Hardware Implementation of An LQR Controller of A Drum-Type Boiler Turbine on FPGA

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***Abstract*—In a steam power generator, boilers produce steam uninterruptedly in large amounts. The drum boiler system is extremely nonlinear with multi-variable parameters rendering it a very difficult process control problem. The boiler is also inherently unstable due to the effect of the dynamic shrink/swell phenomenon in the drum. Drum boiler systems have been controlled by Single-Input, Single-Output (SISO) Proportional-Integral-Differential (PID) controllers. Such SISO control systems do not take into consideration the interaction between the controlled variables or the effect of demanding load change on boiler dynamics. In this work, we present a hardware-based multi-variable Linear Quadratic Regulator (LQR) controller of the boiler-turbine system. Reconfigurable hardware has been recently used to implement a number of complex control systems due to the performance and flexibility gains of such platforms. The proposed controller is implemented and validated on a Xilinx Artix-7 FPGA AC701 Evaluation Kit. Testing results depict a significant improvement in the control system characteristics compared to the classical PID control techniques.**

***Index Terms*—LQR Controller; Drum-Boiler; Multi-variable Control; FPGA-Based Control System.**

I. INTRODUCTION

Steam generation is an expensive and complex process. Boilers burn large amounts of fuel and produce large amounts of dangerous exhausts and damaging gases. Improving the boiler-turbine control process reduces fuel cost and resulting pollution, enhances safety, and helps to produce green energy. Conventionally, boilers have been controlled by Proportional-Integral-Differential (PID) controller, however, given the complexity of the boiler turbine, it is preferred to use a more advanced control technique to better address coupling between various control variables. The boiler process is subject to a number of control problems [1]:

- The process dynamics fluctuate with operating point (nonlinear). This problem can be observed when the boiler operates in a cycle mode to improve efficiency. Consequently, the control system must be capable of providing good control characteristics over a range of operating points.
- The drum boiler process is inherently multivariable with strong coupling between the control variables. Single-Input, Single-Output (SISO) control methods cannot capture and respond to such interaction between control variables. Moreover, in SISO control systems, various control loops will compete with each other to achieve their objectives.
- The process is inherently unstable due to the effect of shrink and swell phenomenon in the drum level.
- Boilers are commonly used in situations where the load can be changed suddenly without warning.

The main objective of this work is to address some of the boiler-turbine control problems through the use of a linearization strategy and a Multi-Input, Multi-Output (MIMO) Linear-Quadratic Regulator (LQR) optimal state-space control technique [2] and compare the performance of the proposed control method to the industrial standard PID control strategy [3]. Unlike PID controllers, an LQR controller can optimally accommodate coupling between various system variables. The second goal is to build the proposed LQR control system and test it on a reconfigurable hardware platform. FPGAs are widely used in modern industrial control systems due to their performance and flexibility characteristics [2]. The Xilinx Systm Generator software provides hardware co-simulation of the developed controller using a system model running on the Simulink tool which facilitates validating the controller operation on an emulated version of the physical system.

Both the proposed LQR controller and the classical PID controller are designed and analyzed for the model of a large scale fossil-fueled boiler turbine alternator power generation unit developed by Bell and Astrom [2] and Morton and Price group [4]. This model is typically used for control studies as well as macro design simulations. The sampling time is set to 0.1 sec which is a practical value for the drum boiler physical system operation and appropriate for FPGA implementation. The developed controllers are implemented and validated on a Xilinx Artix-7 FPGA AC701 Evaluation Kit.

The remaining of this paper is organized as follows: Design of the drum-boiler LQR state feedback controller with a full state estimator is advanced in Section II. Also, a PID controller is developed for the same model. Performance evaluation of the LQR and PID controllers is introduced in Section II-E. Hardware implementation of The LQR Controller on a Xilinx Artix-7 FPGA AC701 Evaluation is presented in Section III. Conclusions and future work are portrayed in Section IV.

II. DRUM-BOILER TYPE LQR CONTROLLER DESIGN

The drum boiler state-space model has three inputs (U), three outputs (Y), and three states (X) represented as vectors. The system inputs are the position of actuators that drive the valves controlling the fuel (Q), feed-water (q_f), and steam flow (q_s) while its outputs or measured variables are the drum steam pressure (P), electrical power output (E), and drum water level (X_m). The model is described as a third-order

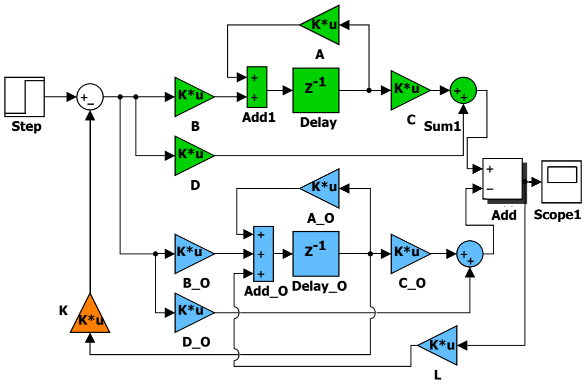

Figure 1. The LQR control system with the full state feedback controller and state observer.

MIMO nonlinear state-space system [2]. In [4], the drum boiler model is linearized around its operating point. The linear model parameters (A, B, C, D) are calculated in the matrix form for a 160 MW oil-fired natural circulation drum unit [5].

In this section, the LQR state-space controller design procedures are presented and the LQR controller performance is compared to the industrial PID controller to check the achieved performance improvements. Before designing the controller, the open-loop system is analyzed for stability, controllability, and observability. The open-loop drum boiler process is unstable and the state-space model is fully controllable and observable. Afterwards, the full state-feedback controller and state estimator are developed.

A. *Linear Quadratic Regulator (LQR) Controller Design*

The block diagram of the full control system is illustrated in Figure 1. Full state feedback is developed by commanding the input u vector according to the following equation:

$$u = -kx \tag{1}$$

Thus, the state space equations can be written as:

$$\dot{x} = Ax + B(r - Kx) = (A - Bk)x + Br \tag{2}$$

$$y = Cx + D(r - kx) = (C - Dk)X + Dr \tag{3}$$

The controller gain is calculated using the optimal LQR control strategy [5], [6]. Using the Riccati equations, the values of Q and R matrices are carefully selected to achieve the control system design requirements including: the settling time for all outputs is less than 5 seconds and the rise time is less than 2 seconds with no steady state error or overshoot for a step input to the system. In the LQR method, the feedback gain k is calculated as following:

$$k = R^{-1}(B^T P + N^T) \tag{4}$$

where P is evaluated by solving the continuous time algebraic Riccati equation:

$$A^T P + PA - (PB + N)R^{-1}(B^T P + N^T) + Q = 0 \tag{5}$$

The resulting Q and R matrices are:

$$Q = \begin{bmatrix} 50 & 0 & 3.220846e-05 \\ 0 & 10 & 0 \\ 3.220846e-05 & 0 & 20 \end{bmatrix} \tag{6}$$

$$R = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{7}$$

The previous procedures are completed using MATLAB and the state feedback gain k is calculated as :

$$k = \begin{bmatrix} 5.145923 & 0.127003 & 0.322861 \\ -0.037916 & 0.627538 & -0.007305 \\ -0.263712 & 0.023235 & 3.099836 \end{bmatrix} \tag{8}$$

The developed LQR controller has brought good stability characteristics to the system and fulfilled the design requirements. However, if the reference input is different from zero, $r(t) = a \neq 0$, the system performance will be degraded. To overcome this problem, an asymptotic tracking of the reference input must be designed to scale the reference input by a factor of $\bar{N}$ to the compared states [7], [8]. For good tracking performance, the following equation must be satisfied:

$$y(t) \approx r(t) \quad for \quad t \longrightarrow \infty \tag{9}$$

To satisfy this equation, one solution is to scale the reference input $r(t)$ such that $u = \bar{N}r = k$, where $\bar{N}$ is the feed-forward gain used to scale the closed-loop system inputs. Then, the system state and output equations become:

$$\dot{x} = (A - Bk)x + B\bar{N}r \tag{10}$$

$$y = (C - Dk)X + D\bar{N}r \tag{11}$$

Using MATLAB, the scaling factor $\bar{N}$ is calculated to:

$$\bar{N} = \begin{bmatrix} 4.7524994 \\ 1.7159563 \\ 4.943310 \end{bmatrix} \tag{12}$$

B. *State Observer Design*

In physical systems, not all system states can be measured and alternatively an estimate of them is used as an input to the state-feedback controller [9]. The system state is estimated based on the known model of the system, system inputs, and measured outputs using a state observer or estimator as shown in Figure 1. Similar to the state-feedback gain calculations, an observer feedback gain matrix L is calculated.

The observer gain is designed in such a manner that ensures rapid convergence of the estimation error to zero which allows usage of the corrected states for feedback. The estimator eigenvalues must be faster than the desired eigenvalues of the state feedback. To achieve this, the estimator poles must be 4-10 times closer to the S-plane origin than the closer controller pole [7]. Making the estimator poles too close can be problematic if the measurement is corrupted by noise or if there are errors in the sensor measurements in general [8]. Controller poles from the above system with error tracking controller are calculated to $P = [0.0398,\ 0.5455,\ 0.4732]^T$. Based on the controller poles, the observer poles are placed at $[-0.2,\ -0.21,\ -0.22]^T$ which can be modified later if needed. The MATLAB function `place` is used to find L.

$$L = \begin{bmatrix} 1.0997 & 0 & -3.4694e-18 \\ 0.008272 & 1.11 & -1.3552e-20 \\ -2.009 & 0 & 2.65445e+02 \end{bmatrix} \tag{13}$$

Finally, the full system is integrated as demonstrated in Figure 1. The state-space equations of the full system are:

$$\begin{bmatrix} \dot{x} \\ \dot{\hat{x}} \end{bmatrix} = \begin{bmatrix} A & -BK \\ LC & A - LC - BK \end{bmatrix} \begin{bmatrix} x \\ \hat{x} \end{bmatrix} + \begin{bmatrix} B\bar{N} \\ 0 \end{bmatrix} r \tag{14}$$

$$\begin{bmatrix} y \\ \hat{y} \end{bmatrix} = \begin{bmatrix} C & -DK \\ 0 & C - DK \end{bmatrix} \begin{bmatrix} x \\ \hat{x} \end{bmatrix} + \begin{bmatrix} D\bar{N} \\ 0 \end{bmatrix} r \tag{15}$$

C. Drum-Boiler Type PID Controller Design

The most common type of industrial controllers is the PID controller. If U is the controller output and E is the received error signal, the PID control law has the following form [3]:

$$C(s) = \frac{U(s)}{E(s)} = k_p[1 + \frac{1}{\tau_i s} + \frac{\tau_d s}{1 + \tau_f s}] \tag{16}$$

where k_p is overall gain, and τ_i and τ_d are the time characteristic constants of the integral and derivative parts, respectively. The filter frequency τ_f applied to the derivative term is mandatory from both practical and theoretical aspects. The additional low-pass filter τ_f pole is placed in a manner that attenuates high-frequency noise [8]. The Matlab Simulink continuous PID block offers functionalities that exactly meet our needs, thus a separate realization of the drum-boiler type PID controller was not required. Output feedback is adopted and three independent PID controllers are designed for each of the boiler input valves based on the three measured variables. The discrete PID controller is developed for 0.1 sec sampling time and trained using MATLAB to produce lower settling time and overshoot as well as prompt stability [10]. The calculated PID controller parameters are depicted in Table I.

Table I
THE DRUM-BOILER TYPE PID CONTROLLER PARAMETERS

Output loop	P	I	D
P loop controller	0.9	0.03276e-05	0.248324
E loop controller	0.12165	0.00323866	0.458024
L loop controller	1.214426e-04	6.943123e-05	4.97465e-05

D. Valve Limiter Design

When directly controlling the level, it is not sufficient for the controller by itself to directly open or close the valve as it can give negative orders to the valve. Also controller can command issue values higher than 1 to the valve which is not possible mechanically. The valve is fully opened at 1, fully closed at 0, and half open at 0.5. Therefore, a valve limiter is designed to force negative controller commands to 0 (fully closed) and force higher value signals to 1 (fully opened) [9].

E. Closed-Loop System Simulation Results

In the automatic control literature, simulation is the main tool to evaluate control system performance. After implementing the proposed controllers on the target FPGA, Xilinx hardware co-simulation is also used to validate the controllers' operation. For the LQR controller, the system response of the closed-loop system is examined for a step increase in the load demand represented by the fuel quantity input Q. The LQR step response is drawn twice for the controller designed with and without the state observer to evaluate the observer's performance. Afterwards, the step response of the LQR controller is compared to the PID controller to indicate the performance improvements gained by the former. The step response of the three closed-loop control systems is shown in Figure 2. It is clear that both outputs of the LQR control system with and without observer are almost matched indicating that the state estimator is well-designed. Compared to the PID controller step response, the LQR controller has a faster settling time, a lesser steady-state error, yet a larger overshot in the drum level output.

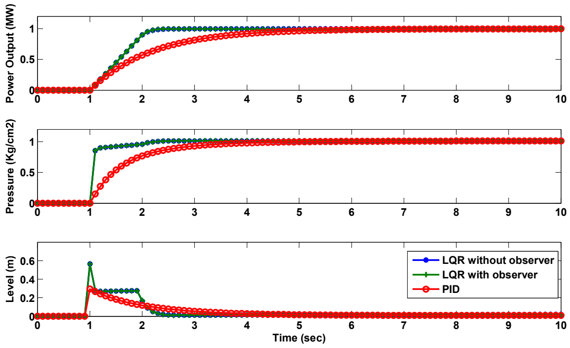

Figure 2. Closed-loop response for load demand step change

In Figure 2, the output power increases to follow the increase in load demand; the settling time is less than 2 sec in the LQR controller and more than 6 sec in the PID controller. The drum pressure increases to follow the demanding increase in pressure; the settling time is less than 2 sec in the LQR controller and more than 5 sec in the PID controller. The LQR drum water level has a higher overshot value than that of the PID controller but less settling time. The maximum overshoot/undershoot in the drum water level does not exceed the allowed values of ±100 mm during transients, and the pressure never surpasses the safety limits which might lead to operating the safety valve. The LQR state controller was smart enough paying attention to the initial inverse response and shrink/swell physical phenomena by considering the inner dynamics (states) of the system instead of its outputs.

III. HARDWARE IMPLEMENTATION AND TESTING OF THE LQR CONTROLLER ON FPGA

The second objective of this work is to implement the LQR controller on a reconfigurable hardware platform resembled by a Xilinx Artix7 prototype board fitted with an XC7A200T FPGA chip. In order to use the Simulink environment to design the controller on hardware, Xilinx System Generator is used to generate the HDL design files of the controller from the Simulink models. The Xilinx SysGen add-on supplements the current Simulink library with a Xilinx blockset of arithmetic and DSP components [10], [11]. The new controller model developed using the Xilinx blockset can then be used to generate the HDL design files. Xilinx project navigator is used to check the HDL and schematic of the developed controller, simulate the generated HDL testbenches, physically map the design to the FPGA chip, and generate a programming file that can be used to program the FPGA. Finally, the target FPGA running the developed controller is connected to the drum boiler model running in Matlab via the JTAG port to facilitate hardware co-simulation of the full control system.

The Simulink model of the drum boiler turbine connected to the FPGA-based LQR controller is illustrated in Figures 3. The controller feeds the physical system model and observer, while the physical system model provides the measurement signals to the observer model. Gateway In and Out are used to convert the Simulink data types to the fixed-point data type. The FPGA-based controller is implemented for various fixed- and floating-point data types of various sizes including 16- and 32-bit fixed-point and single and double precision floating-point representations [11]. The closed-loop control system is tested for various controller implementations in the following setup: a hardware co-simulation is conducted for the controller running on the Artix7 FPGA connected to the drum boiler system model running in Matlab. The sampling time is set to 0.1 sec and the FPGA clock frequency is set to 50 MHz.

The LQR controller implementation results are illustrated in Table II and the system step response is shown in Figure 4. Reading the simulation results shows that the 16-bit fixed-point has a significant error due to the used data representation compared to the other three implementations which have quite similar response. On the other hand, reading the implementation results depicts an exponential increase in the FPGA chip utilization for the floating-point implementations. Therefore, based on the previous notes, it is recommended to use the 32-bit fixed-point implementation for the FPGA-based controller which gives an acceptable performance at low resource usage.

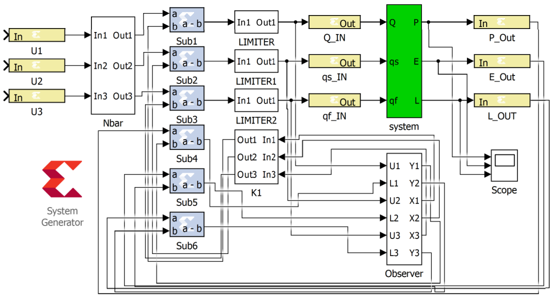

Figure 3. Drum boiler closed-loop system augmented with the Xilinx-based LQR controller

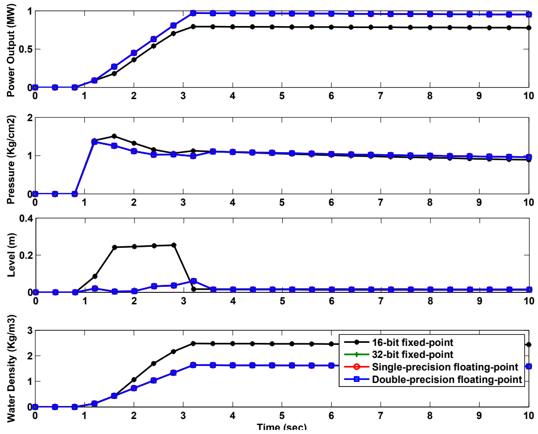

Figure 4. The drum boiler response for load demand step change for different data type implementations

Table II
RESOURCE UTILIZATION AND POWER CONSUMPTION RESULTS

	# of FFs (FPGA Utilization %)	# of LUTs (FPGA Utilization %)	Total power (W)
16-bit FP	588 (0.22%)	2917 (2.18%)	0.274
32-bit FP	774 (0.29%)	9024 (6.74%)	0.376
Single-precision	678 (0.25%)	34298 (25.63%)	0.501
Double-precision	971 (0.36%)	106166 (79.35%)	1.258
PID	971 (0.36%)	19244 (14.38%)	0.414

IV. CONCLUSIONS

In this work, we presented an optimal LQR control system for the drum-type boiler turbine and its implementation in reconfigurable hardware. A full state feedback controller was developed to ensure the boiler steady-state accuracy and set value tracking. A state estimator was presented that guarantees correct estimation of the state variables required for feedback. The developed LQR controller performance is compared to a classical PID controller of our design using the Matlab Simulink environment. Simulation results show that the LQR controller outperforms the PID controller in terms of the control characteristics and performance.

On the practical perspective, the proposed LQR controller was implemented on an Atrix-7 FPGA for various fixed- and floating-point data representations. The full closed-loop system was tested using hardware co-simulation and the implementation and simulation results were illustrated. The 32-bit fixed-point controller's realization is the best candidate for hardware platforms in terms of both the control system performance and the hardware resource utilization perspectives. As a future work, we plan to investigate hardware design of other control strategies such as the computational-intensive model-predictive control technique for drum-type boiler turbines.

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