

Optimal Linear Quadratic Gaussian Control Based Frequency Regulation with Communication Delays in Power Systems

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Published Date: -
13 November 2025,

Page No.: - 07-12

KEYWORDS

Load Frequency Control,
Linear Quadratic Gaussian
Control, Communication
Delay, Power Systems,
Optimal Control, Kalman
Filter, Multi-area Systems,
Frequency Regulation, Smart
Grid.

ABSTRACT

Frequency regulation in interconnected power systems remains a critical challenge due to increasing system complexity, renewable integration, and communication constraints. Traditional load frequency control (LFC) strategies often fail to maintain system stability under stochastic disturbances and time delays. This study presents an advanced control framework based on Optimal Linear Quadratic Gaussian (LQG) control for frequency regulation in multi-area power systems considering communication delays. The proposed approach integrates state estimation through Kalman filtering with optimal control synthesis to enhance robustness and dynamic performance. A delay-aware modeling framework is developed to capture network-induced latencies, and a modified LQG controller is designed accordingly. Comparative analysis with conventional PID, fuzzy, and sliding mode controllers demonstrates superior performance in terms of frequency deviation minimization, settling time, and robustness against disturbances. The results indicate that the proposed methodology effectively mitigates the adverse effects of communication delays while ensuring optimal system performance. The study contributes to modern power system control by bridging optimal control theory with practical network constraints.

1. Introduction

1.1 Background and Problem Statement

Load frequency control (LFC) is essential for maintaining system frequency within acceptable limits in multi-area interconnected power systems. Frequency deviations arise due to imbalances between generation and load demand, and these deviations can destabilize system operation if not properly controlled. Traditional controllers such as PID and fuzzy logic-based approaches have been widely applied but often struggle under uncertainties and communication delays.

The integration of communication networks into power systems introduces latency, packet loss, and stochastic disturbances, which significantly affect control performance. These delays degrade system stability and can lead to oscillatory or unstable behavior if not adequately addressed. Therefore, designing a robust control framework that accounts for such delays is

imperative.

1.2 Research Relevance and Objectives

This research aims to develop an optimal LQG-based frequency regulation framework that explicitly considers communication delays. The objectives include:

- Developing a mathematical model of multi-area power systems with communication delays
- Designing an LQG controller incorporating delay compensation
- Evaluating system performance under various disturbances
- Comparing the proposed method with existing control strategies

1.3 Scope and Significance

The study focuses on interconnected multi-area power systems operating under network-induced delays. It contributes to enhancing system reliability and efficiency in modern smart grids, where communication infrastructure plays a critical role.

2. Literature Review

The literature on load frequency control reveals a wide range of control strategies, including classical, intelligent, and robust control methods.

Fuzzy and PID-based controllers have been extensively used due to their simplicity and ease of implementation. For instance, hybrid fuzzy PID controllers have demonstrated improved performance under nonlinear conditions (Sahu et al., 2014). Similarly, decentralized PID controllers have been applied to multi-area systems to handle disturbances (Saxena and Hote, 2016). However, these approaches often lack robustness under varying system dynamics.

Metaheuristic optimization techniques have also been employed for controller tuning. Firefly algorithm-based PID controllers (Jagatheesan et al., 2017) and ant lion optimizer-based controllers (Raju et al., 2016) show improved convergence but are computationally intensive.

Sliding mode control (SMC) techniques provide robustness against uncertainties. Various studies have explored higher-order and adaptive SMC for LFC (Dev and Sarkar, 2019). Decentralized sliding mode approaches have also been proposed for multi-area systems (Mi et al., 2013). Notably, the decentralized SMC framework provides robustness but suffers from chattering issues and implementation complexity.

Optimal control approaches such as Linear Quadratic Gaussian control have gained attention due to their theoretical optimality. LQG-based designs combine state estimation and control optimization (Mohamed et al., 2015). Extensions incorporating Kalman filters have improved system performance in restructured power systems (Shahalami and Farsi, 2018). However, most existing LQG-based studies neglect communication delays.

Recent works have focused on delay-aware control strategies using H-infinity methods (Pradhan and Das, 2020) and event-triggered schemes (Lv et al., 2020). Although effective, these methods often involve complex

formulations.

Research Gap

Despite significant advancements, the integration of optimal LQG control with explicit communication delay modeling remains underexplored. Additionally, existing approaches either focus on robustness or optimality, but not both simultaneously.

3. Methodology

3.1 System Modeling of Multi-Area Power Systems

The interconnected power system is modeled using linearized state-space equations:

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) + Dw(t) \\ &= Ax(t) + Bu(t) + Dw(t)x'(t) \\ &= Ax(t) + Bu(t) + Dw(t)y(t) \\ &= Cx(t)y(t) = Cx(t)y(t) = Cx(t) \end{aligned}$$

where $x(t)$ represents system states, $u(t)$ is the control input, and $w(t)$ denotes disturbances.

Each area includes governor, turbine, and generator dynamics. Tie-line power exchange is incorporated to model inter-area interactions.

3.2 Communication Delay Modeling

Communication delays are modeled as time-lagged signals:

$$u(t - \tau)$$

where τ represents delay. This delay is introduced into the state-space model, resulting in:

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t - \tau) \\ &= Ax(t) + Bu(t - \tau)x'(t) \\ &= Ax(t) + Bu(t - \tau) \end{aligned}$$

This formulation captures realistic network-induced delays in smart grids.

3.3 LQG Control Framework

The LQG controller combines Linear Quadratic Regulator (LQR) and Kalman Filter.

3.3.1 LQR Design

The control objective minimizes the cost function:

$$\begin{aligned} J &= \int_0^\infty (x^T Q x + u^T R u) dt \\ &= \lim_{t \rightarrow \infty} (x^T Q x + u^T R u) dt \\ &= \int_0^\infty (x^T Q x + u^T R u) dt \end{aligned}$$

The optimal control law is:

$$u(t) = -Kx(t)u(t) = -Kx(t)u(t) = -Kx(t)$$

where KKK is the gain matrix obtained from the Riccati equation.

3.3.2 State Estimation Using Kalman Filter

Since all states are not measurable, a Kalman filter is used:

$$\begin{aligned} \hat{x}(t) &= A\hat{x}(t) + Bu(t) + L(y(t) \\ &\quad - C\hat{x}(t)) \\ &= A\hat{x}(t) + Bu(t) + L(y(t) \\ &\quad - C\hat{x}(t)) \\ &= A\hat{x}(t) + Bu(t) + L(y(t) \\ &\quad - C\hat{x}(t)) \end{aligned}$$

where LLL is the observer gain.

3.4 Delay Compensation Strategy

To address delays, a predictive control approach is integrated:

- Future states are estimated based on system dynamics
- Control signals are adjusted to compensate for delay effects

This ensures stability despite delayed feedback.

3.5 Algorithm Implementation

The implementation involves:

1. System parameter identification
2. State-space model formulation
3. LQR gain computation
4. Kalman filter design

5. Integration of delay compensation

6. Simulation under disturbances

3.6 Comparative Framework

The proposed method is compared with:

- PID controllers
- Fuzzy logic controllers
- Sliding mode controllers

Performance metrics include:

- Frequency deviation
- Settling time
- Overshoot
- Robustness

4. Results / Findings

The simulation results demonstrate that the proposed LQG-based controller significantly improves frequency regulation performance under communication delays. The system exhibits reduced frequency deviations compared to conventional PID and fuzzy controllers. The settling time is notably shorter, indicating faster stabilization.

Under varying load disturbances, the LQG controller maintains system stability with minimal oscillations. The integration of Kalman filtering enhances state estimation accuracy, which directly improves control performance. Compared to sliding mode control approaches (Mi et al., 2013), the proposed method eliminates chattering while maintaining robustness.

Furthermore, delay compensation effectively mitigates the impact of communication latency. Even with increased delay values, the system remains stable, demonstrating the robustness of the proposed framework. The results confirm that optimal control combined with delay-aware modeling outperforms traditional methods in modern networked power systems.

5. Discussion

The findings highlight the effectiveness of LQG control in addressing frequency regulation challenges in interconnected power systems. The combination of optimal control and state estimation provides a balanced approach to handling uncertainties and disturbances.

Compared to conventional PID and fuzzy controllers, the proposed method offers superior performance due to its optimization-based design. While sliding mode control provides robustness (Mi et al., 2013), it suffers from chattering and implementation complexity. The LQG framework avoids these issues while maintaining comparable robustness.

The inclusion of communication delay modeling is a significant advancement. Many existing studies neglect delays, leading to unrealistic assumptions. By incorporating delay compensation, the proposed method aligns more closely with real-world smart grid environments.

However, the approach has certain limitations. The reliance on accurate system modeling may affect performance if model uncertainties are significant. Additionally, computational complexity increases due to Kalman filtering and Riccati equation solutions.

Despite these limitations, the proposed method provides a scalable and efficient solution for modern power systems. It can be extended to incorporate renewable energy sources and distributed generation systems.

6. Conclusion

This study presents a novel LQG-based framework for load frequency control in multi-area power systems with communication delays. By integrating optimal control with state estimation and delay compensation, the proposed method achieves superior performance in frequency regulation.

The results demonstrate improved stability, reduced frequency deviations, and enhanced robustness compared to traditional control methods. The study bridges the gap between theoretical optimal control and practical implementation in networked power systems.

Future research can focus on adaptive LQG designs, integration with renewable energy systems, and real-time implementation using advanced communication technologies.

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