

Drum Boiler Control with Output Constraints using Model Predictive Control Method

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Abstract

Drum boilers consume is one of the most important equipment of the thermal power plants in many countries and are widely used in industrial process applications. A boiler-turbine unit is a typical multivariable industrial control system in power plant. The boiler is so manufactured that the drum level must be in the specified range. Output constraints are an important challenge in boiler drum systems to have safety and efficient operation. In this paper, the problem of state space model predictive control for a constrained nonlinear boiler drum systems is investigated. Predictive control is a highly efficient and strong method since its control performance has been reported to be best among other conventional techniques to control the multivariable dynamical plants with various inputs and outputs constraints. Simulation results demonstrate the satisfactory performance and effectiveness of this method and compatibility with practical implementation in boiler.

Keywords:drum boiler, constrained MIMO MPC, drum pressure, drum water level

Nomenclature

l	Drum water level, [m]
p	Drum pressure, [kg/cm ²]
$t \in \mathbb{R}_+$	Time [s]
$k \in \mathbb{N}_+$	Sample
N_1	Minimum prediction horizon
N_2	Maximum prediction horizon
N_3	Control horizon
J	Cost function
$x \in \mathbb{R}^n$,	Plant states
$n \in \mathbb{N}_+$	
$u \in \mathbb{R}^m$,	Controlled plant inputs

$m \in \mathbb{N}_+$	
$y \in \mathbb{R}^r$,	Plant outputs
$r \in \mathbb{N}_+$	
$A \in \mathbb{R}^{n \times n}$	State parameter matrix (continuous-time)
$B \in \mathbb{R}^{n \times m}$	Input parameter matrix (continuous-time)
$C \in \mathbb{R}^{r \times n}$	Measurement parameter matrix
$D \in \mathbb{R}^{r \times m}$	Feedforward matrix
$M \in \mathbb{R}^{n \times n}$	State parameter matrix (Discrete-time)
N	Input parameter matrix (Discrete-time)
$\in \mathbb{R}^{n \times m}$	
\bar{R}	Weighting matrix for control effort
\bar{Q}	Weighting matrix for error
w	Reference trajectory
$\hat{\cdot}$	Estimated value
$E[.]$	Expected value

1. Introduction

Current requirements on safe and economic power generation with higher level of efficiency cause that modernization of aged thermal power plants becomes extremely in consideration. The boilers are ones of the most important equipment of the thermal power plants in many countries and the drum boiler system is an essential part of a power plant. The drum boiler system exhibits nonlinear, time-varying, coupling behavior which supplying high-pressure steam to rotate the generator in thermal electric power generation. Boiler is a closed vessel in which steam is produced from water. Production is done by the combustion of fuel. Boiler drum level control systems are extensively used in process industries for many purposes such as for generating power in steam engines or steam turbines, for sizing and bleaching in textile industries, for heating the buildings in cold weather and so on. In process industries, different kinds of boilers are used to fulfil the industrial process applications. Hence, the control of such system is complex and challenging and a linear model cannot capture the nonlinear dynamics sufficiently.

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The primary requirements of a boiler are to contain the water safely and the steam must be delivered in desired condition (as regard its pressure, temperature, quality and required rate.). So the purpose of the drum boiler system control is to keep the output of mechanical energy in balance with the electrical load demand and meet the load demand of electric power while maintaining the internal variables such as drum steam pressure, temperature and drum water level within tolerance. The control of pressure and level on boilers is a delicate issue in situations requiring good robustness of system. Therefore emerging new technologies in computer science has attained a great attention in employing model-based strategies in process control system such that different classes of computer control algorithms have been developed in this regard [1].

It is essential that the developed dynamic model can capture the dynamics of the system in different operating while keeping the model relatively simple, suitable for the design of feedback controllers. Continuous process in power plant and power station are complex systems characterized by nonlinearity, uncertainty and load disturbance. Hence to design a controller, the boiler-turbine system is usually modeled as a Multi-Input Multi-Output (MIMO) nonlinear system numerous modeling have been applied for boiler-turbine system. A key feature of drum boilers is that there is a very efficient energy and mass transfer between all parts that are in contact with steam [2]. Numerous modeling and control methodologies have been applied for boiler-turbine system. In the early works, dynamic modelling of a boiler-turbine unit based on data logs, parameter estimation, system identification, and simplification of nonlinear models have been done. Using basic conservation a model for water level dynamics in natural circulation of drum-type boilers has been developed [3,4].

The drum-level control is difficult because of the complicated shrink and swell dynamics. These create a non-minimum phase behavior, which changes significantly with the operating conditions. The severe nonlinearity and wide operation range to the boiler-turbine plant have resulted in many challenges of power system control engineers. In most existing work, a class of PID controllers is widely employed to regulate the drum water level. However, it is difficult to obtain satisfactory control performance when a sudden change in feed water flow condition or heating rate occurs [5]. In [6] multiple model predictive control methodology where the system is modeled by piecewise linear models is applied for control of a boiler turbine unit. Hogg and Ei-Rabaie presented an application of self-tuning generalized predictive control

It is shown in Figure 1 that supplied water fed by the pump to the drum inlet is preheated through the economizer, in order to reduce energy consumption. Water is fed into the steam drum and Due to the gravity, it flows down through a downcomer-riser closed loop

(GPC) to a boiler system [6]. Rovnak and Corlis presented an application of dynamic matrix control to fossil power plant [7]. the performance of receding horizon is minimized by real-time optimization. Dimeo and Lee used a genetic algorithm to enhance the wide range performance of PI controller or linear quadratic regulator (LQR) [8]. Prasad, Swidenbank, and Hogg proposed a predictive control based on an NN model [9]. Lei and Wu [10] presented a dynamic matrix control that can update the rules adaptively by a simple set-point error checking process. Salim and etal presented controller for drum-boiler system based dynamic matrix control method [11]. Wang and Meng proposed an optimal control for boiler system [12].

An important characteristic of process control problems such as drum boiler is the presence of constraints on output variables. A successful industrial controller for the process industries must therefore maintain the system as close as possible to constraints without violating them. Model Predictive Control (MPC) is a very efficient and strong method to control multivariable processes with constraints. The predictive controller is able to take into consideration directly the constraints on the inputs and the process outputs. The industrial success of MPC is largely attributable to its explicit constraint handling capability. This paper focuses on designing a controller based on Model Predictive Control method for drum boiler system. For this purpose boiler operation is introduced in section 2 then the state space model of drum boiler is presented in section 3. In section 4 state space constrained predictive control for MIMO systems is explained. Section 5 provides simulation results. Finally concluding remarks are made in section 6.

3. System Description

The simplified performance of boiler shown in following figure illustrates steam production using the drum-boiler unit.

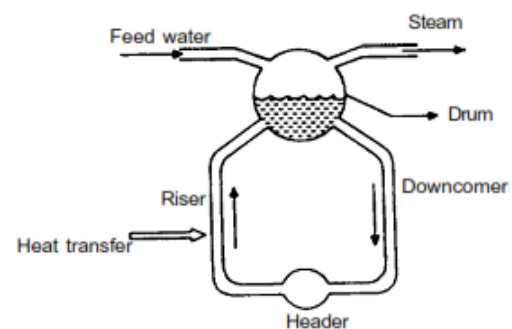


Figure 1. Schematic diagram of drum boiler [14]

producing saturated steam, which flows along the riser tubes before being collected and fed back into the drum. Passing through the risers, water is heated and changed to saturation condition. The saturated steam flows through the water level until it exits upon reaching the

drum outlet. This saturated mixer of steam and water enters the steam drum. There, Steam separate from water and then it is reheated one more time at the superheater. Then, steam is more heated and is fed in to the header. There is a spray attemperator between two super-heaters that regulates the steam temperature by mixing low temperature water with the steam from the primary super-heater. The inflow from the feedwater pump is regulated using one control valve.

A boiler-turbine unit can be described as a multi-input multi-output multivariable plant and has explicit input constraints. Controlled variables are drum stream pressure and drum level, while manipulated variables are the fuel actuator position and the feed water actuator position. The boiler turbine model is presented in Figure2.

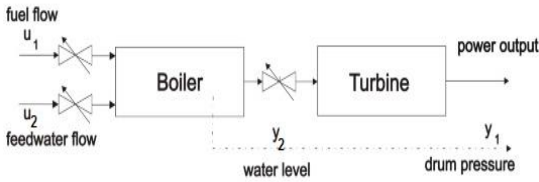


Figure 2. Boiler Turbine Model [12]

For proper performance of the boiler–turbine unit, control system must satisfy some requirements according to varying operating conditions and load demands. The main objective of the control system is to make the electric output follow the load command rapidly while maintaining the drum level and the drum pressure. Stable control of drum water level is of great importance for economic operation of power plant steam generator systems. Sometimes, poor control of drum water level causes the emergency shutdowns in power plants. On the other hand, the steam temperature must be maintained at the desired level to prevent over-heating of the super-heaters and to prevent wet steam entering turbines.

4. STATE-SPACE MODEL OF DRUM Boiler System

The boiler-turbine model used in this paper was first developed by Bell and Astrom and has been popularly adopted in validating various controllers for the boiler-turbine system in simulation. In this model much of the system behaviour is captured by considering the mass and energy balances for total system. The behaviour of the drum-level is obtained by accounting for the distribution of steam and water in the system. The equations are non-linear and are characterized by a few parameters only, which were obtained from first principles. The global mass and energy balances for the system as a whole describe the response of drum pressure and the total water volume to changes in feed water flow rate and steam flow rate very well.

Hence, most available simulation software requires state equations, the adapted model is thus a set of differential algebraic equations. A fourth order non-linear state space model was obtained from global mass and energy

balance equations for the total system as well as for the sub systems namely riser, downcomer and drum. The non-linear model is linearized by taking a Taylor's series approximation at the nominal operating point. The terms in the Taylor's series of order higher than one are discarded. The resulting linear model is expressed by following state equation [14].

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) \\ y &= Cx(t) + Du(t), \end{aligned} \quad (1)$$

Where

$$\begin{aligned} A &= \begin{bmatrix} 3.74e-15 & 7.65e-6 & 0 & 0 \\ -4.09e-16 & -6.55e-5 & 0 & 0 \\ 2.38e-16 & 0.00059 & -0.143 & 0 \\ -8.16e-14 & -0.0554 & 18.216 & 0.083 \\ & 0.0015 & -0.0015 & \end{bmatrix} \\ B &= \begin{bmatrix} -5.9548e-5 & -9.0316e-5 \\ 3.4622e-5 & 5.2512e-5 \\ -0.0167 & 0.0239 \end{bmatrix} \\ C &= \begin{bmatrix} 0.05 & -0.0484 & 6.7128 & 0.05 \\ 0 & 1 & 0 & 0 \end{bmatrix} \\ D &= \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix} \end{aligned} \quad (2)$$

In this model, drum pressure (p) and drum water level (l) are selected as output variables and feed-water flow rate and fuel flow rate as input variables. Total water volume, drum pressure, steam volume and steam-mass fraction is considered as state variables. This state space model create a non-minimum phase behaviour then it is necessary to have a controller [14].

5. State Space Constrained MMO Predictive Control

Model Predictive Control (MPC) is a control strategy based on the explicit use of a model to predict the process output over a long-range period of time. In this method, control signal is obtained by optimizing a cost function. The general expression for such as cost function will be:

$$\begin{aligned} J(N_1, N_2, N_3) &= \sum_{j=N_1}^{N_2} \|\hat{y}(k+j|k) \\ &\quad - w(k+j)\|_{\bar{Q}}^2 \\ &\quad + \sum_{j=1}^{N_3} \|\Delta u(k+j-1)\|_{\bar{R}}^2 \end{aligned} \quad (3)$$

In equation (3), \bar{R} and \bar{Q} are positive definite weighting matrices of cost function, $\hat{y}(k+j|k)$ is an optimum j step ahead prediction of the system output on data up to time t ; that is, the expected value of the output vector at time t if the past input and output vectors and the future control sequence are known. $w(k+j)$ is a future set-point or reference sequence for the output vector [15].

A multivariable process described by the following state space model described by following expression:

$$\begin{aligned} x(k) &= Mx(k) + N\Delta u(k) \\ y(k) &= Cx(k) \end{aligned} \quad (4)$$

The output of the model for instant $k + j$, assuming that the state at instant k and future control increments are known, can be computed by recursively applying Equation (4), resulting in:

$$y(k + j) = CM^j x(k) + \sum_{i=0}^{j-1} CM^{j-i-1} N\Delta u(k + i) \quad (5)$$

By Taking the expected value of $y(k + j)$, the optimal j ahead prediction is given by:

$$\hat{y}(k + j|k) = E[y(k + j)] = CM^j E[x(k)] + \sum_{i=0}^{j-1} CM^{j-i-1} N\Delta u(k + i) \quad (6)$$

A set of $N_2 j$ ahead predictions is given by:

$$\mathbf{y} = \begin{bmatrix} \hat{y}(k + 1|k) \\ \hat{y}(k + 2|k) \\ \vdots \\ \hat{y}(k + N_2|k) \end{bmatrix} = \begin{bmatrix} CME[x(k)] + CN\Delta u(k) \\ CM^2 E[x(k)] + \sum_{i=0}^1 CM^{1-i} N\Delta u(k + i) \\ \vdots \\ CM^{N_2} E[x(k)] + \sum_{i=0}^{N_2-1} CM^{N_2-i-1} N\Delta u(k + i) \end{bmatrix} \quad (7)$$

which can be expressed as:

$$\mathbf{y} = \mathbf{F}\hat{x}(k) + \mathbf{H}\mathbf{u} \quad (8)$$

where $\hat{x}(k) = E[x(k)]$, \mathbf{H} is a block lower triangular matrix with its non-null elements defined by $(\mathbf{H})_{ij} = CM^{i-j}N$ and matrix \mathbf{F} is defined as:

$$\mathbf{F} = \begin{bmatrix} CM \\ CM^2 \\ \vdots \\ CM^{N_2} \end{bmatrix} \quad (9)$$

The prediction equation (8) requires an unbiased estimation of the state vector $x(k)$. If the state vector is not accessible, a Kalman filter is required. By defining a set of j ahead predictions affecting the cost function: $\mathbf{y}_{N_{12}} = [\hat{y}(k + N_1|k)^T \cdots \hat{y}(k + N_2|k)^T]^T$ and the vector of N_3 future control moves $\mathbf{u}_{N_3} = [\Delta u(k)^T \cdots \Delta u(k + N_3 - 1)^T]^T$,

$$\mathbf{y}_{N_{12}} = \mathbf{F}_{N_{12}}\hat{x}(k) + \mathbf{H}_{N_{123}}\mathbf{u}_{N_3} \quad (10)$$

where matrices $\mathbf{F}_{N_{12}}$ and $\mathbf{H}_{N_{123}}$ are formed by the corresponding sub-matrices in \mathbf{F} and \mathbf{H} respectively. Equation (3) can be rewritten as:

$$J = (\mathbf{H}_{N_{123}}\mathbf{u}_{N_3} + \mathbf{F}_{N_{12}}\hat{x}(k) - \mathbf{w})^T \bar{R} (\mathbf{H}_{N_{123}}\mathbf{u}_{N_3} + \mathbf{F}_{N_{12}}\hat{x}(k) - \mathbf{w}) + \mathbf{u}_{N_3}^T \bar{Q}\mathbf{u}_{N_3} \quad (11)$$

If there are no constraints, the optimum can be expressed as:

$$\mathbf{u} = \left((\mathbf{H}_{N_{123}}^T \bar{R} \mathbf{H}_{N_{123}}) + \bar{Q} \right)^{-1} \mathbf{H}_{N_{123}}^T \bar{R} (\mathbf{w} - \mathbf{F}_{N_{12}}\hat{x}(k)) \quad (12)$$

Because of the receding control strategy in predictive control, only $\Delta u(k)$ is needed at instant k . Therefore, only first m rows of $\left((\mathbf{H}_{N_{123}}^T \bar{R} \mathbf{H}_{N_{123}}) + \bar{Q} \right)^{-1} \mathbf{H}_{N_{123}}^T \bar{R}$ called \mathbf{K} need to be computed and control law is expressed as following [15]:

$$\Delta u(t) = \mathbf{K}(\mathbf{w} - \mathbf{F}_{N_{12}}\hat{x}(t)) \quad (13)$$

MPC has the advantage that can consider the constraints of input and output variables. Output constraints usually are associated with operational limitations such as equipment specifications and safety considerations. The constraints acting on a process can originate from amplitude limits in the process outputs. These constraints can be posed as:

$$y_i^{min} \leq y_i(k) \leq y_i^{max} \quad (14)$$

where y_{min} and y_{max} are the minimum and maximum values of the outputs, respectively. Constraints on the state variables also may be specified if appropriate. The MPC algorithm when constraints are taken into account consists of minimizing expression (3) subject to inequality constraints; that is, the optimization of a quadratic function with linear constraints, what is usually known as a quadratic programming problem [16].

6. Simulation Results

First, we design the controller without taking into consideration the constraints on outputs and then we design the controller under outputs constraints. The multivariable MPC have been computed with prediction horizon of 20 and a control horizon of 10 for all the variables. Because of both outputs are of the same type and are approximately in the same level The weighting matrix Q is considered equal to identity matrix and input weighting matrix $R = 0.1I$. The reference trajectories are supposed to be equal to the actual set-points 1.2 and 1 for the first and second outputs in the simulations, respectively. The outputs variables are also constrained as follows: The drum pressure and drum water level must be changed within the maximum and minimum 10 percent of their set points. Simulation result of MPC

without outputs constraints can be seen in figure 3 and figure 4 and Simulation result of MPC under outputs constraints can be seen in figure 5 and figure 6.

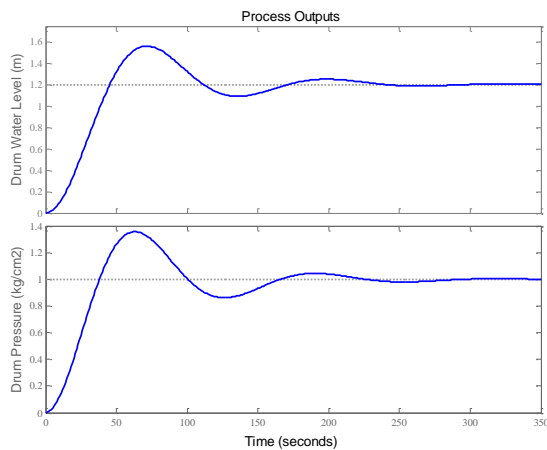


Figure 3. Process outputs without considering the output constraints

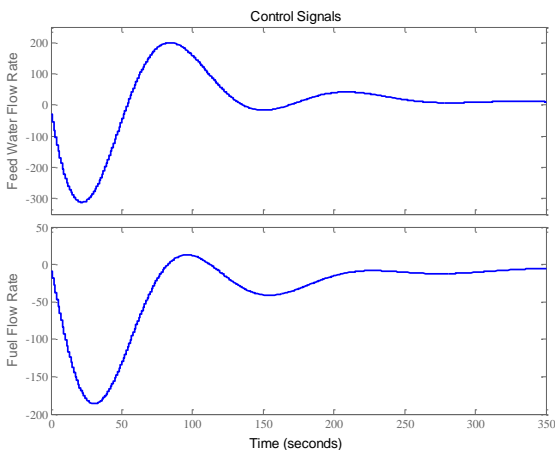


Figure 4. Feed water flow and fuel flow rate of boiler without considering the output constraints

As can be seen in Figure 3 the outputs track the reference trajectory appropriately; but this simulation was done with supposing lack of constraints in the outputs; hence, drum pressure and drum water level violate their constraints in amplitude. In Figure 4 is shown the control signals in this case.

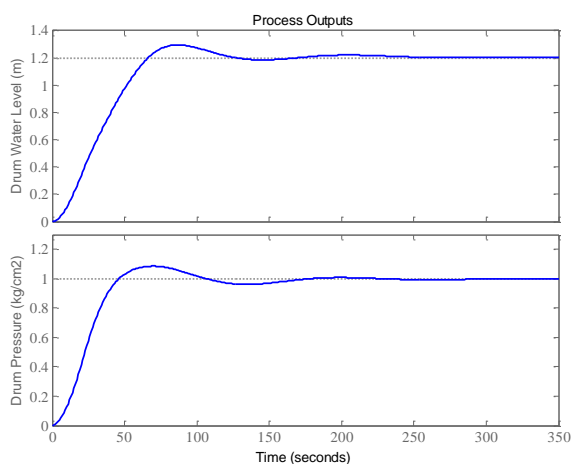


Figure 5. Process outputs under constraints

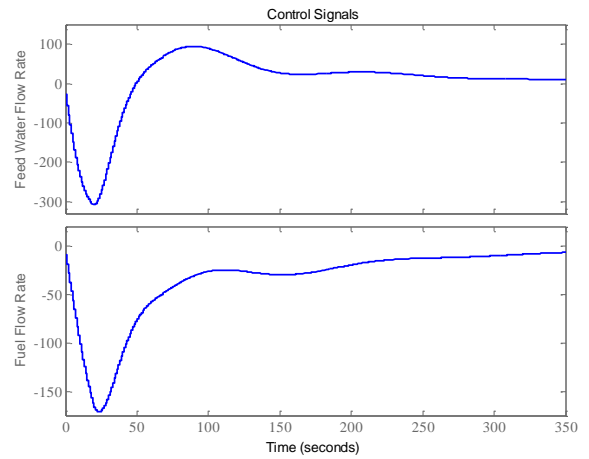


Figure 6. Feed water flow and fuel flow rate of boiler under output constraints

Figure 5 showing the controller implementation in which the process output constraints are considered. As can be seen, the outputs are not more than their permitted ranges that is 10 percent of their setpoints ($y_1(t) \leq 1.32$ and $y_2(t) \leq 1.1$). It also shows good tracking performance when considering output constraints, which is often the case in real industrial systems. Simulation results confirmed the computational equations mentioned in section 4. Figure 6 shows manipulated variables of process when the process output constraints are considered.

7. Conclusion

Stable control of drum water level and drum pressure is very important for economic operation of power plant steam generator systems. Sometimes, poor control of these variables causes the emergency shutdowns in power plants. In this research, a constrained model predictive control methodology is applied to a boiler-turbine system. Model predictive control is one of the most interesting approaches for solving the problems associated with MIMO processes with constraints because of its ability to including constraints in the formulation of the controller. By including constraints in the optimization problem, the controller is able to predict future constraint violations and respond accordingly. A major advantage of MPC as compared to other control strategies is that it provides the same constraint handling capability. In simulation results, it has been observed that outputs are not more than their permitted ranges with very good set point tracking. These results can provide a good practical guidance in implementing the MPC.

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