

A robust estimator-based optimal algebraic approach to steam generator feedwater control system

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Abstract: Feedwater control systems are used to maintain the steam generator water level within prescribed narrow limits and to provide constant supply of steam during power demand variations. Current feedwater control systems are often found to be unsatisfactory during startup and low power operations. A robust nonlinear estimator-based optimal algebraic control is developed for feedwater control systems to solve the water level tracking problem during power demand variations. It is shown that the proposed control provides an optimal and robust water level tracking with a single automatic controller over the complete range of power operations in the presence of plant uncertainties and noisy measurements.

Key words: Steam generator, feedwater control, robust estimator, algebraic control, nuclear plant

1. Introduction

Steam generator feedwater control systems are used extensively throughout nuclear power plants and process industries to control boiling water levels and supply high quality steam. Water level variations in the steam generators can cause problems, including flooding of the steam purification equipment and damaging turbine blades when the water level is too high, and reducing the efficiency of the recirculation function when the water level is too low. It is necessary to keep the water level within the range of the prescribed narrow limits for providing a smooth and uninterrupted plant operation in the face of varying power demand.

Steam generators are highly complex, nonlinear, and time-varying systems because of fluctuations in plant parameters with time-varying operating conditions. Several studies have shown that the steam generator feedwater control system is a major contributor to plant unavailability, about 25% of the causes, mainly due to poor control of the steam generator water level [1–3]. For this reason, the steam generator feedwater control designs have expanded over the last thirty years in the literature, including adaptive control [1], PID type controllers [4–10], H_∞ controller [11,12], L_2 controller [13], model predictive controller [14–17], output feedback control [18], linear quadratic regulator method [19], adaptive observer based method [20], fuzzy and neurofuzzy controllers [21,22], data driven-based methods [23], adaptive backstepping-based control [24], and sliding mode control [25–27]. Most of these methods considered either local operating conditions (specifically for a low power mode) or piece-wise linear regions to provide a feedwater control mechanism. Theoretically, the above studies have achieved impressive results. However, from a practical point of view, the following problems remain: 1) a single automatic control over the complete range of power operations; 2) reduction in control equipment to

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lower price and increase reliability; and 3) reduction in control algorithms and information load in the whole feedwater control system.

The objective of this work is to develop a robust, efficient, and simple estimator-based optimal algebraic control strategy for the steam generator feedwater system from start-up to full load conditions. The main advantages of this approach are optimal performance, low sensitivity to system parameter variations and disturbances, easy implementation in practice, and utilization of the good features of the modern and classical control.

The organization of the paper is as follows: Section 2 provides a background on steam generator feedwater control systems; the approach to feedwater control system design is given in Section 3; Section 4 provides the numerical results; and the conclusion that can be drawn from this work is given in Section 5.

2. Steam generators and problem formulation

The steam generator is a heat exchanger that is used to transfer heat generated by the reactor into steam energy. It is one of the major components of many nuclear power plants, including pressurized water reactors (PWR) and heavy-water moderator reactors (PHWR). The power demand from the grid or users causes variations in the water level of the steam generator. The water level must be maintained within its specified lower and upper limits to avoid serious consequences, including unintended plant shutdowns and system damage. Difficulties in keeping the water level constant in steam generators during power demand variations arise from the nonlinear plant characteristics, time-varying parameters, constraints on the available control action, limits on the water level, and noise level and flow measurements.

2.1. Mathematical model of the steam generators

For control purposes and simulations, the following linear, time-varying parameter model has been widely used in describing the steam generator dynamics accurately [1]:

$$y(s) = \frac{K_1}{s} (u - q) - \frac{K_2}{1 + \tau_2 s} (u - K_4 q) + \frac{K_3 s}{\tau_1^{-2} + 4\pi^2 T^{-2} + 2\tau_1^{-1} s + s^2} u \quad (1)$$

In Eq. (1), u is the feedwater flow rate, q is the steam flow rate, and y is the water level (narrow range level). The term K_1/s represents the mass capacity effect of the steam generator, which integrates the steam-feedwater flow difference to calculate the change in water level. The second term $K_2/(1 + \tau_2 s)$ represents the thermal negative effect caused by the swell-shrink phenomenon, which appears initially in the case of feedwater or steam flow rate changes. The last term is the mechanical oscillation effect caused by the inflowing feedwater to the steam generator. The power-dependent parameters $\tau_1(p)$ and $\tau_2(p)$ are the damping time constants, $T(p)$ is the mechanical oscillation period, and K_1 , $K_2(p)$, $K_4(p)$, and $K_3(p)$ are the magnitudes of the mass capacity effect, swell-shrink phenomenon, and mechanical oscillation effect, respectively. Here, p (in % rated power) denotes the operating power, which determines the values of all the parameters. The model parameters identified from experimental data in [1] are given in the Table.

The water level is the balance between feedwater flow and steam flow under steady-state conditions. For this reason, one of the most commonly used reduced-order models is the mass capacity effect [28]:

$$y_0(s) = \frac{K_1}{s} (u - q) \quad (2)$$

Table. Steam generator model parameters in terms of operating power [1].

Power	Experimental parameters							
level	K_1	K_2	K_3	K_4	T	τ_1	τ_2	q
(p%)	(mm/kg)	(mm-s/kg)	(mm/kg)		(s)	(s)	(s)	(kg/s)
5%	0.058	9.63	0.181	1.60	119.6	41.9	48.4	57.4
15%	0.058	4.46	0.226	1.90	60.5	26.3	21.5	180.8
30%	0.058	1.83	0.310	2.25	17.7	43.4	4.5	381.8
50%	0.058	1.05	0.215	2.80	14.2	34.8	3.6	660.0
100%	0.058	0.47	0.105	4.82	11.7	28.6	3.4	1434.7

The swell–shrink phenomenon, which appears in the case of feedwater or steam flow rate changes, has strong effects under transient conditions [29–31]. On the other hand, the effect of the mechanical oscillations is much smaller when compared with the mass capacity effect and swell–shrink phenomenon as showed in [29]. Therefore, the steam generator model of Eq. (1) can also be represented as a second order system by ignoring the effects of the mechanical oscillations. That is, in the state-space, the steam generator can be modeled by:

$$\begin{cases} \dot{x}_1 = K_1(u - q) \\ \dot{x}_2 = -\frac{1}{\tau_2(p)}x_2 - \frac{k_2(p)}{\tau_2(p)}(u - K_4(p)q) \\ y = x_1 + x_2 \end{cases} \quad (3)$$

where $x = [x_1, x_2]^T$ is the state vector, u is the control input (feedwater flow), and y is the system output (water level). The state vector x_1 (in mm) represents the contribution to the water level due to the total mass of water in the steam generator, and x_2 (in mm) represents the reverse dynamic effect related to the swell–shrink phenomenon (i.e. a level increase (swell) instead of a decrease following a steam flow increase due to expansion of bubbles in the two-phase fluid, and vice versa).

The variations in the steam generator model parameters are shown graphically in Figure 1. It is seen that all parameters related to the swell–shrink phenomenon and mechanical oscillation vary nonlinearly within their bounds as a function of operating power. Since operating power is not represented explicitly in Eqs. (1) or (3), the steam generator model has parameter uncertainties from a control viewpoint. The control problem is to track a water level reference signal during power demand variations by using the feedwater flow rate as the manipulated variable.

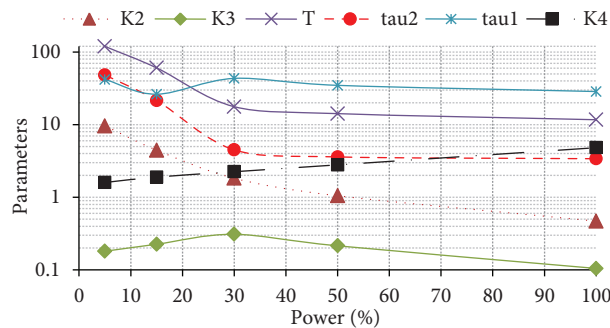


Figure 1. Steam generator model parameters as a function of power.

The sensor and actuator dynamics can be expressed with first order dynamics in order to account for

their effects on controllers for simplicity [32,33]. The level and flow sensors can be modeled as follows:

$$G_s(s) = \frac{1}{\tau_s s + 1}, \quad (4)$$

and the feedwater valve dynamics can be expressed with a first order plus dead-time model:

$$G_a(s) = \frac{1}{\tau_a s + 1} e^{-T_0 s}, \quad (5)$$

where the time constants τ_s and τ_a , and dead-time T_0 are assumed to be 0.25, 0.25, and 2 seconds, respectively. The measuring elements play an important role in the overall system performance of the control system. However, the time constants of the measuring elements are negligibly small as compared with the time constant of the steam generator, and thus they might be ignored in the control system designs.

2.2. The conventional feedwater control system

The conventional feedwater control system is shown in Figure 2 and corresponds to that of a currently operating PWR [28,34,35]. The feedwater control system of the steam generator is based on PI controllers. The feedwater system is manually controlled below a 2% power level. Above the 2% power level, the control system has two automatic modes of operation, a low power mode (2% to 15%) using single-element control, and a high power mode (above 15%) using three-element control. The single-element control is based on the water level error signal, and the bypass valve is utilized as the manipulated element. The three-element control uses the water level, steam flow, and feedwater flow as the measured inputs, and the main feedwater valve as the manipulated element.

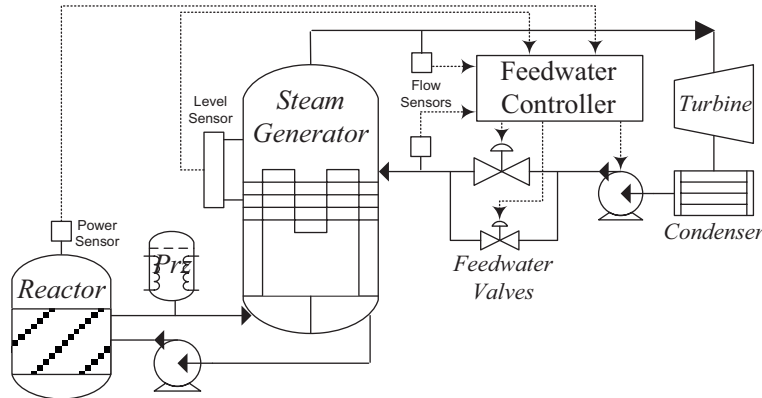


Figure 2. Schematics of the conventional steam generator feedwater control system. Dotted lines denote the measurements and control signals.

In general, the control equations describing the operation of the feedwater control system under normal operation conditions can be given as follows:

$$u_{LP} = k_{pl}(y - r) + k_{il} \int (y - r) dt \quad (6)$$

for the low power mode of operation, and

$$u_{HP} = k_{ph} ((y - r) + A_h(u - q)) + k_{ih} \int ((y - r) + A_h(u - q)) dt \quad (7)$$

for the high power mode of operation ($p > 15\%$).

The control problem is difficult at the low power operating mode due to the steam generator reverse thermal-dynamic (swell–shrink) effect. Relying only on the water level signal has proven inadequate because the water level response can become unstable when single-element control is used during start-up and low power operating mode [1–3]. This frequently forces operators to manually control the water level in the low power mode, which has been found to be unreliable, resulting in poor overall system performance and causing numerous plant shutdowns [1–3,5,9]. With the usage of modern technology in the feedwater control systems, the control performance is improved [36], but still the overall performance is poor due to the same traditional control strategy.

3. Control system design

A control system must provide stability, robustness, and good performance for steam generator feedwater systems in the presence of the swell–shrink effect, mechanical oscillations, and steam flow fluctuations. While it is difficult to obtain an optimal performance under these conditions, a simultaneous algebraic approach that handles the denominator and numerator of the transfer function of a system independently can be used to design the characteristic polynomial of the closed loop system, which specifies stability, response, and robustness requirements. The strength of the algebraic approach is that a simple, optimal, and robust controller can be designed for any plant under practical limitations.

3.1. Design of an optimal algebraic control system

The optimal algebraic approach combines the good features of the modern and classic controls. An optimal controller is selected to meet the stability and performance requirements. A block diagram for the optimal algebraic controller based system is shown in Figure 3. The plant is described through the transfer function with numerator $N(s)$ and denominator $D(s)$. The algebraic controller is specified with the controller denominator $A(s)$, feedback numerator $B(s)$, and reference numerator $F(s)$.

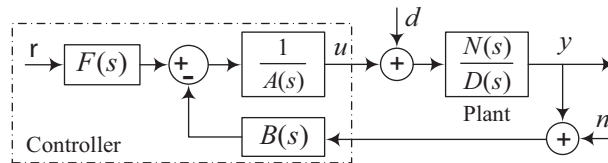


Figure 3. Block diagram of the optimal algebraic control system.

The output of the closed-loop system can be expressed using Figure 3 by:

$$y = \frac{N(s)F(s)}{P(s)}r + \frac{A(s)N(s)}{P(s)}d - \frac{N(s)B(s)}{P(s)}n, \tag{8}$$

where y is the system output, r is the reference signal, d is the disturbance, and n is the measurement noise. Consider the transfer function of a linear time-invariant plant:

$$\frac{N(s)}{D(s)} = \frac{c_z s^z + \dots + c_1 s + c_0}{b_m s^m + \dots + b_1 s + b_0} \tag{9}$$

where $z \leq m$. Considering Figure 1, the objective is to develop a control scheme that forces the system output y to follow a reference signal r with desired performance specifications. The controller polynomials $A(s)$, $B(s)$,

and $F(s)$ are given by [37–39]:

$$A(s) = \sum_{i=0}^p l_i s^i \quad (10)$$

$$B(s) = \sum_{i=0}^q k_i s^i \quad (11)$$

$$F(s) = (P(s)/N(s))|_{s=0} \quad (12)$$

where p and q are the degrees of the controller denominator $\deg\{A(s)\}$ and feedback numerator $\deg\{B(s)\}$, respectively. If the plant does not contain disturbance or noise, $\deg\{A(s)\} = \deg\{B(s)\} = m - 1$, where m is the order of $D(s)$ in (9), $\deg\{D(s)\}$. If the plant contains disturbance or noise, then the controller polynomials are selected such that the effects of disturbance and noise are minimized, e.g., $\deg\{A(s)\} = \deg\{B(s)\} = m$. If the reference numerator $F(s)$ is selected as given in Eq. (12), the steady-state error of the controlled system becomes zero, and the closed loop transfer function turns out to be a type-1 system (no overshoot in the system response), so that a good closed-loop time response can be acquired. The denominator $P(s)$ is the characteristic polynomial given by:

$$P(s) = A(s)D(s) + B(s)N(s) = a_n s^n + \dots + a_1 s + a_0 = \sum_{i=0}^n a_i s^i. \quad (13)$$

The main aim in the algebraic controller is to determine the coefficients of the characteristic polynomial a_i to satisfy stability, response, and robustness requirements of the plant. The performance specifications are given with stability index γ_i , equivalent time constant τ , and stability limit γ_i^* . The relations between these parameters and the coefficients of the characteristic polynomial are as follows:

$$\begin{aligned} \tau &= a_1/a_0 \\ \gamma_i &= a_i^2/(a_{i+1}a_{i-1}), i = 1, 2, \dots, n-1, \gamma_0 = \gamma_n = \infty. \\ \gamma_i^* &= 1/\gamma_{i-1} + 1/\gamma_{i+1} \end{aligned} \quad (14)$$

One significant feature of the algebraic controller is that the stability index (or coefficient ratio) γ_i can be assigned optimally (or arbitrarily) to solve the design problem. An optimal standard form for the stability index is given by [39,40]:

$$\gamma_1 = 2.5, \gamma_i = 2, i = 2, \dots, n-1. \quad (15)$$

From the relationship given in Eq. (14) and the optimal standard form of the stability index in Eq. (15), the coefficients of Eq. (13) can easily be calculated as follows:

$$\begin{aligned} a_1 &= a_0 \tau \\ a_i &= \frac{a_0 \tau^i}{\gamma_{i-1} \gamma_{i-2}^2 \gamma_{i-3}^3 \dots \gamma_2^{i-2} \gamma_1^{i-1}}, \text{ for } i = 2, \dots, n \end{aligned} \quad (16)$$

The standard form of Eq. (15) is recommended in order to get optimal stability and response performances. The equivalent time constant τ is selected to satisfy the settling time t_s requirement. It is shown in [41] that τ

characterizes the speed of a closed-loop system with denominator $P(s)$, and if the standard form of the stability index is used, the shortest settling time is obtained:

$$t_s = 2.5\tau \sim 3\tau \quad (17)$$

On the other hand, the equivalent time constant τ can always be adjusted by changing the stability index of Eq. (15) to satisfy the design requirements depending on the plant characteristics. The stability of the closed loop system is determined from the Routh–Hurwitz criterion for third and fourth order characteristic polynomials. Based on the results given in [42] for higher order systems, the stability criterion is given by:

$$\gamma_i > 1.12\gamma_i^*, i = 2, 3, \dots, n - 2 \quad (18)$$

and the sufficient condition for instability is given by:

$$\gamma_i\gamma_{i+1} \leq 1, \text{ for some } i = 1, 2, \dots, n - 2. \quad (19)$$

In order to guarantee the stability of the characteristic polynomial based on the above stability and robustness conditions, all γ_i s are usually chosen within interval $\gamma_i \in [1.5, 4]$.

3.2. A practical controller for the feedwater control system

A simple algebraic controller can be designed by using the mass capacity effect model since the water level is the balance between feedwater flow and steam flow under steady-state conditions. The other parts of the steam generator model, swell–shrink phenomenon and mechanical oscillation effect, have negligible effects on the system response under steady-state and high power conditions. Thus, by using the model of Eq. (2), the numerator and denominator of the steam generator can simply be written as:

$$\begin{aligned} N(s) &= K_1 \\ D(s) &= s \end{aligned} \quad (20)$$

where $K_1 = 0.058$ (see Table). Following the control design approach given in Section 3.1, the polynomials of the optimal algebraic controller are designed as follows:

$$\begin{aligned} A(s) &= l_1s \\ B(s) &= k_1s + k_0 \\ F(s) &= k_0 \end{aligned} \quad (21)$$

The main aim in such selections is to eliminate the effects of the disturbance, i.e. steam flow rate. From Eqs. (20) and (21), the characteristic polynomial of the closed-loop system in the form of Eq. (13) can be obtained as:

$$P(s) = l_1s^2 + k_1K_1s + k_0K_1. \quad (22)$$

To determine the controller parameters, l_1 , k_1 , and k_0 , the standard design specifications will be used, i.e. $\gamma_1 = 2.5$. The desired setting time for a steam generator is about $t_s = 300$ s, which leads to a time constant of $\tau = 100$ s by using Eq. (17). Then the control parameters can easily be found as:

$$k_0 = 1, k_1 = 100, l_1 = 232 \quad (23)$$

Stability analysis: the stability of the steam generator plant under optimal algebraic controller and reduced-order model Eq. (2) can be evaluated as follows. If we consider state-space representation of plant (Eq. (1)) and control (Eq. (21)) with state variables $x = [x_1, x_2, x_3, x_4]^T$ where x_1 = mass capacity effect, x_2 = swell-shrink effect, x_3 = mechanical oscillation effect, and x_4 = time-derivative of x_3 , the augmented closed-loop system under the optimal algebraic controller can be written as:

$$\dot{x} = (A - BK)x \quad (24)$$

where

$$x = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ \sigma \end{bmatrix}, A = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & -\tau_2^{-1} & 0 & 0 & 0 \\ 0 & 0 & -2\tau_1^{-1} & 1 & 0 \\ 0 & 0 & -\tau_1^{-2} - 4\pi^2 T^{-2} & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \end{bmatrix}, B = \begin{bmatrix} K_1 \\ -K_2\tau_2^{-1} \\ K_3 \\ 0 \\ 0 \end{bmatrix}, K = \begin{bmatrix} \frac{k_1}{l_1} & 0 & 0 & 0 & \frac{k_0}{l_1} \end{bmatrix}$$

where $\dot{\sigma} = x_1 - r$. It is obvious that (A, B) is controllable (respectively, stabilizable), and $A - BK$ is Hurwitz, i.e. all the eigenvalues λ_i of $A - BK$ always have negative real parts, $Re(\lambda_i) < 0$ for the control gains (Eq. (23)), and all steam generator parameter values are given in the Table.

3.3. A robust estimator for the feedwater control system

To implement the proposed optimal algebraic controller (Eq. (21)), the error signal e_1 must be available online. However, e_1 is not a measurable quantity since the state variable x_1 is not directly measurable. Having e_1 available online, an estimator can be designed to estimate the state variables. For this aim a robust nonlinear estimator by using the reduced-order model in Eq. (3) is proposed as follows:

$$\begin{cases} \dot{\hat{x}}_1 = K_1(u - q) + \delta sat(e) \\ \dot{\hat{x}}_2 = -\frac{1}{\hat{\tau}_2}\hat{x}_2 - \frac{\hat{K}_2}{\hat{\tau}_2}(u - q) \\ \hat{y} = \hat{x}_1 + \hat{x}_2 \end{cases} \quad (25)$$

where $(\hat{x}_1, \hat{x}_2, \hat{y})$ are the estimations of (x_1, x_2, y) respectively, the output error e is $e = y - \hat{y}$, δ is the constant estimator gain, and the parameters \hat{K}_2 and $\hat{\tau}_2$ are the nominal values of the corresponding parameters in the Table. The parameters $\hat{\tau}_2$ and $\hat{K}_2/\hat{\tau}_2$ are selected as the 5% values of $\tau_2(\theta)$ and $K_2/\tau_2(\theta)$ given in the Table in order to account for the reverse dynamic characteristics (the swell-shrink phenomenon). The saturation function is defined by the following:

$$sat(e) = \begin{cases} 1 & \text{if } e > 1 \\ e & \text{if } |e| \leq 1 \\ -1 & \text{if } e < -1 \end{cases} \quad (26)$$

Stability analysis: the robust estimator can accommodate large parameter variations and modeling uncertainties. The region of the state-space in which Eq. (25) is asymptotically stable can be determined using Lyapunov's

stability theorem [43]. For this aim, a candidate Lyapunov function can be selected as follows:

$$V(e) = \frac{1}{2}e^2, \quad e = y - \hat{y}. \quad (27)$$

Using Eqs. (3) and (25), the time derivative of $V(e)$ is found below:

$$\begin{aligned} \dot{V}(e) = e\dot{e} &= e \left(K_1(u - q) - \frac{1}{\tau_2}x_2 - \frac{K_2}{\tau_2}(u - K_4q) - K_1(u - q) + \frac{1}{\hat{\tau}_2}\hat{x}_2 + \frac{\hat{K}_2}{\hat{\tau}_2}(u - q) - \delta \text{sat}(e) \right) \\ &= e \left(-\frac{1}{\tau_2}x_2 + \frac{1}{\hat{\tau}_2}\hat{x}_2 - \frac{K_2}{\tau_2}(u - K_4q) + \frac{\hat{K}_2}{\hat{\tau}_2}(u - q) - \delta \text{sat}(e) \right) \\ &\leq |e| \cdot \left(\left| -\frac{1}{\tau_2}x_2 + \frac{1}{\hat{\tau}_2}\hat{x}_2 - \frac{K_2}{\tau_2}(u - K_4q) + \frac{\hat{K}_2}{\hat{\tau}_2}(u - q) \right| - \delta \right) \end{aligned} \quad (28)$$

If the gain δ is selected large enough, i.e. $\delta > \left| -1/\tau_2 x_2 + 1/\hat{\tau}_2 \hat{x}_2 - K_2/\tau_2 (u - K_4q) + \hat{K}_2/\hat{\tau}_2 (u - q) \right|$, the asymptotic stability of the state estimation can be achieved since the time-derivative of $V(e)$ will be $\dot{V} < 0$. Consequently, by choosing the estimator gain δ large enough, the estimation error approaches zero as the time increases. With the usage of the robust nonlinear estimator of Eq. (25), the proposed optimal algebraic controller described by Eq. (21) is now suitable for practical implementation because it makes the error signal e_1 available online. The block diagram of the proposed control system is given in Figure 4.

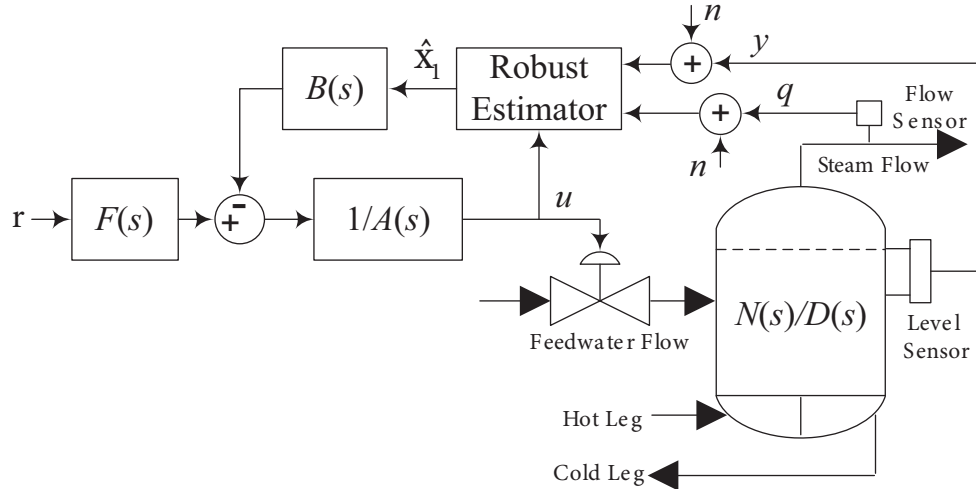


Figure 4. Block diagram of the robust estimator-based optimal algebraic control strategy.

4. Numerical results

The performance of the proposed feedwater control system for steam generators is evaluated with a set of simulations using MATLAB/Simulink programs. The robust nonlinear estimator parameters are selected as $\delta = 2$, parameters $\hat{\tau}_2 = 48.4$ and $\hat{K}_2 = 9.63$ by considering parameter values at a 5% power level. There is a trade-off in the selection of the robust estimator gain δ because a very large gain can result in degradations in the process output under highly noisy measurements. Numerical simulations are given for step water reference changes and ramp power demand (steam demand) variations. The robustness of the proposed methodology is illustrated under power demand variations, parameter uncertainties (see Figure 1), and noisy measurements.

Figure 5 shows the response of the water level for step water reference variations. The step response of the plant is given for step reference water level changes at the 5%, 15%, 30%, 50%, and 100% power level. The effect of the negative thermodynamic behavior (swell–shrink phenomenon) can be seen at low power levels clearly, i.e. the level decreases initially for a power level less than or equal to 15%. A nonovershoot transient response is seen in the figure as desired in the plant specifications for all power operations.

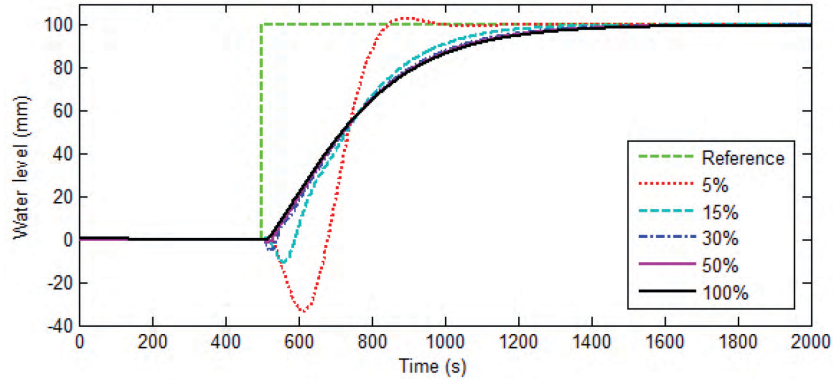


Figure 5. Steam generator water level (in mm) variations as a function of time during step reference water level variations.

The robustness and performance of the proposed control under parameter variations (see Figure 1) and noisy measurements are given in Figure 6. The proposed controller is compared with the traditional control approach for $K_{pl} = 0.1$, $K_{il} = 0.00017$, $K_{ph} = 0.315$, $K_{ih} = 0.0054$ (based on Ziegler–Nichols tuning method). When the power demand (or steam flow demand) varies in the full operating range (from the 0% to 100% power level), the time-responses of the plant output (water level) and the feedwater flow input are demonstrated. During the assumed power demand (in % rated power) variations (Figure 6a), the feedwater flow behavior is displayed in Figure 6b, and the water level response is displayed in Figure 6c. The noise on the water level measurement channel is assumed to be normally distributed with a mean of 0mm and a standard deviation of ± 10 mm. The noise on the steam flow measurement channel is assumed to be normally distributed with a mean of 0 kg/s and a standard deviation of ± 13.4 kg/s. The narrow range reference water level is assumed to be 300 mm. Figure 6b shows that the feedwater flow rate (in kg/s), which is the control signal, follows perfectly the steam flow rate (in kg/s) over all the operating power ranges during power demand variations. On the other hand, the traditional control given in Eqs. (6) and (7) has large transient variations. Figure 6c shows that the water level stays very close to the reference level during transients and stays on the reference signal when power demand stays constant. While the traditional control given in Eqs. (6) and (7) has $-950/+180$ mm water level variations, the proposed controller assures $-100/+100$ mm level variations. It is clear from the figures that the robust estimator-based optimal algebraic control provides excellent results even though the steam generator model has model/parameter uncertainties (see Table and Figure 1) and noisy measurements. A quite robust control response is obtained against the plant uncertainties and noise.

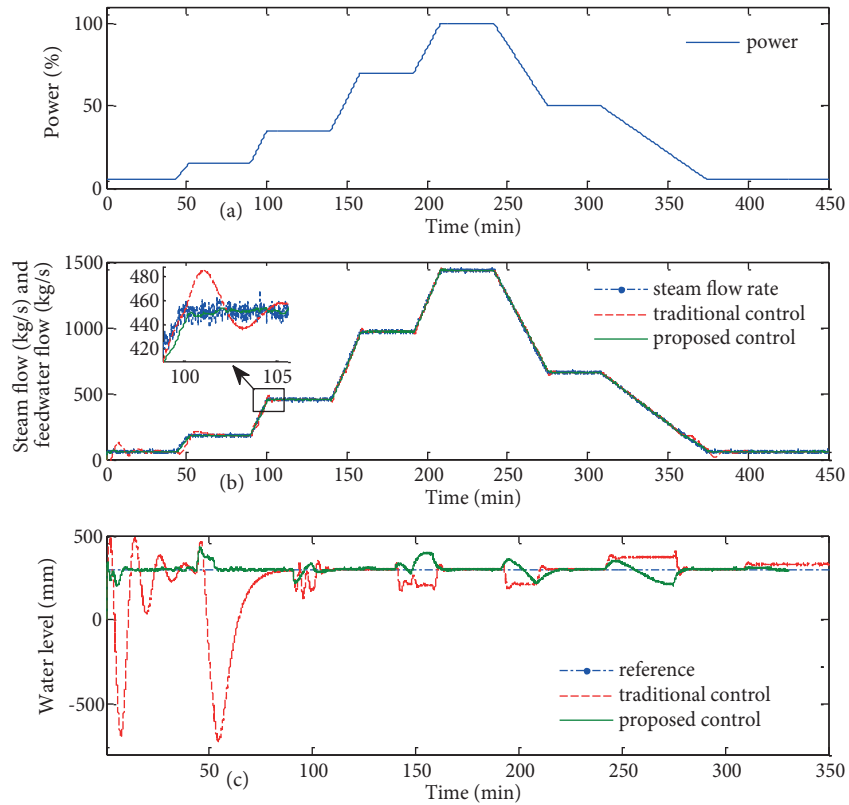


Figure 6. Robustness and performance of the proposed feedwater control system under parameter uncertainties and noisy measurements. (a) Power demand (in %) variations; (b) steam flow rate (in kg/s) and feedwater flow rate (in kg/s); (c) water level (in mm) during power demand variations as a function of time.

5. Conclusion

A robust estimator-based optimal algebraic control strategy is developed for the steam generator feedwater control system. It is shown that the proposed control strategy is capable of efficiently controlling the steam generator feedwater system in the presence of noise, and modeling and parameter uncertainties with the following features:

- Efficiency: ability to handle operational maneuvers with small water deviation from the reference;
- A single automatic control over the complete range of normal power operation: the conventional single-element/three-element control system is reduced to a single control system;
- Robustness: ability to address power demands with minor impact to control system stability and desired performance.

The proposed robust controller uses a minimum number of pieces of equipment that lowers the price, but increases the reliability of the system. Since a single automatic controller is designed for the complete range of normal power operations, control algorithms and information load in the entire feedwater control system are reduced. Finally, the optimal algebraic controller has a nonovershoot response and a smooth control signal, which decreases the possible mechanical vibrations of the entire system.

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