Design of Digital Control System for U-tube Steam Generator Water Level

Aditi Vidyarthi
PG student, Electronics department
U.C.E, R.T.U Kota

Abstract: The water level of the U-tube steam generator 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. Steam generator is a highly complex, non-linear and time varying system and its parameter vary with operating condition. Poor control of steam generator water level can lead to frequent reactor shutdowns. An optimal control system using LQR scheme is developed. SG model is implemented using MATLAB/ SIMULINK. Also, a fuzzy controller is also developed and compared with the proposed controller to show how LQR controller improves the performance of steam generator.

Keywords: U-tube steam generator, LQR control, fuzzy logic control

1. INTRODUCTION

Steam generator is a very important component of nuclear plant. It is of significance for nuclear reactor normal operation to maintain it work safely and reliably. During the operation of the nuclear power station, different changes in the operating conditions may occur such as water level in steam generator. For the steam generator (SG) in a nuclear power plant, the main goal of its control system is to maintain the SG water level at a desired value by regulating the feed water flow rate. The water level of the steam generator must not be allowed to rise too high in order to prevent the excessive moisture carryover and the pressure build up of the containment in the break of secondary side flow loop. Also the low water level should be prevented in order to avoid the uncovery of the U-tubes in the secondary side. Therefore, the control of the steam generator water level is important to determine power plant responses in the event of changes in the operating load.

2. MODELLING OF U-TUBE STEAM GENERATOR

The parameter-dependent transfer function model identified by Irving *et al.* (1980) is the most widely accepted SG models for use in controller design.

Let *y1* and *y2* be the narrow and wide range water levels *L1* and *L2*, and let *w* and *d* be the feed-water and steam flow-rates. Then, the transfer functions relating the inputs *w* and *d* to the water levels *y1* and *y2* are given by:

$$Y(S) = \frac{G_1}{s}\left(q_w(s) - q_v(s)\right) - \frac{G_2}{1+\tau_2 s}\left(q_w(s) - q_v(s)\right) + \frac{G_3 s}{\tau_1^{-2} + 4\pi^2 T^{-2} + 2\tau_1^{-2} s + s^2} q_w(s)$$

where,

$Y(s)$, $q_w(s)$, and $q_v(s)$ are water level, feed-water flow-rate, and steam flow-rate respectively,

$\frac{G_1}{s}$ is the mass capacity effect of the UTSG. It integrates the flow difference to calculate the change in water level. This term accounts for the level change due to feed water inlet to steam generator and the steam outlet from it. This quantity means the actual water capacity which critically affects the removal capability of the primary heat. G_1 is a positive constant and does not depend on load.

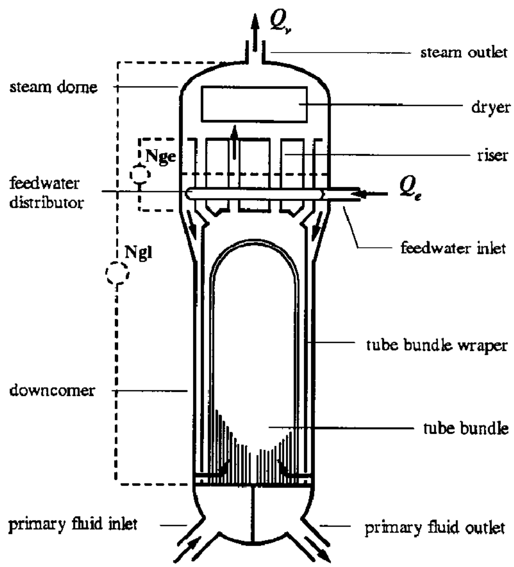

Fig.1 Schematic of UTSG

$\frac{G_2}{1+\tau s}$ is the thermal negative effect caused by "swell and shrink". Since these phenomena exhibit exponential responses for step changes of the feed water flow-rate and the steam flow-rate, they are described by a first-order equation. G_1 is positive and dependent on load. As load increases G_2 decreases. The third term is the mechanical oscillation effect caused by the inflow of the feed-water to the UTSG. This is a mechanical oscillation term due to momentum of the water in the downcomer. All the water removed from the steam is returned to the downcomer and is recirculated. The recirculating water has large momentum acting against relatively small flow-rate changes. When the feed-water flow-rate is suddenly decreased, the water level in the down comer falls initially and then begins to oscillate. This is due to the momentum of the water in the down comer keeping the recirculating flow going down initially and then slowing down. The mechanical oscillation disappears completely after a small multiple of the damping time constant. The variable G_3 is positive.

The state equations are defined as follows:

$$\delta\dot{x}_1(t) = G_1\big(\delta q_w(t) - \delta q_v(t)\big)$$

$$\delta\dot{x}_2(t) = -\tau_2^{-1}\delta x_2(t) - \frac{G_2}{\tau_2}\big(\delta q_w(t) - \delta q_v(t)\big)$$

$$\delta\dot{x}_3(t) = -2\tau_1^{-1}\delta x_3(t) + \delta x_4(t) + G_3\delta q_w(t)$$

$$\delta\dot{x}_4(t) = -(\tau_1^{-2} + 4\pi^2 T^{-2})\delta x_3(t)$$

and the output (water level) is

$$\delta y_p(t) = \delta x_1(t) + \delta x_2(t) + \delta x_3(t)$$

If we define,

$$\delta x_p(t) \triangleq [\delta x_1\ \delta x_2\ \delta x_3\ \delta x_4]^T$$

the dynamics of the steam generator system can then be reduced to the following state-space equations:

$$\delta\dot{x}_p(t) = A_p\delta x(t) + B_p\delta q_w(t) + F_p\delta q_v(t)$$

$$\delta y_p(t) = C_p\delta x(t)$$

where *Ap*, *Bp*, and *Cp* matrices are given as:

$$A_P = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & a_{22} & 0 & 0 \\ 0 & 0 & a_{33} & a_{34} \\ 0 & 0 & a_{43} & 0 \end{bmatrix}, B_P = \begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ 0 \end{bmatrix}, F_P = \begin{bmatrix} d_1 \\ d_2 \\ 0 \\ 0 \end{bmatrix}, C_P = [1 \quad 1 \quad 1 \quad 0]$$

Where

$$a_{22} = -\tau_2^{-1}, a_{33} = -2\tau_1^{-1}, a_{34} = 1, a_{43} = -(\tau_1^{-2} + 4\pi^2 T^{-2})$$

$$b_1 = G_1, b_2 = -G_2\tau_2^{-1}, b_3 = G_3$$

$$d_1 = G_3, d_2 = \frac{G_2}{\tau_2}$$

The dynamic parameters with respect to operating power linearized at different power level are shown in the table below:

Table 1. Dynamic parameters

q_v (kg/s)	57.4	180.8	381.7	660	1435
P (%power)	5	15	30	50	100
G_1	0.058	0.058	0.058	0.058	0.058

G_2	9.63	4.46	1083	1.05	0.47
G_3	0.181	0.226	0.310	0.215	0.105
τ_1	41.9	26.3	43.4	34.8	28.6
τ_2	48.4	21.5	4.5	3.6	3.4
T	119.6	60.5	17.7	14.2	11.7

3. CONTROL TECHNIQUES

1. *Fuzzy logic controller:* Fuzzy logic control is based on the principles of fuzzy logic developed by Zadeh in 1965. It is a 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. These inputs of UTSG are water level error (WLE) and the rate of change in water level error (CWLE) respectively. Figure 5 shows the initial membership functions of the fuzzy controller. Five triangular membership functions for two inputs and one output, 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. Initial 25-rule base of fuzzy logic controller is shown in Table 2.

Table 2. Fuzzy rules for fuzzy controller

		Water Level error				
		NB	NS	ZE	PS	PB
Change in water level error	NB	NB	NB	NB	NS	ZE
	NS	NB	NS	NS	ZE	PS
	ZE	NB	NS	ZE	PS	PB
	PS	NS	ZE	PS	PS	PS
	PB	ZE	PS	PB	PB	PB

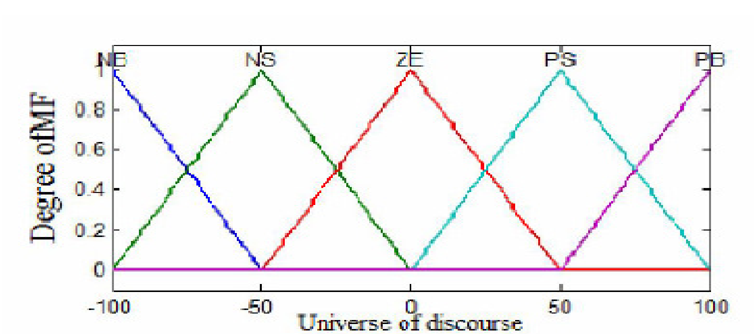

Fig 2. Membership function of fuzzy controller

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:

$$J = \int_{t_0}^{\infty} [x^T(t)Qx(t) + u^T(t)Ru(t)]dt$$

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.

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

$$u(t) = -Kx(t)$$

where K is a constant feedback gain matrix given by $K = R^{-1}B^TP$, and P is the solution of the algebraic matrix Riccati equation $PA - A^TP - Q + PBR^{-1}B^TP = 0$.

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. RESULT

Simulation results are provided to validate the effectiveness of the designed controller as shown below

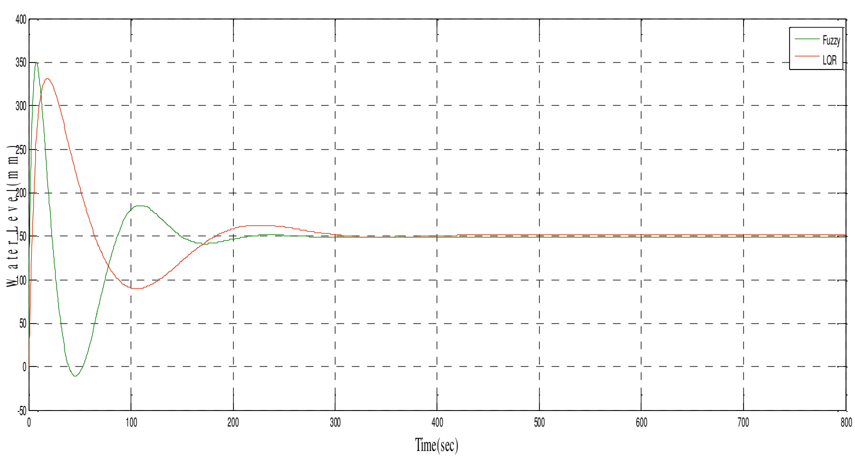

Fig.3 Comparision of SG water level response for LQR and fuzzy controller

5. CONCLUSION

Control of UTSG water level strongly affects nuclear power station availability. There has been a special interest in this problem during low power transients because of the dominant thermal dynamic effects known as shrink and swell. Also, the non-minimum phase property, changing parameter according to power level, make it difficult to control the water level of SG to control the water level of a steam generator. In this paper, linear quadratic controller is presented for water level control of the SG in a nuclear power station. The proposed controller is compared with fuzzy logic controller in controlling the water level of SG. The simulations demonstrated the effectiveness of the proposed controller in diverse operating conditions. Comparisons between proposed controller and fuzzy controller show an improvement in water level set point tracking and an increased ability in disturbance (in the form of steam flow rate changes) rejection. The main advantage of the proposed controller is capability to deal with sudden changes in water level variation, hence it reduces impulses appears in feed water flow rate.

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