Multivariable Feedwater Control Design for a Steam Generator

Thomas D. Younkins and Joe H. Chow

ABSTRACT: A multivariable feedwater control design for drum water-level regulation in a heat-recovery steam generator is presented. The control design is based on a projective output feedback scheme and is used to coordinate the tandem-connected feedwater valves of a low-pressure and a high-pressure drum. One of the design objectives is to minimize the blowdown from the drums during start-ups. Results demonstrating the control performance and the improvement over a traditional single-loop feedwater control design are shown.

Introduction

Traditional power plant control design is based on single-loop methodology. Some recent power plant control studies have examined the use of multivariable control design to coordinate two or more feedback measurements with two or more control signals to produce better performance [1], [2]. This type of control is readily implementable with existing hardware and is especially easy to apply with today’s distributed control hardware. The purpose of this article is to present a multivariable feedwater control design applied to a dual-drum heat-recovery steam generator (HRSG) to illustrate the potential improvement in performance.

The steam generator considered is a type currently used in some combined-cycle (gas turbine/steam turbine) power plants. The control design is performed on a model with a low-pressure (LP) drum and a high-pressure (HP) drum (Fig. 1). Conventional feedback control design is to use single proportional-integral loops to control each of the feedwater valves to regulate the water level in the corresponding drum. In a multivariable design, the water-level and flow-rate measurements of both drums are input to each of the valves to regulate the drum levels. Since the low-pressure drum supplies the high-pressure feedwater, we expect that, if the control is fully coordinated, the low-pressure feedwater valve will regulate the total water volume in the drums; whereas, the high-pressure feedwater valve will regulate the difference of the water volume in the drums. The multivariable design results confirm this intuition. This control strategy also explains the reduction of the blowdown from the drums during start-ups.

Steam Generator Model

The basic flowpaths of a forced-circulation, dual-drum heat-recovery steam generator model are shown in Fig. 1. The steam generator is a heat exchanger in which the hot gas from the gas turbine is used to supply low- and high-pressure steam to the steam turbine. As noted, the feedwater flow for the high-pressure drum is taken from the low-pressure drum via a transfer pump. Since the feedwater control can be considered as “open loop” from the rest of the combined-cycle plant, the following inputs were used as forcing functions with time:

1. Hot-gas flow rate and temperature, from the gas-turbine exhaust.
2. HP steam flow rate, to the steam turbine.
3. Low-pressure steam flow rate, to the steam turbine.

In addition, condensate flow was assumed to be available on demand, and both the condensate pump discharge and the pressure drop across the low-pressure feedwater valve were assumed to be constant. The resulting

Fig. 1. Dual-drum HRSG flow diagram.
model of the heat-recovery steam generator and the feedwater controller includes 27 states and was set up to initialize in a steady state at any feasible operating condition.

Control Objective

The objective of feedwater control is to maintain the water levels of the drums at their desired set points. Blowdown will occur when the water level is too high, and pumps will be tripped if the level is too low. The water levels may change substantially during some transients. A particularly challenging transient is the start-up following an overnight shutdown. In this case, just before the start-up, the heat-recovery steam generator is still warm but there is no boiling. As the start-up proceeds, steam is generated in the steam generator boiling sections and some water must be blown down to prevent excessive swell in the high- and low-pressure drum water levels. Both the high- and low-pressure blowdown valves are on/off devices; they open wide when the water level exceeds 38 in. and close when the water level decreases below 37 in. The conventional single-loop control would result in blowdown of 6500 lb of water from only the low-pressure drum. A natural question to ask is whether this amount of blowdown can be reduced by using a multivariable controller. In particular, since no blowdown occurs from the high-pressure drum, some of the blowdown from the low-pressure drum can be passed to the high-pressure drum via the high-pressure feedwater valve. Thus, one design objective is to test whether a multivariable controller can exploit this situation.

Control Structure

The existing conventional feedwater valve controls and measurement signals were used in the design study (see Fig. 2). Note that a washed out proportional signal is used for the net flow measurement (feed flow minus steam flow); this minimizes the effect of measurement errors at low flow rates.

The conventional controller uses only the high-pressure measurements \( y_1, y_2, y_3 \) to control the high-pressure feedwater valve \( u_1 \). Likewise, only the low-pressure measurements \( y_4, y_5, y_6 \) are used to control the low-pressure feedwater valves. The multivariable controller will use all six measurements to control both feedwater valves.

Output Feedback Multivariable Control Design

A multivariable control (MVC) design method that meets the design objectives is the projective control method [3]. In essence, the method requires first a satisfactory full state feedback design. Then the full state feedback is mapped into an output feedback to retain only the dominant eigenstructure of the full state feedback system. The application of the method to the heat-recovery steam generator feedwater control is described in the following.

Since the design objective is to regulate and balance the water levels, the full state design can be formulated as a linear quadratic regulator problem [4]. The heat-recovery steam generator model is linearized at the nominal operating condition to obtain the state-space model

\[
\dot{x} = Ax + Bu,
\]

\[
y = Cx
\]

where the state \( x \) is of 27th order, the control \( u = [u_1, u_2]^T \), and the measurement \( y = [y_1, y_2, y_3, y_4, y_5, y_6]^T \). The control \( u \) is designed to minimize the performance index

\[
J = \frac{1}{2} \int_{0}^{\infty} \left( q_2 y_2^2 + q_3 y_3^2 + \right. \\
+ \left. r_1 u_1^2 + r_2 u_2^2 \right) dt
\]

where the output weights \( q_2 \) and \( q_3 \), on the water-level measurements, and the control weights \( r_1 \) and \( r_2 \) are adjusted to obtain the full state feedback control \( u = Gx \) to achieve the desired performance.

Once the desired \( u = Gx \) is found, an output feedback control is computed as

\[
u = Gx(CX)^{-1}y = Ky
\]

where \( X \) is the dominant eigensubspace of the closed-loop system

\[
\dot{x} = (A + BG)x
\]

Since there are six measurements available for feedback, a six-dimensional eigensubspace \( X \) can be retained in the output feedback system. For the feedwater control problem, the dominant eigensubspace \( X \) contains the dynamics related to the drum-level regulation and actuator dynamics. The desired eigensubspace can be identified using eigenvalue sensitivities [5]. Although the full state feedback system is asymptotically stable, there is no guarantee that the output feedback system will be asymptotically stable. In general, one expects that by retaining the dominant eigensubspace, the stability of the rest of the system is somewhat compromised. Thus, provided that the rest of the system has a certain margin of stability, the stability of the output feedback system would not be jeopardized if the control action from \( u = Ky \) is not excessive. This is the case with the feedwater control design.

Design Results

The design tuning was done by varying \( q_2 \) for the low-pressure drum-level measurement, since the low-pressure drum swell tended to be larger than the high-pressure drum swell. The final design gain matrix \( K \) is shown in Table 1. The gain factors are not in per unit, so the magnitudes cannot be compared with each other. However, the algebraic signs of the gain factors, which are determined by the control design method,

CONCLUSIONS

A MULTIVARIABLE FEEDWATER CONTROL HAS BEEN DESIGNED TO MEET THE OBJECTIVE OF MAINTAINING DRUM LEVELS AND REDUCING BLOWDOWN DURING HOT START-UPS. AN IMPORTANT FEATURE OF THE DESIGN IS THAT THE CONTROLLER EXPLOITS THE STRUCTURE OF THE SYSTEM TO ACHIEVE ITS OBJECTIVES. SUCH A CONTROLLER TENDS TO HAVE DESIRABLE ROBUSTNESS PROPERTIES.

REFERENCES

Thomas D. Younkins received a B.S.M.E. degree from the Pennsylvania State University in 1954. He has worked for the General Electric Company since that time and graduated from the GE Advanced Engineering Program in 1957. From 1959 to 1978, he held a variety of engineering design and management assignments while working on naval nuclear power plants at the Kolls Atomic Power Laboratory. Since 1978, he has been a Senior Application Engineer with the Systems Development and Engineering Department, working on the dynamic interaction and control of power plants and power systems. Mr. Younkins is a Registered Professional Engineer in New York State. He is an Adjunct Professor at Union College and has taught a reactor technology course at Union for many years.

Joe H. Chow is an Associate Professor of Electrical, Computer, and Systems Engineering at Rensselaer Polytechnic Institute. He received his bachelor’s degrees in electrical engineering and mathematics from the University of Minnesota in 1974, and his M.S. and Ph.D. degrees in electrical engineering from the University of Illinois at Urbana in 1975 and 1977, respectively, for his work on application of singular perturbations to control system design. From 1978 to 1987, he was an Application Engineer at the General Electric Company, where he worked on power system model reduction, emergency control, stability analysis, and multivariable control design. His current interests include large scale systems, power system dynamics, and applications of multivariable controls. He is a Registered Professional Engineer in New York State. He received the Donald P. Eckman Award from the American Automatic Control Council in 1979 for contributions to control theory. Since 1982, he has been an Associate Editor of Automatica. Currently, he is an Associate Editor of the IEEE Transactions on Automatic Control and serves on the Board of Governors of the IEEE Control Systems Society. (Dr. Chow’s photo was not available at the time of publication.)

1987 IFAC Closing Ceremony

The picture shows city center in Munich, Bavaria, in the Federal Republic of Germany, which was the site of the Tenth World Congress of the International Federation of Automatic Control on July 26–31, 1987. The banner in the upper left-hand corner of the picture shows the IFAC logo.

The transfer of the IFAC Presidency takes place as M. Thoma hands the formal attributes of his office—gavel and seal—to his successor B. Tamm, who will be IFAC President for the next three years, 1988–1990. The Eleventh IFAC World Congress will be held August 13–17, 1990 in Tallinn, USSR. Seated in the background (from left) are L. Ljung, S. Kahne, and W. Schaufelberger.