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Adaptive Fuzzy Load Frequency Control for Multi-Area Interconnected Power Systems

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Introduction

The rising demand for electricity and the integration of renewable energy sources have increased the complexity and uncertainty in multi-area interconnected power systems, posing significant challenges to load frequency control (LFC). As a key automatic generation control (AGC) strategy, LFC aims to stabilize tie-line power and frequency fluctuations. Existing approaches include sliding mode control, model predictive control, fractional-order methods, and T-S fuzzy logic control.

Research Questions

Traditional linear control methods often fail to handle nonlinearities, uncertainties, and external disturbances in practical systems. To address these issues, this paper proposes a memory-based event-triggered adaptive fuzzy LFC approach. By integrating interval type-2 Takagi-Sugeno (IT2 T-S) fuzzy modeling, sliding mode observer design, and integral adaptive sliding mode control, the method enhances robustness and reduces communication load.

Methodologies

To describe the nonlinear dynamics of each control area, an interval type-2 Takagi-Sugeno (IT2 T-S) fuzzy model is adopted. Accordingly, the *p*th area of the LFC system is modeled as

$$\begin{cases} \dot{x}_p(t) = \sum_{i=1}^{r} h_p^i(\theta_p)\left\{A_p^i x_p(t) + B_p u_p(t) + E_p \omega_p(t)\right\} \\ y_p(t) = \sum_{i=1}^{r} h_p^i(\theta_p) C_p^i x_p(t), \end{cases} \tag{1}$$

where $h_p^i(\theta_p) \in [0,1]$ is the normalized membership function satisfying $\sum_{i=1}^{r} h_p^i = 1$, and A_p^i, C_p^i are given system matrices. $\theta_p(t)$ is the fuzzy scheduling variable. IT2 fuzzy sets improve robustness to uncertainty.

Then, the event generator function $J(\cdot)$ is constructed as

$$\begin{aligned} J(y_p, \lambda_p) = v_p \Big\{ &\varepsilon_p y_p^T\left(t - d_k^n(t)\right)\Phi_p y_p\left(t - d_k^n(t)\right) - \\ &\sum_{l=0}^{s-1} \sigma_{pl} e_{(k-l),p}^T(t)\Phi_p e_{(k-l),p}(t)\Big\} + \lambda_p\left(t - d_k^n(t)\right) \geqslant 0 \end{aligned} \tag{2}$$

$$\begin{aligned} \dot{\lambda}_p(t) = &\varepsilon_p y_p^T\left(t - d_k^n(t)\right)\Phi_p y_p\left(t - d_k^n(t)\right) - \sum_{l=0}^{s-1} \sigma_{pl} \\ &e_{(k-l),p}^T(t)\Phi_p e_{(k-l),p}(t) - \mu_p \lambda_p\left(t - d_k^n(t)\right) \end{aligned} \tag{3}$$

where Φ_p is a weighting matrix to be designed, $\varepsilon_p \in [0,1]$ and $v_p > 0$ are known event-triggered parameters, $\sigma_{pl} \in [0,1] (l = 0,1,\ldots,s-1)$ are given weighting parameters and

$$\sum_{l=0}^{s-1} \sigma_{pl} = 1,$$

$$e_{(k-l),p}(t) = y_p\left(t_{k-l}^n T\right) - y_p\left(t - d_k^n(t)\right),$$

$$e_{k,p}(t) = y_p\left(t_k^n T\right) - y_p\left(t - d_k^n(t)\right).$$

$d_k^n(t)$ denotes the internal delay between current and previous communication times.

Finally, the system trajectories can be driven onto the sliding surface by the following controller

$$u_p(t) = K_{p1}\hat{x}_p(t) - \left(\rho_p + u_{ap}(t) + \kappa_p(t)\right) \times \mathrm{sat}\left(s_p(t)\right)$$

$$\mathrm{sat}\left(s_p(t)\right) = \begin{cases} \dfrac{s_p(t)}{\delta_p}, & \|s_p(t)\| < \delta_p, \\ \dfrac{s_p(t)}{\|s_p(t)\|}, & \|s_p(t)\| \geqslant \delta_p, \end{cases} \tag{4}$$

with

$$s_p(t) = B_p^T X_p\left[\hat{x}_p(t) - B_p K_p \int_0^t \hat{x}_p(\alpha) d\alpha\right],$$

$$u_{ap}(t) = \sum_{j=1}^{r} h_p^j \eta_p^j(t) + \left\|\left(B_p^T X_p B_p\right)^{-1}\right\| \left\|B_p^T X_p\right\| \times \left\|\sum_{j=1}^{r} h_p^j\left(A_p^j - L_p C_p^j\right)\hat{x}_p(t)\right\|,$$

$$\kappa_p(t) = \left\|\left(B_p^T X_p B_p\right)^{-1}\right\| \left\|B_p^T X_p\right\| \left\|L_p y_p\left(t_k^n T\right)\right\|,$$

$$\dot{\hat{x}}_p(t) = \sum_{i=1}^{r} h_p^i\left\{A_p^i \hat{x}_p(t) + B_p u_p(t) + L_p\left[y_p\left(t_k^n T\right) - C_p^i \hat{x}_p(t)\right]\right\}$$

and the adaptive law is

$$\dot{\eta}_p^j(t) = \begin{cases} 0, \text{ if } \eta_p^j(t) \le 0, \text{ or if } \eta_p^j(t) \ge 1 \\ \phi_p^j(t), \text{ otherwise} \end{cases} \quad (5)$$

where $\phi_p^j(t) \triangleq q_j h_p^j\left(\theta_p(t)\right)\eta_p^j(t)\left\|s_p(t)\right\|$, are positive scalars with $0 \le \eta_p^j(\vartheta) \le 1 (j = 1, 2, \ldots, r)$, ϑ is the initial instant, $\rho_p > 0$ and $\delta_p > 0$ are known constants, K_{p1} is a control parameter.

Figures

We present an example of a three-area interconnected power system.

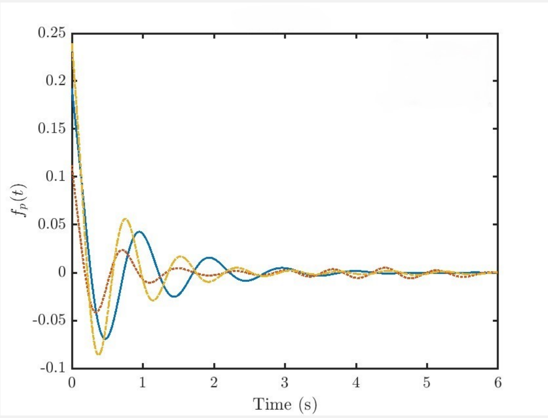

Figure 1. Three-area frequency deviation

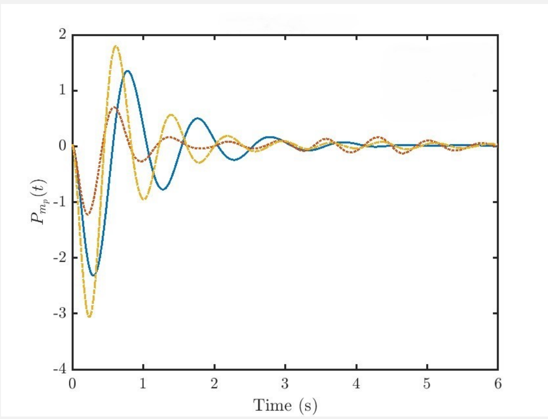

Figure 2. Three-area generator power deviation

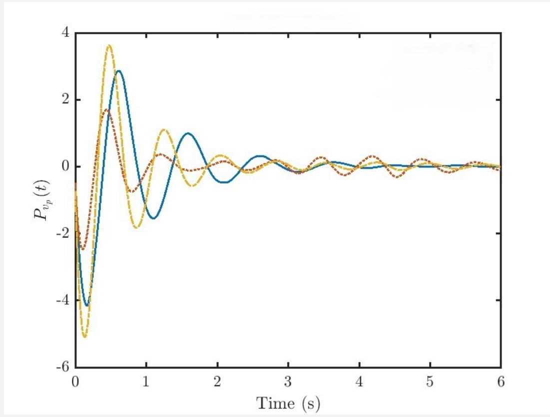

Figure 3. Three-area governor valve position deviation

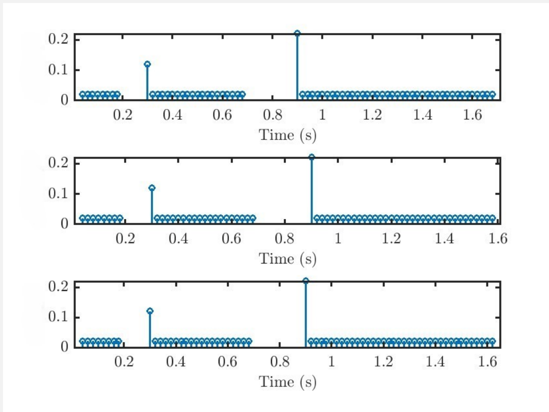

Figure 4. Response of the event-triggered mechanism in the three-area system

Conclusion

A memory-based event-triggered adaptive fuzzy LFC strategy is proposed to address system nonlinearities, uncertainties, and communication constraints. By integrating IT2 fuzzy modeling, dynamic triggering, and observer-based adaptive sliding mode control, the method enhances robustness and reduces communication load.