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REDUCED ORDER MODEL OF U-TUBE STEAM GENERATOR AND APPLICATION OF FUZZY AND LQR IN ITS LEVEL CONTROL

Jeetendra Agarwal[1], Girish Parmar[2] and Rajeev Gupta[3]
Department of Electronics and Communication Engineering, Rajasthan Technical University, India
E-mail: [1]jitu.leo@gmail.com, [2]girish_parmar2002@yahoo.com, [3]rajeev_eck@yahoo.com

Abstract

The water level of the U-tube steam generator (UTSG) in a nuclear power unit, which is an important process parameter, must be maintained in a safe range whether the unit is working under fixed or variable conditions. In this paper, a higher order UTSG model derived from the state equations is reduced using Balanced Truncation technique. Two controllers using Fuzzy logic and LQR techniques have been designed for the reduced UTSG model to control its water level. Comparison of these two controllers has also been shown through the simulation results. Also, a comparative analysis of the reduced order model and a previously developed UTSG model is presented by simulating both UTSG models with Fuzzy Logic and LQR techniques and the results are compared.

Keywords:

Nuclear Reactor, UTSG Model, Model Order Reduction, LQR, Fuzzy Logic

1. INTRODUCTION

Economic feasibility of a nuclear power plant requires smooth and uninterrupted plant operation even when the demand for electrical power is varying. Unplanned shutdowns or reactor trips initiated due to conservative safety considerations are particularly expensive and must be minimized. Steam generators which are among the most important components of nuclear power reactors perform three basic functions: steam generation for power turbine to produce power, remove the reactor residual heat with reactor shut down and finally the most important, create a separating boundary between the primary and secondary water coolant [1].

The water level regulation of SG is a difficult control problem due to its non-linear behaviour, non-minimum phase characteristics, unstable plant dynamics and unreliable sensor feedback at low power. Too high water level produces wet steam which can damage the turbine blades. Too low water level causes poor cooling of the nuclear reactor, which ultimately results in reactor trips. Thus, both at upper and lower levels, there are limitations for level regulation [2].

The numerical simulation for verifying the “swell and shrink” behaviour has been carried out by simulating the transient responses of the narrow range water level of SG at different operating powers (5%, 15%, 30%, 50% and 100% full power) due to step increase in feed water flow rate and transient responses of the narrow range water level of SG at the same different operating powers due to step increase in the steam flow-rate. Figure 1 and 2 show responses of the water level to step increase in feed water and steam flow rates at different operating powers. For generating the responses, the power dependent linear parameter varying model has been used [3], [11].

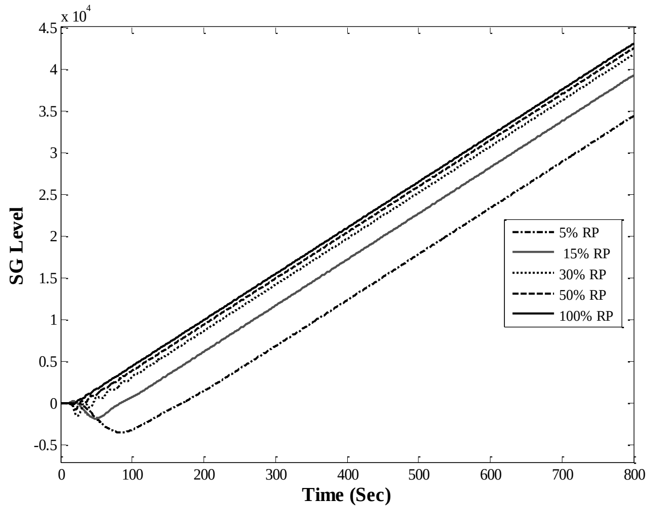

Fig.1. SG water level at different operating powers to a step increase in feed water flow rate

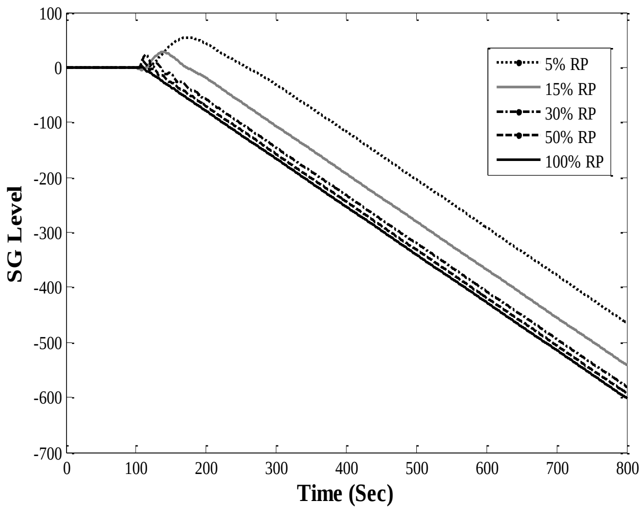

Fig.2. SG water level at different operating powers to a step increase in steam flow rate

It is difficult to maintain the water level within the permissible span when the power is low. Particularly, during the start up, a great attention should be paid by the operator as the reactor trips due to the limitations at low power are the main causes of plant unavailability [4].

2. U-TUBE SG MODEL

The steam generator also acts as a heat sink for the reactor coolant. The surface area and volume of the vapour space in the steam generator is critical to the efficient separation of the steam bubbles from the water. Too small an area can result in an excessive surface tension and high velocities, which result in wasted heat and drum water. Too large, an area is simply a waste of material and labour to construct the vessel. The boiler level control is critical for both turbine protection and reactor safety and applies equally for high and low levels of water with in the boiler drum [5].

The three outputs of a UTSG that are usually measured are the cold-leg temperature, $T_{cl}(t)$, the down-comer water level, $L_w(t)$, and the secondary steam pressure, $P_s(t)$; while the five disturbances acting upon the system are the feed-water temperature, $T_{fw}(t)$, the hot-leg temperature, $T_{hl}(t)$, the primary mass flow rate, $W_{pr}(t)$, the primary pressure, $P_{pr}(t)$, and the steam flow rate, $W_{st}(t)$. There is only one manipulated control input which is the feed water flow rate, $W_{fw}(t)$ [1].

A brief description of the simulator used is presented, for the reader to appreciate the complexity of the involved UTSG water-level control problem. For the primary side model, a set of three differential equations with three unknowns is used. In matrix form these are,

$$E_1\left(T(t)\right)\dot{T}(t) = f_p\left(T(t), Q_B, T_{hl}(t), P_{pr}(t), W_{pr}(t)\right) \quad (1)$$

where,

$$E_1\left(T(t)\right) = \begin{bmatrix} E_{11}\left(T(t)\right) & 0 & 0 \\ 0 & E_{22}\left(T(t)\right) & 0 \\ 0 & 0 & E_{33}\left(T(t)\right) \end{bmatrix} \quad (2)$$

$$T(t) = \left[T_1(t), T_2(t) T_3(t)\right]^T \quad (3)$$

where, $f_p(.)$ is a three-dimensional vector forcing function, $T_1(t)$, $T_2(t)$ and $T_3(t)$ are the temperatures of the inlet, the tube bundle and outlet, respectively, $E_1(.)$ is a diagonal nonlinear matrix function of the temperature vector, $T(t)$ and $Q_B(t)$, the thermal load, is the thermal energy transferred from the primary side to the secondary side across the tube bundle region. The heat load is calculated using,

$$Q_B(t) = U_{over} A_0 \Delta T_{LM}(t) \quad (4)$$

where, U_{over} is the overall heat transfer coefficient, A_0 is the total outside surface area of the tubes, and $\Delta T_{LM}(t)$ is the log-mean temperature difference given by,

$$\Delta T_{LM}(t) = \frac{T_1(t) - T_2(t)}{\ln\left[T_1(t)\frac{T_{sat}}{T_2(t)} - T_{sat}\right]} \quad (5)$$

where, T_{sat} is the saturation temperature of water at pressure P_{pr}.

For the secondary side, the mass and energy conservation equations are summed up over the control volumes, and the momentum equation is used to describe the re-circulation flow. The secondary equations can then be represented as,

$$E_2\left(x_s(t)\right)\dot{x}_s(t) = f_s\left(x_s(t), Q_B, W_{fw}(t), W_{st}(t), T_{fw}(t), v(t)\right)$$

or

$$E_2\left(X_s(t)\right)\frac{d}{dt}\begin{bmatrix} U_0(t) \\ V_v(t) \\ \alpha_N(t) \\ \alpha_R(t) \\ P_s(t) \\ \overline{W(t)} \end{bmatrix} = \begin{bmatrix} f_1(t) + f_2(t) \\ f_2(t) \\ f_3(t) \\ f_4(t) \\ f_5(t) \\ f_6(t) \end{bmatrix} \quad (6)$$

where, the secondary states, $X_s(t)$, are the internal energy at the down comer exit, $U_0(t)$, the vapour volume in the steam dome, $V_v(t)$, the void fractions at the riser inlet and outlet, $\alpha_N(t)$ and $\alpha_R(t)$, respectively, the secondary side steam pressure, $P_s(t)$, and the re-circulation flow rate, $W(t)$.

The output shaping filter was instrumental in tuning the performance of the designed compensators. Each of the linearized UTSG models has nine states. An 11^{th} order open loop model is obtained by augmentation of the nine states of the linearized UTSG model with the filter states and is given by,

$$T(s) = \frac{A}{B} \quad (7)$$

where,

$$A = 0.01s^{10} + 97s^9 + 448s^8 + 826s^7 + 789s^6 + 432s^5 + 143s^4 + 26s^3 + 2s^2 + 0.03s + 3*10^{-5}$$

$$B = 0.001s^{11} + 9s^{10} + 66s^9 + 187s^8 + 277s^7 + 233s^6 + 113s^5 + 32s^4 + 6s^3 + s^2 + 0.03s + 3*10^{-6}.$$

This model is then reduced to 4th order by using model order reduction technique and is then simulated to design suitable controllers for UTSG water level.

2.1 MODEL ORDER REDUCTION BY BALANCED TRUNCATION

In the current study, since UTSG model is not so simple that it can be easily analysed, a numerically linearized UTSG model is obtained by perturbing the system states, the input variable and the disturbances one at a time, about an equilibrium point. The rates of change of the system states and outputs are then computed. For increasingly smaller perturbations from the equilibrium point the, the local (or linear) behaviour of UTSG is computed.

The large scale complex systems like that of a UTSG, model order reduction is required. These large system models are converted into smaller ones so that without losing any important information, their behaviour can be accurately studied. Various mathematical approaches are used for this purpose. In this work, a method called Balanced Truncation is used for reducing the 11^{th} order transfer function of UTSG into 4^{th} order [6-7]. Consider a stable system $G \in RH_\infty$ and suppose $G = \left[\left\langle \frac{\bar{A}}{\bar{C}} \middle| \frac{\bar{B}}{\bar{D}} \right\rangle\right]$ is a balanced realization [6]. Denoting the balanced Grammian by Σ; we have

$$\bar{A}\Sigma + \Sigma\overline{A^*} + \bar{B}\overline{B^*} = 0 \quad (8)$$

$$\Sigma\bar{A} + \overline{A^*}\Sigma + \overline{C^*}\bar{C} = 0. \quad (9)$$

Now partition the balanced Grammian as,

$$\Sigma = \begin{bmatrix} \Sigma_1 & 0 \\ 0 & \Sigma_2 \end{bmatrix} \quad (10)$$

and partition the system accordingly,

$$G = \left[\left\langle \begin{array}{cc|c} \overline{A_{11}} & \overline{A_{12}} & \overline{B_1} \\ \overline{A_{21}} & \overline{A_{22}} & \overline{B_2} \\ \hline C_1 & C_2 & D \end{array} \right\rangle \right]. \quad (11)$$

Then Equations can be written in terms of their partitioned matrices as,

$$\overline{A_{11}}\Sigma_1 + \Sigma_1 \overline{A_{11}^*} + \overline{B_1}\,\overline{B_1^*} = 0 \quad (12)$$

$$\Sigma_1 \overline{A_{11}} + \overline{A_{11}^*}\Sigma_1 + \overline{C_1^*}\,\overline{C_1} = 0 \quad (13)$$

$$\overline{A_{21}^*}\Sigma_1 + \Sigma_2 \overline{A_{12}^*} + B_2 B_1^* = 0 \quad (14)$$

$$\Sigma_2 \overline{A_{21}} + \overline{A_{21}^*}\Sigma_1 + \overline{C_2^*}\,\overline{C_1} = 0 \quad (15)$$

$$\overline{A_{22}}\Sigma_2 + \Sigma_2 \overline{A_{22}^*} + \overline{B_2}\,\overline{B_2^*} = 0 \quad (16)$$

$$\Sigma_2 \overline{A_{22}} + \overline{A_{22}^*}\Sigma_2 + \overline{C_2^*}\,\overline{C_2} = 0. \quad (17)$$

By virtue of the method adopted to construct [8], the most energetic modes of the system are in Σ_1 and the less energetic ones are in Σ_2. Thus, the system with balanced Grammian would be a good approximation of the original system. Using the above described method the reduced 4th order transfer function calculated using MATLAB for UTSG is given by,

$$T(s) = \frac{12.45s^3 + 870.7s^2 + 12.96s + 0.0003513}{s^4 + 1.209s^3 + 0.0712s^2 + 0.04099s + 1.16 * 10^{-7}} \quad (18)$$

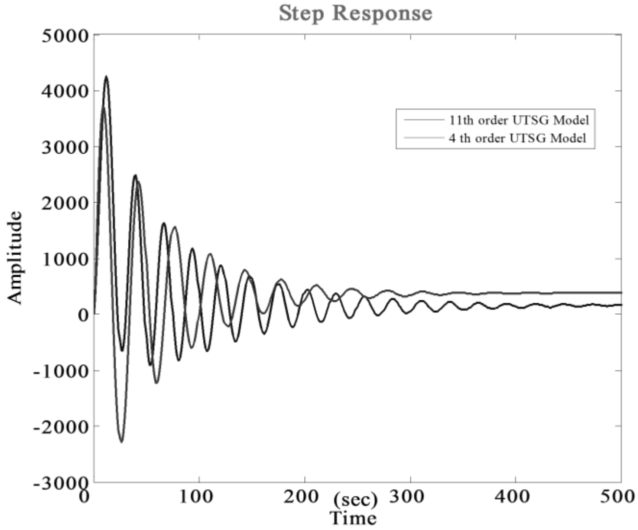

Fig.3. Step Response of the two UTSG models

The step responses of the 11th order transfer function and the 4th order transfer function of UTSG models are compared and the comparison has been shown in Fig.3.

3. FUZZY AND LQR CONTROLLERS FOR UTSG MODEL

3.1 FUZZY LOGIC CONTROLLER

Fuzzy logic control is nonlinear control method, which attempts to apply the expert knowledge to design the required controller. Based on the operator experience, structure of UTSG and flow diagram of water and steam inside the steam generator, the proposed structure of the fuzzy controller has two inputs and one output [9]. These inputs of UTSG are water level error (WLE) and the rate of change in water level error (CWLE), respectively. Initial 25-rule base of fuzzy logic controller is shown in Table.1 [11].

Table.1. Fuzzy rules for fuzzy controller

Change in Water Level		**Water Level Error**				
		NB	**NS**	**ZE**	**PS**	**PB**
	NB	NB	NB	NB	NS	ZE
	NS	NB	NB	NS	ZE	PB
	ZE	NB	NS	ZE	PS	PB
	PS	NB	ZE	PS	PB	PS
	PB	ZE	PS	PB	PB	PB

The Fig.4 shows the initial membership functions of the fuzzy controller. Five triangular membership functions for two inputs and one output have been used for designing the controller. The linguistic terms for defining the membership functions are: NB is negative big, NS is negative small, ZE is zero, PS is positive small, and PB is positive big.

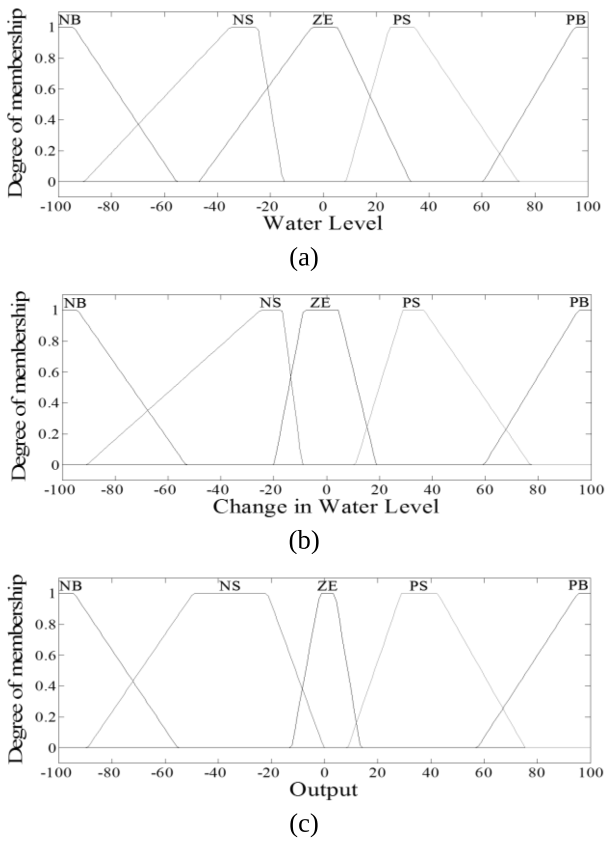

Fig.4. Membership Functions for Fuzzy controller

3.2 LINEAR QUADRATIC REGULATOR

LQR technique is applied to design an optimum controller that forces the plant output water level to follow a desired water level. The controller design lie on finding the $u(t)$ control vector that minimize the following cost functional:

$$J = \int_{t_0}^{\infty} \left[x^T(t) Q_X(t) + u^T(t) R u(t) \right] dt \tag{19}$$

where, Q and R are constant weighting matrices; the state weighting matrix Q must be symmetric and at least positive semi-definite and the control weighting matrix R is selected to be symmetric and positive definite. In this work the values of Q and R are taken as follows:

$$R = 1 \text{ and } Q = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}.$$

The block diagram representing the design of LQR controller is shown in Fig.5 [10].

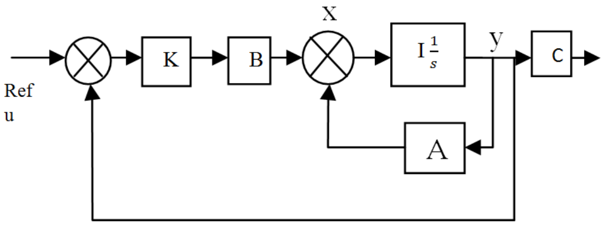

Fig.5. State Feedback Controller

The optimal control u(t) is generated from the state perturbation $x(t)$ by a linear constant gain feedback:

$$u(t) = -K_x(t) \tag{20}$$

where, K is a constant feedback gain matrix given by,

$$K = R\text{-}1B^TP. \tag{21}$$

The value of K calculated using MATLAB is given by,

$$K = [2.116\ 4.4159\ 3.1175\ 1.0000] \tag{22}$$

and P is the solution of the algebraic matrix Riccati equation,

$$PA - A^TP - Q + PBR^{-1}B^TP = 0. \tag{23}$$

The existence and uniqueness of solution for the above equation are guaranteed by the following assumptions: (A, B) is a controllable pair and (A, $Q_{1/2}$) is an observable pair.

4. SIMULATION RESULTS

Simulation results are provided to validate the effectiveness of the reduced order model and the designed controllers as shown in Fig.6 to Fig.10. Firstly, the Fuzzy Logic controller is designed for the reduced order model. In this simulation at 5% of full power of nuclear power plant, the water level is step increased from 130mm to 150mm at instant 100seconds, then at time 200seconds the water level is subjected to sudden change in steam flow rate as disturbance. The response of the Fuzzy controller is shown in Fig.6.

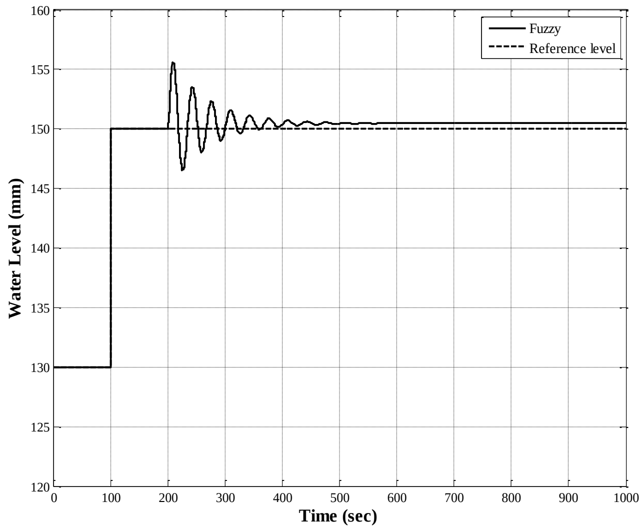

Fig.6. SG level response by Fuzzy controller for reduced order UTSG model

Water level rises to 149mm at first step change and then goes up to 155mm due to sudden disturbance at 200seconds. It takes about 500seconds to go back to the set point of 150mm. Fuzzy Logic controller for Irving's model [1] has also been designed here and the comparison of the simulation results has been shown in Fig.7. It can be verified that the reduced order model provides good performance for the designed Fuzzy controller.

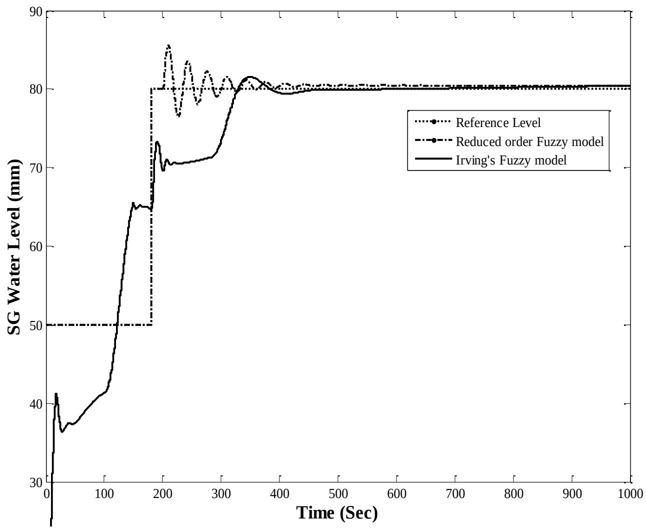

Fig.7. Comparison of Fuzzy controllers of reduced order model with that of Irving's UTSG model

The Fuzzy controller, although, seems to be efficient in maintaining the water level of UTSG to the desired level but still there is a scope of improvement which can be achieved by using LQR technique. The LQR controller is designed for both the UTSG models and the simulation results are compared.

Another technique based on LQR has been applied to the reduced order model and the simulation results for this LQR controller are as shown in Figu.8.

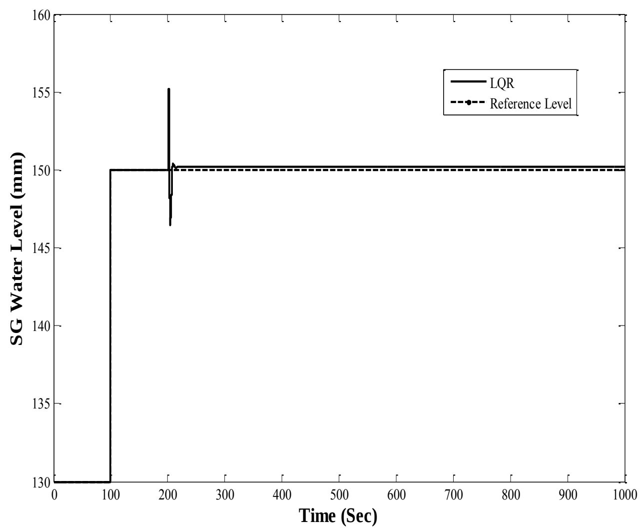

Fig.8. SG response for LQR controller for reduced order UTSG model

In the simulation of UTSG at 5% power using LQR controller, the water level tracks the reference level when step increased to 150mm at 100sec. When subjected to steam flow rate change at time 200seconds, the water level rises to 155mm and takes less than 100seconds to go back to the desired set point as shown in Fig.8. As it has been concluded that the reduced order UTSG model is giving good responses for the designed controllers, it can be further verified by the comparison of simulation results of LQR controllers for the two UTSG models. The comparison has been shown in Fig.9.

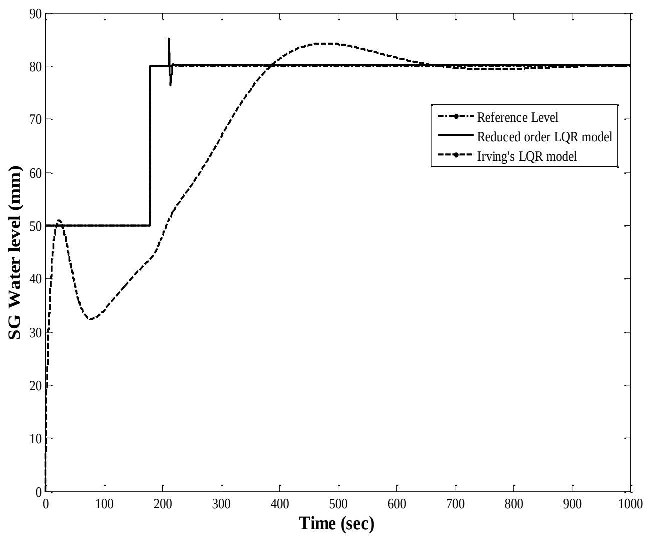

Fig.9. Comparison of LQR controller of reduced order model with that of Irving's UTSG model

Finally, a comparative analysis by comparing the simulation results of the two controllers for the reduced order model has been shown in Fig.10. This comparison shows the effectiveness of LQR controller over Fuzzy controller.

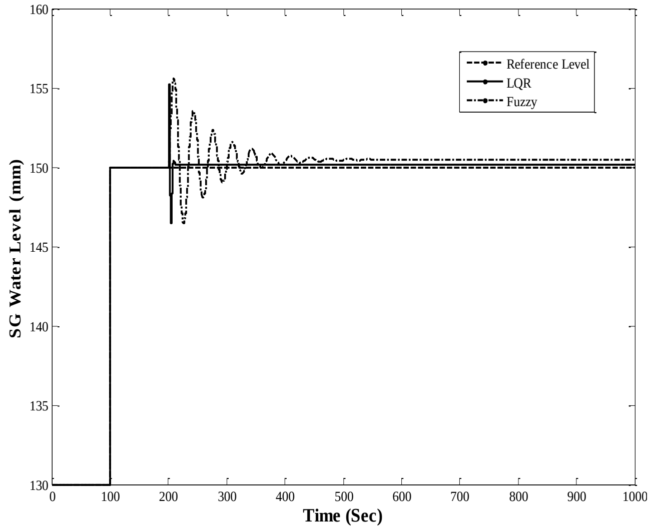

Fig.10. Comparison of responses of the two controllers for the reduced order UTSG model

5. CONCLUSIONS

The paper emphasizes on the model order reduction of UTSG model and application of Fuzzy and LQR in its control. Swelling and shrinking due to many kinds of disturbances like feed water flow rate, feed water temperature, main stream flow rate, and coolant temperature make it extremely difficult to control the water level. The non minimum phase property, changing parameter along with power level also makes it difficult to effectively control the water level of UTSG. In this paper, firstly an 11th order UTSG model is reduced to 4th order by balanced truncation method. Fuzzy logic controller is designed for this model and its response is compared with that of the controller designed for Irving's model. The results validate the reduced order model and the controller designed.

Another controller using LQR technique has also been designed for both the high and low order UTSG models and the simulation results show that LQR controller is more effectively capable to withstand sudden changes in water level. Thus, it can be verified that LQR controller greatly improves the performance of the UTSG model and reduces sudden shut downs in nuclear power plants.

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