve failure, input drain water valve failure, leakage in feed water tubes and sensor fault using the designed FLC.

4.2.1 Input Drain Water Valve Failure

This valve regulates the flow of input drain water to the sub cooling zone of the heater. A failure of this valve causes major changes in the condensate level, pressure inside the heater, specific enthalpy of feed water and specific enthalpy of output drain water flow. Figures 8 and 9 show the response of the pressure, level, specific enthalpy of the output feed water and specific enthalpy of output drain for the simulation of 10 % positive bias and 10% negative bias of the input drain valve at 1000^{th} instant respectively.

4.2.2 Input Steam Valve Failure

The steam valve regulates the flow of bleed steam from the turbine to the shell of the heater. The failure of this valve changes the input flow rate of the steam, causes changes in the condensate level inside the heater, pressure inside the heater, specific enthalpy of output drain and specific enthalpy of feed-water flowing through the tube bundle due to changes of heat transfer. Figures 10 and 11 show response of the pressure, level, specific enthalpy of the output feed water and specific enthalpy of output drain for the simulation of 10% increase in steam flow rate and 10% decrease in steam flow rate due to input steam valve failure at 1000^{th} instant.



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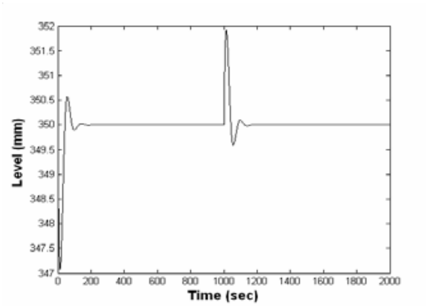

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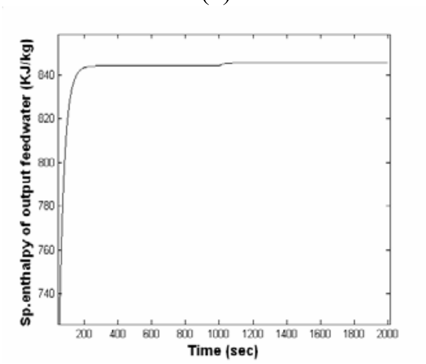

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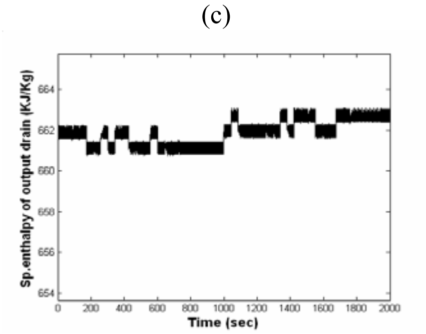

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Figure 8. Response for positive bias of input drain valve failure

4.2.3 Leakage in Feedwater Tube

This malfunction in the condensing area of heater causes the feed water to flow into the external jacket i.e. shell side of the heater. The most visible effects of this fault concern the levels and pressures inside the heater and increase in enthalpy of feed water. If W_{fwin} and W_{fwout} represent the flows of feed water at the input and output of heater then with leakage it can be represented [18] as

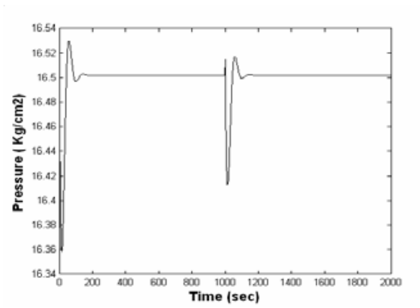
$$W_{fwin} = W_{fwout} + W_{leak} \tag{9}$$

W_{leak} denotes the flow of the fluid coming out of the tube bundle owing to leakage. W_{leak} is calculated by considering the fall in pressure undergone by the water while passing from the tube bundles into the hollow of the heater as follows

$$W_{leak} = \gamma \sqrt{P_{ali} - P_{ris}} \tag{10}$$

where P_{ali} is pressure of feed water at the input of tube bundle, P_{ris} is pressure inside the heater and γ represents percentage of fluid coming out of tube bundle.

The response of the pressure, level, specific enthalpy of the output feed water and specific enthalpy of output drain for the simulation of leakage in feed water tube is shown in Figure 12.



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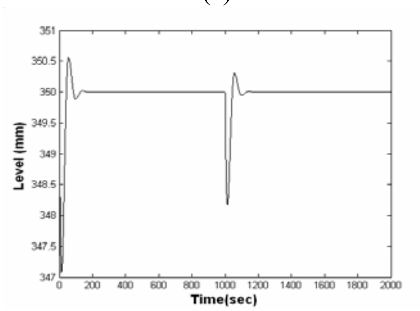

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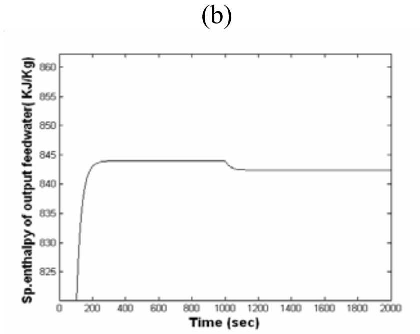

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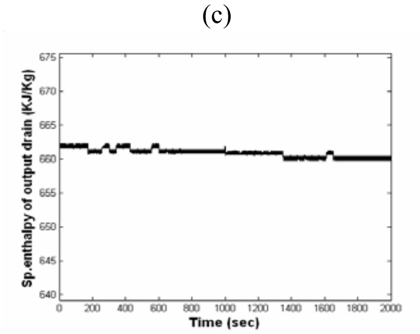

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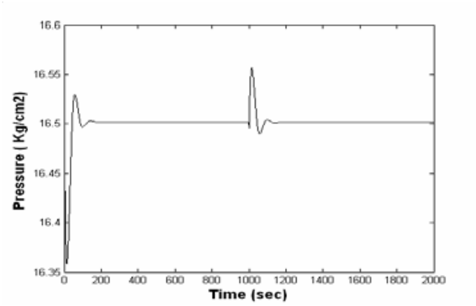
Figure 9. Response for negative bias of input drain valve failure

4.2.4 Sensor Fault

Malfunction of sensor is depicted as

$$e = (Y + \varepsilon) - Y^d \tag{11}$$

where e, ε, Y and Y^d represent input error at the PI block, offset introduced due to malfunction of the sensor, process output measured by sensor and desired level respectively. The response of the pressure, level, specific enthalpy of the output feed water and specific enthalpy of output drain for the simulation of sensor fault is shown in Figure 13.



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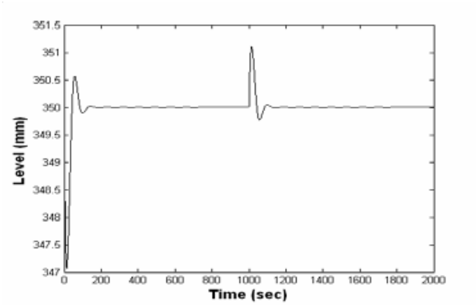

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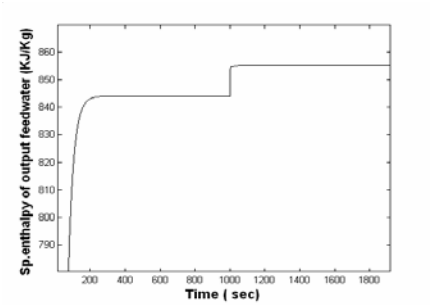

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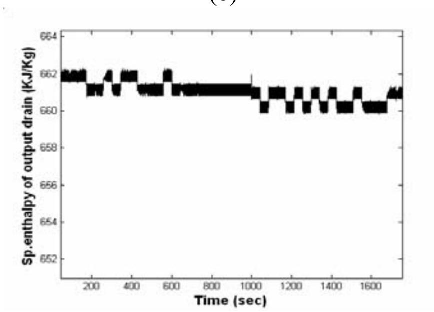

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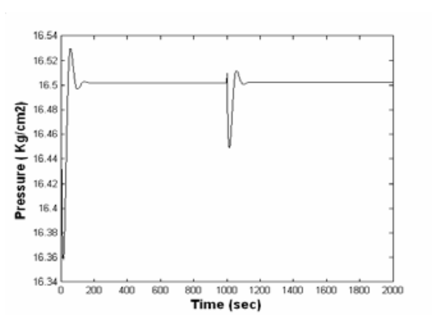
Figure 10. Response for positive bias input steam valve failure



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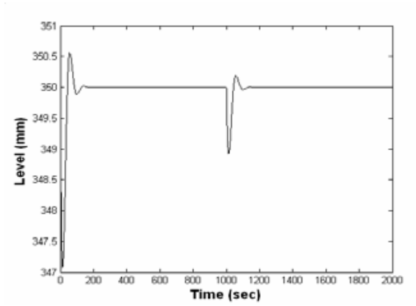

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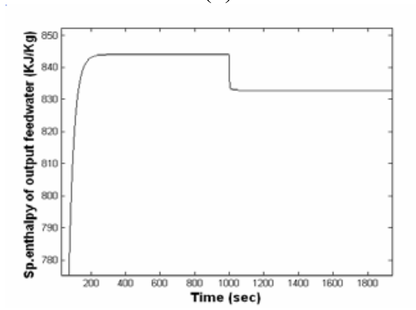

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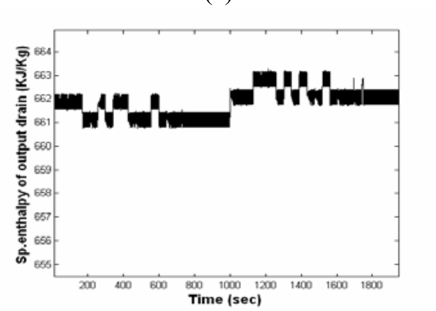

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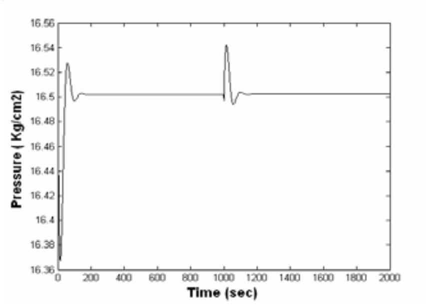
Figure 11. Response for negative bias input steam valve failure

5. CONCLUSION

This paper describes the simulation and design of an FLC for an HP heater. The mathematical model of an HP heater is simulated by expert knowledge and with steady state values obtained from a 210 MW Thermal Power Station, North Chennai, TNEB, India. A FLC is successfully designed and the superior performance of the FLC is complimented by the reduced oscillations, less peak over shoot and less settling time of the control variable about the set point. Hence, the proposed FLC has the advantages like, more accurate tracking of the set point variations, reduced oscillations about the set point and relatively robust to load disturbances over the conventional PI controller. Different faults are simulated using the mathematical model for the HP heater and it is observed that there is a significant change in the measured variable for a 10% variation in the faults.



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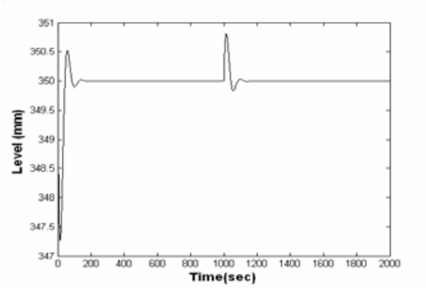

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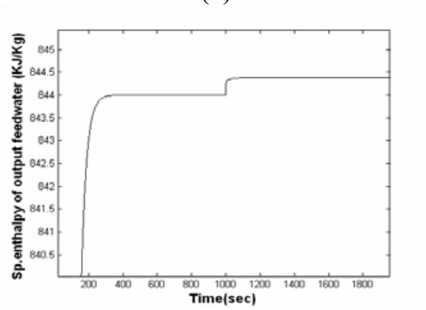

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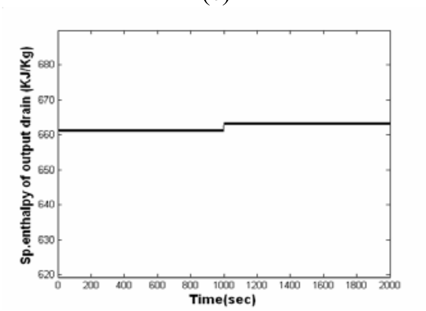

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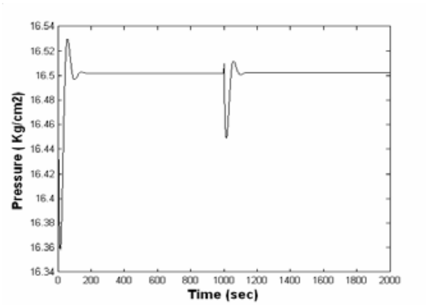
Figure 12. Response for leakage in feed water tubes



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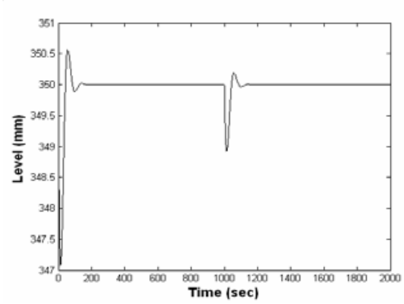

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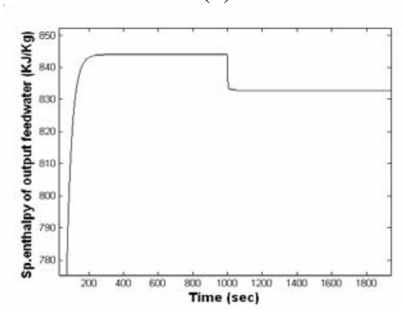

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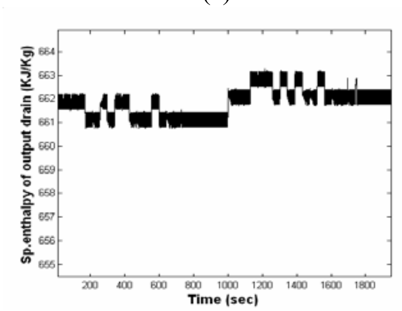

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Figure 13. Response for sensor fault

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APPENDIX

Nominal operating value of system variable

Variables	Description	Value	Unit
W_{idr}	Input drain flow	15	Kg/sec
W_{con}	Condensate steam flow	9	Kg/sec
W_{odr}	Output drain flow	26	Kg/sec
W_{tur}	Steam flow from turbine	9.1663	Kg/sec
Wev	Evaporated water flow	0.163	Kg/sec
W_{fw}	Feed water flow	210.27	Kg/sec
h_{idr}	Sp.Enthalpy of output drain	896	KJ/Kg
h_{sw}	Sp.enthalpy of saturated water	858.5	KJ/Kg
h_{fw}	Sp.Enthalpy of input feed water	716	KJ/Kg
h_{sst}	Sp.enthalpy of saturated steam	2791	KJ/Kg
ρ_{odr}	Density of output drain	907	Kg/m^3
ρ_{sst}	Density of saturated steam	8.08	Kg/m^3
m_w	Mass of liquid in heater	1621	Kg
m_{me}	Mass of water and equivalent metal per unit	18.13	Kg/m
Q_A	Heat exchange in desuperheating area	4581	KJ/sec
Q_B	Heat exchange in condensing area	17392.5	KJ/Sec
Q_C	Heat exchange in sub-cooling area	4942.5	KJ/sec
Tin_{fw}	Input temperature of feed water	169	°c
$Tout_{fw}$	Output temperature of feed water	195	°c
Tdir	Temperature of input drain water	210	°c
Todr	Temperature of output drain water	160	°c
Ttur	Temperature of input steam from turbine	401	°c
Ptur	Input pressure of steam from turbine	16	Kg/cm^2
Pfw	Pressure of feed water flow	155	Kg/cm^2
Vfw	Velocity of feed water flow	1.81	m/sec

Physical parameters of high pressure heater

Variables	Description	Value	Unit
H_l	Shell height including dome	9.2	meters
Ah	Hollow area not including the pipes	46	m^2
Vh	Hollow volume not including the pipes	57	m^3
La	Height of de-superheating area	2.48	meters
Lb	Height of condensing area	11.6	meters
Aa	Heat transfer area (de-superheating zone)	78	m^2
Ab	Heat transfer area (condensing zone)	508	m^2
Ac	Heat transfer area (sub cooling zone)	106	m^2
Lfw	Overall length of feed water tube	8.2	meters
Nfw	Number of tubes	864	-
OD	Outside diameter of tube	15.8	mm
Thk	Thickness of tube	1.8	mm
Gauge	Gauge of tube	18	BWG
Material	Tube material	SA 213* AISI Type 304 stainless steel	
K	Thermal conductivity of tube	16.2	W/ m-k
Material	Shell material	IS 2002 Grade 2	