LQG/LTR CONTROLLER DESIGN FOR A STEAM GENERATOR IN NUCLEAR POWER PLANT

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Abstract
Poor control of the steam generator water level in the secondary circuit of a nuclear power plant can lead to frequent reactor shutdowns.

Such shutdowns are caused by violation of safety limits on the water level and are common at low operating power where the plant exhibits strong non-minimum phase characteristics and flow measurements are unreliable. There is, there for, a need to systematically investigate the problem of controlling the water level in the steam generator in order to prevent such costly reactor shutdowns. Various approaches such as fuzzy [6], adaptive [2], MPC [3] and robust [4] approaches of controller design have been addressed.

In this paper two general LQG/LTR-based controllers for low and high power range have been presented and a switched system approach will be proposed for switching.

1 INTRODUCTION
Whenever a nuclear power plant is tripped off, utility looses money if there is no damage to the plant. The operator must determine the cause of the trip, notify the safety commission and get permission for restart. So each trip costs at least one-day unavailability of the plant. Therefore, for a plant to be economically viable, it is essential that its components be as trouble free as possible to permit continuous operation. Therefore, unplanned shutdowns or reactor trips initiated due to conservation safety consideration, which in fact are necessitated by poor control, and practically expensive must be minimized. Several studies such as [5], [3] investigating the cause of plant unavailability have shown that 25% of all reactor trips were initiating by problems related to the feed water systems. Up to 13% of all reactor trips in France in 1983 were attributed to steam generator control problems. The nonlinear and non-minimum phase plant characteristics in addition with low signal to noise ratio of the flow sensors at low power operation make the designing an effective level control system very difficult.

2 PRVIOUS WORKS
Various approaches have addressed the level control system that will be briefly analyzed in this section:
*Irving [2], 1980, presented a linear parameter-varying model to describe the SG dynamics over the entire operating power range and proposed a model reference adaptive PID level controller. The Irving model was used by Choi,[1], 1989, and Kim,1993 [12].
*Na. And NO provided a quantitative evaluation of the swell and shrink effects in the SG using an adaptive observer to estimate the flow errors, and the parameters of the SG model at low power. [13]
*Bendotti [14] and Ambos [4] proposed a robust $H_\infty$ and $H_2$ level controller respectively.

All above approaches only handle the problem around a local operating point with no clear understanding of how to address the global control problem over the entire operating range.

Fuzzy logic based level control systems have been reported in numerous references. In this case see [6]. Because the stability and robustness of these controllers have not strong approve, will not be considered here.

Optimal and sub-optimal [9] level controller design using linear output feedback and state feedback presented by Feliachi without considering the parameter uncertainties in low power situations.

MPC approach presented by Kothare [3]. MPC is an open loop control design procedure so the study of the close loop stability of these controller designs has not been addressed in that paper.

Using LQG/LTR (Linear Quadratic Gaussian Problem With Loop Transfer Recovery) Friedli [11] and Menon and Parlos [5] have designed level control systems. Friedli used a reduced order model for entire the power range. This reduced order model is minimum phase so LQG/LTR method can easily apply to the model.

Menon and Parlos proposed a more strong design using local linearization of nonlinear validate model of SG. The local linear controllers were then "gain-scheduled" to cover the entire operating range.

In the case of water level control the model parameters uncertainties because of the variation of power range are so much that changing merely the gain cannot satisfy those variations; so model parameters should be changed.

Therefore, using the idea of Menon, in this paper we present two LQG/LTR model for low power and high power range of plant operation and for switching we use CLF (Common Lyapunov Function based switched system) method presented by A. Morse [10].

3 PLANT DESCRIPTIONS AND UTSG MODELING
The nuclear reactor under consideration is a pressurized water reactor (PWR). The PWR plant can be divided into two subsystems: the steam supply system and the power conversion system. In the primary circuit reactor coolant exchanges heat to the water in the S.G., thus, the water fed to the steam generator is vaporized, then released within the turbine where it expands and produces mechanical work that is transferred into electrical power by the generator.

A change in electrical power demand causes a change in the steam demanded by the turbine, thereby requiring a change in the feed water flow rate to the SG and also a change in the thermal energy produced in the nuclear reactor.

Our goal in this paper is to study the use of the feed water flow rate as a manipulated variable to maintain the SG water level within allowable limits in the face of the changing steam demand resulting from a change in the electrical power demand. We will assume that the primary side temperature is appropriately maintained at its reference value by the primary circuit control rod system.

### 3.1 UTSG MODELING

The steam generator is modeled as a parametric system where the parameters are power dependent. This model is governed by the state space equations:

\[
\dot{X}(t) = AX(t) + B_u u(t) + B_w w(t)
\]

\[
y(t) = CX(t) + n(t)
\]

Where \( u(t) \) is the fresh feed water flow rate \( Q_e(t) \); \( w(t) \) as a disturbance is the steam demand \( Q_v \); and \( y=[N_{ge}, N_{gl}, Q_e] \) is the sensors output.

Note that the state space matrices \( A, B_u, B_w, C \) depend on parameters \( \tau, \alpha, \beta, \tau_i \). Parameters values at low power (10\% \( P_n \)) and high power (80\% \( P_n \)) are given in the table 1.

These parameters are given from [8].

\[
A = \begin{bmatrix}
-1/	au_e & 0 & 0 & 0 \\
1/	au_s & -\alpha & -\alpha_0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 0 & -1/	au_i \\
\end{bmatrix}, \quad B_u = \begin{bmatrix}
1 \\
0 \\
0 \\
0 \\
\end{bmatrix}
\]

\[
B_w = \begin{bmatrix}
0 \\
-1/	au_e \\
0 \\
0 \\
\end{bmatrix}, \quad C = \begin{bmatrix}
0 & 1/eta_i & -\beta_i & -1 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
\end{bmatrix}
\]

### 4 WATER LEVEL CONTROLLER DESIGN

A simple eigen value analysis of any of the UTSG linearized models indicates that the open loop system are unstable and non-minimum phase because of the reverse dynamics due to the shrink and swell effects. Therefore it is designed to design a water level controller that:

1. Stabilizes the nominal UTSG model.
2. Achieves desirable performance
3. Exhibits robust stability to UTSG parameter uncertainties and variations.

Indeed, a brief review of the relevant literature indicates that the aforementioned desired characteristics are satisfied by LQG/LTR method.

#### 4.1 LQG/LTR METHOD

An LQG/LTR compensator is an MBC (model based compensator), which is described by these eqs.

\[
z(t) = [\alpha - BG - HC]z(t) - He(t)
\]

\[
u(t) = -Gz(t)
\]

for which the design matrices \( H \) and \( G \) have been chosen using a specific though systematic, procedure. In real world applications some of the assumptions that are made in the derivation of the LQG/LTR algorithm may not be valid. As a matter of fact for UTSG water level problem the technique has been applied, and resulting compensator has an acceptable performance.

#### 4.2 UTSG COMPENSATOR

In this section, the actual design sequence of the LQG/LTR compensator for the UTSG model linearized about 10\% and 80\% of full power will be considered. The LQG/LTR involves two basic steps. The first step involves the generation of an ideal target feedback loop (TFL) that meets all of the desired controller specifications, including the nominal performance and stability robustness characteristics. As a result of this step, the \( H \) matrix of the compensator is determined. The second step involves obtaining the gain matrix \( G \) such that its closed-loop performance tends to the TFL performance. By solving the FARE and CARE equations in an iterative procedure we will obtain the \( H \) and \( G \) matrices.

### Table 1: Steam generator parameters for the two power operating points.

<table>
<thead>
<tr>
<th>Power Level</th>
<th>( \tau_e )</th>
<th>( \tau_g )</th>
<th>( \tau_i )</th>
<th>( \tau_o )</th>
</tr>
</thead>
<tbody>
<tr>
<td>10% ( P_n )</td>
<td>2.433</td>
<td>0.415</td>
<td>701.262</td>
<td>21.739</td>
</tr>
<tr>
<td>80% ( P_n )</td>
<td>5.435</td>
<td>4.167</td>
<td>694.444</td>
<td>13.889</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Power Level</th>
<th>( \alpha_0 )</th>
<th>( \alpha_1 )</th>
<th>( \beta_0 )</th>
<th>( \beta_1 )</th>
<th>( \beta_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>10% ( P_n )</td>
<td>0.025</td>
<td>0.171</td>
<td>-0.023</td>
<td>0.068</td>
<td>0.990</td>
</tr>
<tr>
<td>80% ( P_n )</td>
<td>0.811</td>
<td>0.983</td>
<td>-0.208</td>
<td>0.106</td>
<td>1.325</td>
</tr>
</tbody>
</table>
It is desired to regulate the UTSG water level with zero steady state error. Therefore an integrator is placed at the plant input. The final compensator is:

$$K(s) = G(sI - A + BG + HC)^{-1}H$$

At the end of procedure and following step-by-step LQG/LTR design method, we have two $K_{10}(s)$, $K_{80}(s)$ compensators for 10% and 80% of power level that guarantee the robustness, stability, disturbance reduction and noise effect reduction in that power range. It should be noted that for non-minimum phase systems the recovery procedure is not guaranteed to work. The main reason for the relative success of the recovery procedure in this problem is that the non-minimum phase zero present in the UTSG system is relatively fast compared to the desired bandwidth. So it decays quickly without any major difficulties in the robustness recovery.

4.3 DESIGN OF A SWITCHED SYSTEM

Using the previously described procedure, a linear compensator is designed for each linearized UTSG model such that when operating in the vicinity of the respective equilibrium Point the controlled system exhibits all of the desired specifications. However, it is desired to obtain a single controller that will enable operation of the UTSG in its entire range, both in steady state and transient conditions. To achieve this point we propose the using of a switched system. By a switched system we mean a hybrid dynamical system consisting of a family of continuous time subsystems and a rule that orchestrates the switching between them.

It is fairly well known fact that when all the subsystems are asymptotically stable the switched linear system is globally exponentially stable If we can find a CLF (Common Lyapunov Function) as a switching rule [10]. We did not discuss the precise assumptions and conditions here (in fact there is considerable work still to be done in that regard) but the general idea instead. For simulation results with more details see [7].

5 CONCLUSIONS

Control of UTSG water level strongly affects nuclear power plant availability. To attaining a robust and stable control system we present two controller for 10% and 80% of power range because the specification of the system varies obviously by the change in the power range. These two controllers are asymptotically stable and robust enough among the equilibrium point. Because these two system satisfy The mentioned situations by wasting time we can have a total stable system [10]; In the future studies we will divide the whole system to more than two subsystems and also instead of using theory of dwell time and wasting time we will work to achieve a CLF (Common Lyapunov Function) between subsystems that guaranteed the stability of arbitrary switching.

REFERENCES