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Delay-Dependent Stability Analysis of Load Frequency Control for Power System With EV Aggregator

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In this paper, the stability of load frequency control (LFC) for delayed power systems with an electric vehicle (EV) aggregator is studied based on Lyapunov theory and linear matrix inequalities (LMIs). Through mechanism analysis, the LFC of power systems with an EV aggregator based on a proportional–integral–differential (PID) controller is modeled. By constructing a delay interval information correlation functional and estimating its derivative using Wirtinger inequality and extended reciprocally convex matrix inequality, a new stability analysis criterion is proposed. Finally, in order to verify its advantage, the proposed method is used to discuss the influence of EV aggregator gains and PID controller gains on the delay margins for LFC of power systems with EV aggregator participation in frequency regulation.

Keywords: power system, load frequency control, electric vehicles, stability analysis, time delay

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1 INTRODUCTION

Under the guidance of sustainable development concept, the generation of renewable energy sources (RESs) such as wind power, hydropower, and photovoltaic power has developed rapidly in recent years, and part of traditional thermal power generation will be gradually replaced (Zhou et al., 2018). However, the grid connection of these RESs also brings some problems, especially the wind power generation with great intermittency and volatility (Jin et al., 2021b; Shi et al., 2021). These problems aggravate the imbalance between generation and load consumption in the power systems, resulting in obvious frequency fluctuation. Therefore, load frequency control (LFC) is widely used in power systems (Jin et al., 2019; Shangguan et al., 2021b). The frequency deviation caused by an intermittent energy grid connection is difficult to be eliminated by traditional generator sets. With the grid connection of controllable loads such as electric vehicles (EVs) and the rapid response characteristics of batteries, some studies paid attention to vehicle-to-grid technology, which provides frequency regulation services with a large number of converging EVs (Peng et al., 2017; Jia et al., 2018; Pinto et al., 2021; Teng et al., 2021).

In traditional power systems, the time delay phenomenon of the LFC system is not obvious. However, modern power systems tend to use flexible and open communication networks for information exchange (ShangGuan et al., 2021). For power systems with EVs and intermittent wind power connected, the EV aggregator needs to transmit the control command to the EVs through open communication networks (Ko and Sung, 2019; Li et al., 2019). The use of such networks will inevitably bring unreliable factors, such as time delay, packet loss, and potential failure, which may lead to instability of LFC for power systems (Jin et al., 2021a; Shangguan

TABLE 1 | Parameter of the LFC model.

Parameter	Value	Description
M	10	Inertia constant
D	1	Generator damping coefficient
T_g	0.1	Time constant of the governor
T_{ch}	0.3	Time constant of the turbine
T_{WTG}	1.5	Time constant of the wind turbine generator
T_{EV}	0.1	Time constant of the battery
R	0.05	Speed regulation
β	21	Frequency bias factor

et al., 2021a). Therefore, it is very important to analyze the influence of time delays on the LFC of power systems with an EV aggregator. In addition, in order to ensure the stability of power system LFC, it is necessary to calculate the delay margins and determine all parameters of the proportional–integral–differential (PID) controller (Naveed et al., 2019b; Tek et al., 2020).

In recent years, EVs have been widely used in power systems, and there are also some studies on the influence of time delays and EV aggregator on LFC stability. The Rekasius substitution method is used to determine the stability delay margins of LFC with constant communication delays for an EV aggregator (Naveed et al., 2019a). Then, Naveed et al. presented a graphical method to describe the trajectory of the stable boundary and studied the influence of EV aggregators with communication delays on the stability regions and stability delay margins of the LFC system (Naveed et al., 2021). Based on Lyapunov theory and linear matrix inequalities (LMIs), stability criteria for time-varying delays using the Wirtinger-based improved integral inequality are proposed to calculate the delay margins for LFC with EVs, and the relationship between the gains and the delay margins of the PI controller is given in detail (Ko and Sung, 2018). Two stability criteria are derived, respectively, using Bessel–Legendre inequality and model reconstruction technique, and the interregional delay interaction and the effect of EV gain on the delay margins are discussed (Zhou et al., 2020). Khalil et al. proposed a microgrid model of photovoltaic power generation and EVs considering communication delay, and the maximum allowable delay bound for the stable operation of microgrids is calculated by solving the LMIs (Khalil et al., 2017). Dong et al. characterized the asymptotic stability of EV aggregation delays by using the delay distortion matrix structure of infinite operator dimension reduction and proved that convergence delay affects frequency stability in the form of low-frequency oscillation through three unstable modes (Dong et al., 2020). Although there have been some studies on the stability of delayed LFC systems with an EV aggregator, there are few studies on LFC of renewable energy power systems with an EV aggregator. Also, how to obtain more accurate delay margins remains a challenge.

In this paper, the stability of LFC for power systems with EV aggregator participation in frequency regulation is considered, and the influence of EV aggregator and controller gains on the delay margins is studied. Firstly, based on the PID controller, the LFC of power systems with an EV aggregator is modeled. Then, a new delay stability criterion using Wirtinger inequality and extended reciprocally convex matrix inequalities is proposed. Finally, according to the proposed stability criterion, the delay margins of LFC for power systems with an EV aggregator are obtained, and case studies are performed to show the advantage of the proposed method.

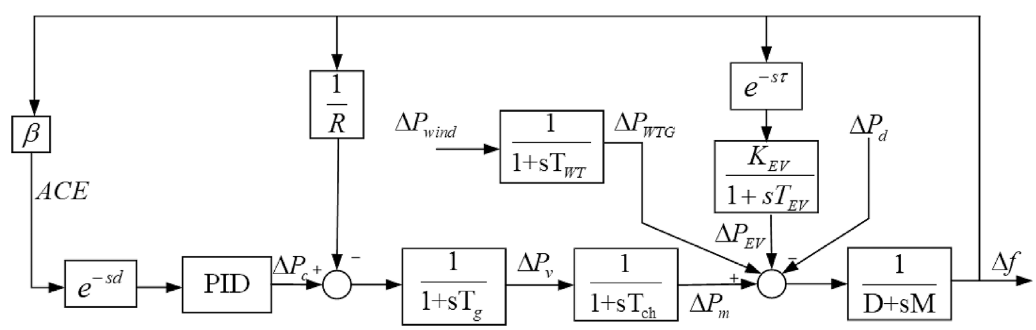

FIGURE 1 | Frequency regulation scheme of the power system with an EV aggregator.

2 MODEL OF LFC FOR POWER SYSTEM WITH EV AGGREGATOR

The block diagram of the LFC for power systems with an EV aggregator is given in **Figure 1**, and the controller is the PID controller. $e^{-s\tau}$ and e^{-sd} denote the time delay of the frequency regulation circuit involved in the EV aggregator and the secondary frequency regulation circuit, respectively; K_{EV} is the gain of the EV aggregator; Δf, ΔP_{EV}, ΔP_{WTG}, ΔP_m, ΔP_v, and ΔP_d are the deviation of frequency, EV aggregator power output, wind turbine generator (WTG) power output, mechanical output of the generator, valve position, and load disturbance, respectively. Definitions of other related symbols in the figure are shown in **Table 1**.

Select the following state variables, output variables, disturbance, and control input:

$$\bar{x}(t) = \left[\, \Delta f \;\; \Delta P_{EV} \;\; \Delta P_{WTG} \;\; \Delta P_m \;\; \Delta P_v \,\right]^T, \tag{1}$$

$$\bar{y}(t) = ACE(t) = \beta \Delta f, \tag{2}$$

$$w(t) = \left[\, \Delta P_d \;\; \Delta P_{\text{wind}} \,\right]^T, \tag{3}$$

$$u(t - \tau(t)) = \Delta P_c(t). \tag{4}$$

Then, the following system state space model can be obtained:

$$\begin{cases} \dot{\bar{x}}(t) = \bar{A}_1 \bar{x}(t) + \bar{A}_2 \bar{x}(t - \tau(t)) + \bar{B}u(t - d(t)) + \bar{F}\omega(t), \\ \bar{y}(t) = \bar{C}\bar{x}(t), \end{cases} \tag{5}$$

where

$$\bar{A}_1 = \begin{bmatrix} -\frac{D}{M} & \frac{1}{M} & \frac{1}{M} & \frac{1}{M} & 0 \\ 0 & -\frac{1}{T_{EV}} & 0 & 0 & 0 \\ 0 & 0 & -\frac{1}{T_{WT}} & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{T_{ch}} & \frac{1}{T_{ch}} \\ -\frac{1}{RT_g} & 0 & 0 & 0 & -\frac{1}{T_g} \end{bmatrix}, \bar{A}_2 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ \frac{K_{EV}}{T_{EV}} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix},$$

$$\bar{B} = \begin{bmatrix} 0 & 0 & 0 & 0 & \frac{1}{T_g} \end{bmatrix}^T \bar{F} = \begin{bmatrix} -\frac{1}{M} & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{T_{WT}} & 0 & 0 \end{bmatrix}^T$$

$$\bar{C} = \left[\, \beta \;\; 0 \;\; 0 \;\; 0 \;\; 0 \,\right].$$

The controller is designed as

$$u(t) = -K_{\text{p}} ACE(t) - K_{\text{i}} \int ACE(t)\text{d}t - K_{\text{d}} \frac{\text{d}ACE(t)}{\text{d}t}. \tag{6}$$

Define the new vectors $x(t) = [\bar{x}^T(t) \quad \int \bar{y}^T(t)dt]^T$, $y(t) = [\bar{y}^T(t) \quad \int \bar{y}^T(t)dt \quad \frac{d}{dt}\bar{y}^T(t)]^T$ and $K = [K_p \;\; K_i \;\; K_d]$. The system (**Eq. 5**) is rewritten as

$$\begin{cases} \dot{x}(t) = A_1 x(t) + A_2 x(t - \tau(t)) + Bu(t - d(t)) + Fw(t), \\ y(t) = Cx(t) + Dw(t), \\ u(t) = -Ky(t), \end{cases} \tag{7}$$

where $A_1 = \begin{bmatrix} \bar{A}_1 & 0 \\ \bar{C} & 0 \end{bmatrix}$, $A_2 = \begin{bmatrix} \bar{A}_2 & 0 \\ 0 & 0 \end{bmatrix}$, $B = \begin{bmatrix} \bar{B} \\ 0 \end{bmatrix}$, $F = \begin{bmatrix} \bar{F} \\ 0 \end{bmatrix}$, $C = \begin{bmatrix} \bar{C} & 0 \\ 0 & 1 \\ \bar{C}\bar{A}_1 & 0 \end{bmatrix}$, and $D = \left[\, 0 \;\; 0 \;\; CF \,\right]^T$.

In order to simplify the analysis, it is assumed that the delay $\tau(t)$ of the frequency regulation circuit involved in the EV aggregator is consistent with the delay $d(t)$ of the secondary frequency regulation circuit. Then, the closed-loop state space equation of LFC for the delayed power system with an EV aggregator can be obtained as follows:

$$\dot{x}(t) = Ax(t) + A_d x(t - d(t)) + F_w w(t), \tag{8}$$

where $A = A_1$, $A_d = A_2 - BKC$, and $F_w = F - BKD$.

3 DELAY-DEPENDENT STABILITY ANALYSIS

When discussing the internal stability of the power system, the influence of external disturbance can be ignored. The model of LFC for the delayed power system with an EV aggregator is obtained as follows:

$$\dot{x}(t) = Ax(t) + A_d x(t - d(t)), \tag{9}$$

where $h_1 \le d(t) \le h_2$ and $\forall t > t_0$.

The following stability criterion for system (**Eq. 9**) is derived by using Wirtinger inequality (Seuret and Gouaisbaut, 2013) and extended reciprocally convex matrix inequality (Zhang et al., 2017).

Theorem 1. For given scalars $\alpha > 0$, $h_2 > h_1 > 0$, the LFC of the closed-loop power system with an EV aggregator (Eq. 9) is exponentially stable, if there exist matrices $P > 0$, $Q_i > 0$, $Z > 0$, $R > 0$, $i = 1, 2$, and any matrix S_1 or S_2 with appropriate dimension, satisfying

$$\Phi_1 = \begin{bmatrix} \Psi_{1,[h_1]} - \Psi_2 - \Psi_4 & E_2^T S_2 \\ * & -\tilde{R} \end{bmatrix} < 0, \tag{10}$$

$$\Phi_2 = \begin{bmatrix} \Psi_{1,[h_2]} - \Psi_2 - \Psi_5 & E_3^T S_1 \\ * & -\tilde{R} \end{bmatrix} < 0, \tag{11}$$

where

$$\Psi_{1,[d(t)]} = \Pi_1^T P \Pi_2 + \Pi_2^T P \Pi_1 + e_1^T Q_1 e_1 + e_2^T (Q_2 - Q_1) e_2 - e_4^T Q_2 e_4 + e_s^T \left[h_1^2 Z + h_{12}^2 R \right] e_s$$

$$\Psi_2 = E_1^T [\text{diag}\{Z, 3Z\} e^{-\alpha h_1}] E_1$$

$$\Psi_4 = \begin{bmatrix} E_2 \\ E_3 \end{bmatrix}^T \begin{bmatrix} 2\tilde{R} & S_1 \\ * & \tilde{R} \end{bmatrix} \begin{bmatrix} E_2 \\ E_3 \end{bmatrix}$$

$$\Psi_5 = \begin{bmatrix} E_2 \\ E_3 \end{bmatrix}^T \begin{bmatrix} \tilde{R} & S_2 \\ * & 2\tilde{R} \end{bmatrix} \begin{bmatrix} E_2 \\ E_3 \end{bmatrix}$$

$$\Pi_1 = \text{col}\{e_1, h_1 e_5, (d(t) - h_1) e_6 + (h_2 - d(t)) e_7\}$$

$$\Pi_2 = \text{col}\{e_s, e_1 - e_2, e_2 - e_4\}$$

TABLE 2 | Delay margins for different methods.

K_p	Methods	K_i				
		0.2	0.3	0.4	0.6	1
0.2	Theorem 1 (Jiang et al., 2012)	3.2831	0.9930	0.7983	0.5286	0.2301
	Theorem 1	5.2094	3.9441	3.0267	1.8634	0.7617
0.3	Theorem 1 (Jiang et al., 2012)	3.4021	0.9833	0.7922	0.5469	0.2600
	Theorem 1	3.6493	3.1177	2.6172	1.7828	0.7617
0.4	Theorem 1 (Jiang et al., 2012)	1.1328	0.8411	0.7214	0.5280	0.2753
	Theorem 1	2.4823	2.2650	2.0142	1.4911	0.7074
0.5	Theorem 1 (Jiang et al., 2012)	0.7916	0.7050	0.6250	0.4840	0.2765
	Theorem 1	1.6492	1.5436	1.4124	1.1115	0.6177
0.6	Theorem 1 (Jiang et al., 2012)	0.6421	0.5859	0.5316	0.4315	0.2679
	Theorem 1	1.1084	1.0474	0.9753	0.8154	0.5249
1	Theorem 1 (Jiang et al., 2012)	0.3253	0.3094	0.2930	0.2600	0.1953
	Theorem 1	0.4144	0.4004	0.3851	0.3540	0.2875

$e_i = [0_{n\times(i-1)n}, I, 0_{n\times(7-i)n}], i = 1, 2, \ldots, 7$
$E_i = \mathrm{col}\{e_i - e_{i+1}, e_i + e_{i+1} - 2e_{i+4}\}, i = 1, 2, 3$
$\tilde{R} = \mathrm{diag}\{R, 3R\}e^{-\alpha h_2} h_{12} = h_2 - h_1$, $e_s = Ae_1 + A_d e_3$.

Proof: Construct the following Lyapunov–Krasovskii functional:

$$\begin{aligned} V(t) = {} & \eta^T(t)P\eta(t) + h_1\int_{-h}^{0}\int_{t+\theta}^{t} e^{\alpha(s-t)}\dot{x}^T(s)Z\dot{x}(s)dsd\theta \\ & + h_{12}\int_{-h_2}^{-h_1}\int_{t+\theta}^{t} e^{\alpha(s-t)}\dot{x}^T(s)R\dot{x}(s)dsd\theta \\ & + \int_{t-h_1}^{t} e^{\alpha(s-t)}x^T(s)Q_1x(s)ds \\ & + \int_{t-h_2}^{t-h} e^{\alpha(s-t)}x^T(s)Q_2x(s)ds, \end{aligned} \tag{12}$$

where $\eta(t) = \mathrm{col}\left\{x(t), \int_{t-h_1}^{t} x(s)ds, \int_{t-h_2}^{t-h_1} x(s)ds\right\}$.

Calculating the derivative of $V(t)$, we get

$$\begin{aligned} \dot{V}(t) + \alpha V(t) \le {} & \eta^T(t)P\dot{\eta}(t) + \dot{\eta}^T(t)P\eta(t) + \alpha\eta^T(t)P\eta(t) \\ & + \dot{x}^T(t)\left(h_1^2 Z + h_{12}^2 R\right)\dot{x}(t) \\ & - h_1\int_{t-h}^{t} e^{-\alpha h_1}\dot{x}^T(s)Z\dot{x}(s)ds - h_{12}\int_{t-h_2}^{t-h} e^{-\alpha h_2}\dot{x}^T(s)R\dot{x}(s)ds \\ & + x^T(t)Q_1x(t) \\ & + e^{-\alpha h_1}x^T(t-h_1)(Q_2 - Q_1)x(t-h_1) \\ & - e^{-\alpha h_2}x^T(t-h_2)Q_2x(t-h_2) \\ = {} & \zeta^T(t)\psi_{1,[d(t)]}\zeta(t) - h_1\int_{t-h}^{t} e^{-\alpha h_1}\dot{x}^T(s)Z\dot{x}(s)ds \\ & - h_{12}\int_{t-h_2}^{t-h} e^{-\alpha h_2}\dot{x}^T(s)R\dot{x}(s)ds, \end{aligned} \tag{13}$$

where

$$\zeta(t) = \mathrm{col}\{x(t), x(t-h_1), x(t-d(t)), x(t-h_2), \int_{t-h_1}^{t}\frac{x(s)}{h_1}ds, \int_{t-d(t)}^{t-h_1}\frac{x(s)}{d(t)-h_1}ds, \int_{t-h_2}^{t-d(t)}\frac{x(s)}{h_2-d(t)}ds\}.$$

Based on Wirtinger inequality, we have

$$h_1\int_{t-h_1}^{t} e^{-\alpha h}\dot{x}^T(s)Z\dot{x}(s)ds \ge \varepsilon_1^T(t)\begin{bmatrix} e^{-\alpha h_1}Z & 0 \\ 0 & 3e^{-\alpha h_1}Z \end{bmatrix}$$
$$\varepsilon_1(t) = \zeta^T(t)\psi_2\zeta(t), \tag{14}$$

$$\begin{aligned} h_{12}\int_{t-h_2}^{t-h} e^{-\alpha h_2}\dot{x}^T(s)R\dot{x}(s)ds = {} & h_{12}\left(\int_{t-d(t)}^{t-h_1} e^{-\alpha h_2}\dot{x}^T(s)R\dot{x}(s)ds\right. \\ & \left. + \int_{t-h_2}^{t-d(t)} e^{-\alpha h_2}\dot{x}^T(s)R\dot{x}(s)ds\right) \\ \ge {} & \frac{h_{12}}{d(t)-h_1}\varepsilon_2^T(t)\tilde{R}\varepsilon_2(t) + \frac{h_{12}}{h_2-d(t)}\varepsilon_3^T(t)\tilde{R}\varepsilon_3(t), \end{aligned} \tag{15}$$

where

$$\varepsilon_1(t) = \begin{bmatrix} x(t) - x(t-h_1) \\ x(t) + x(t-h_1) - 2\int_{t-h_1}^{t}\frac{x(s)}{h_1}ds \end{bmatrix},$$

$$\varepsilon_2(t) = \begin{bmatrix} x(t-h_1) - x(t-d(t)) \\ x(t-h_1) + x(t-d(t)) - 2\int_{t-d(t)}^{t-h_1}\frac{x(s)}{d(t)-h_1}ds \end{bmatrix},$$

$$\varepsilon_3(t) = \begin{bmatrix} x(t-d(t)) - x(t-h_2) \\ x(t-d(t)) + x(t-h_2) - 2\int_{t-h_2}^{t-d(t)}\frac{x(s)}{h_2-d(t)}ds \end{bmatrix}.$$

Using extended reciprocally convex matrix inequality to estimate **Eq. 15** yields

$$\begin{aligned} \frac{h_{12}\varepsilon_2^T(t)\tilde{R}\varepsilon_2(t)}{d(t)-h_1} + \frac{h_{12}\varepsilon_3^T(t)\tilde{R}\varepsilon_3(t)}{h_1-d(t)} \ge {} & \varepsilon_2^T(t)\tilde{R}\varepsilon_2(t) + \varepsilon_3^T(t)\tilde{R}\varepsilon_3(t) \\ & + \frac{h_2-d(t)}{h_{12}}\begin{bmatrix} \varepsilon_2(t) \\ \varepsilon_3(t) \end{bmatrix}^T\begin{bmatrix} \tilde{R} - S_2\tilde{R}^{-1}S_2^T & S_1 \\ * & 0 \end{bmatrix}\begin{bmatrix} \varepsilon_2(t) \\ \varepsilon_3(t) \end{bmatrix} \\ & + \frac{d(t)-h_1}{h_{12}}\begin{bmatrix} \varepsilon_2(t) \\ \varepsilon_3(t) \end{bmatrix}^T\begin{bmatrix} 0 & S_2 \\ * & \tilde{R} - S_1^T\tilde{R}^{-1}S_1 \end{bmatrix}\begin{bmatrix} \varepsilon_2(t) \\ \varepsilon_3(t) \end{bmatrix} \\ = {} & \zeta^T(t)\psi_{3,[d(t)]}\zeta(t), \end{aligned} \tag{16}$$

TABLE 3 | Delay margins for K_d = 0.

$K_p - K_i$	0.05	0.1	0.15	0.2	0.3	0.4
0.1	15.8185	11.2262	8.2007	6.2970	4.1388	2.9816
0.2	7.3389	6.7004	5.9119	5.1477	3.9001	2.9550
0.3	4.1736	4.0625	3.8623	3.6151	3.0890	2.5940
0.4	2.6349	2.5977	2.5397	2.4573	2.2430	1.9946
0.6	1.1597	1.1414	1.1194	1.0938	1.0333	0.9625

TABLE 4 | Delay margins for K_d = 0.2.

$K_p - K_i$	0.05	0.1	0.15	0.2	0.3	0.4
0.1	1.5466	1.5955	1.6443	1.6943	1.7902	1.8616
0.2	1.4648	1.5125	1.5607	1.6101	1.7096	1.7920
0.3	1.3391	1.3818	1.4258	1.4722	1.5674	1.6571
0.4	1.1835	1.2177	1.2537	1.2915	1.3721	1.4563
0.6	0.8734	0.8887	0.9039	0.9198	0.9540	0.9900

TABLE 5 | Delay margins for K_d = 0.5.

$K_p - K_i$	0.05	0.1	0.15	0.2	0.3	0.4
0.1	0.4761	0.4785	0.4810	0.4834	0.4889	0.4944
0.2	0.4663	0.4688	0.4712	0.4736	0.4791	0.4840
0.3	0.4559	0.4578	0.4602	0.4626	0.4675	0.4730
0.4	0.4443	0.4462	0.4486	0.4510	0.4553	0.4602
0.6	0.4193	0.4211	0.4230	0.4248	0.4285	0.4327

where

$$\psi_{3,[d(t)]} = E_2^T \tilde{R} E_2 + E_3^T \tilde{R} E_3 + \frac{h_2 - d(t)}{h_{12}} \begin{bmatrix} E_2 \\ E_3 \end{bmatrix}^T \begin{bmatrix} \tilde{R} - S_2 \tilde{R}^{-1} S_2^T & S_1 \\ * & 0 \end{bmatrix} \begin{bmatrix} E_2 \\ E_3 \end{bmatrix}$$

$$+ \frac{d(t) - h_1}{h_{12}} \begin{bmatrix} E_2 \\ E_3 \end{bmatrix}^T \begin{bmatrix} 0 & S_2 \\ * & \tilde{R} - S_1^T \tilde{R}^{-1} S_1 \end{bmatrix} \begin{bmatrix} E_2 \\ E_3 \end{bmatrix}.$$

Then, we can get

$$h_{12} \int_{t-h_2}^{t-h} e^{-\alpha h_2} \dot{x}^T(s) R \dot{x}(s) ds \geq \zeta^T(t) \psi_{3,[d(t)]} \zeta(t). \tag{17}$$

Applying **Eq. 14** and **Eq. 17** to **Eq. 13**, the following holds:

$$\dot{V}(t) + \alpha V(t) \leq \zeta^T(t) \left[\psi_{1,[d(t)]} - \psi_2 - \psi_{3,[d(t)]} \right] \zeta(t). \tag{18}$$

By using the Schur complement, **Eqs 10**, **11** are equal to the following inequalities:

$$\psi_{1,[h_1]} - \psi_2 - \psi_{3,[h_1]} \leq 0, \tag{19}$$

$$\psi_{1,[h_2]} - \psi_2 - \psi_{3,[h_2]} \leq 0, \tag{20}$$

which implies

$$\psi_{1,[d(t)]} - \psi_2 - \psi_{3,[d(t)]} \leq 0. \tag{21}$$

Thus, it follows from **Eq. 21** that $\dot{V}(t) + \alpha V(t) \leq 0$, which further leads to

$$V(t) \leq e^{-\alpha(t-t_0)} V(t_0). \tag{22}$$

Noting that $V(t) \geq \rho \|x(t)\|^2$, $V(t_0) \leq \beta \|\phi\|^2$, $\rho > 0$, and $\beta > 0$, we have

$$\|x(t)\| \leq \sqrt{\frac{\beta}{\rho}} e^{-0.5\alpha(t-t_0)} \|\phi\|, \tag{23}$$

which implies the system (**Eq. 9**) is exponentially stable (Yang et al., 2020).

According to the above, system (**Eq. 9**) is exponentially stable if **Eqs 10**, **11** hold. The proof is completed.

Remark 1. The method proposed in this section establishes the constraint relation between the delay information and the exponential stability of the LFC for power systems with an EV aggregator, which can be used to analyze the influence of delays on the stability of the system and calculate the delay margins. The margins represent the time delay tolerance range of the system to ensure exponential stability, which is composed of the delay lower bound h_1 and delay upper bound h_2.

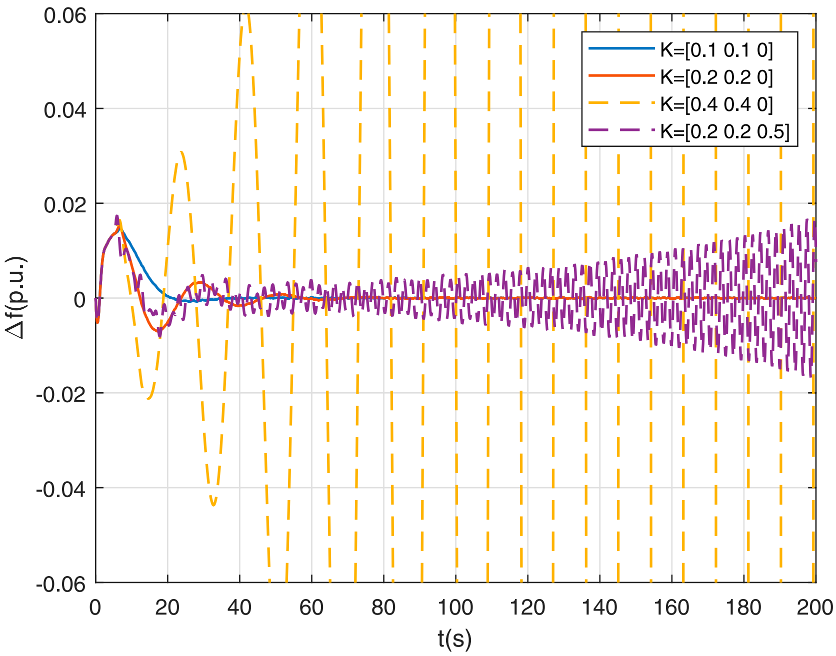

FIGURE 2 | Frequency deviations for different *K*.

TABLE 6 | Delay margins for different values of K_{EV} and K.

K_{EV} – K	[0.1 0.05 0]	[0.1 0.1 0]	[0.1 0.1 0.2]	[0.2 0.2 0.2]
1	15.8185	11.2262	1.5955	1.6101
2	13.3228	10.4242	1.4941	1.5259
3	8.9191	7.7698	1.3904	1.4270
4	6.3446	5.7806	1.2891	1.3226
5	4.8284	4.5056	1.1969	1.2250

Remark 2. In **Theorem 1**, the LFC for power systems with an EV aggregator is exponentially stable if **Eqs 10**, **11** are satisfied. The calculation steps of the delay margins for the stability of the system can be briefly summarized as follows:

1) Construct the LFC closed-loop model for power systems with an EV aggregator and a PID controller.
2) Choose the values of α, the EV aggregator gain K_{EV}, and the allowable lower bound h_1.
3) Calculate the delay margin h_2 of the power system by using the binary search technique (Zhang et al., 2013) and MATLAB/LMI toolbox to solve the LMIs in **Theorem 1**.

4 CASE STUDIES

Case studies of LFC for power systems with an EV aggregator are presented to verify the advantage of the proposed method and study the influence of PID controller and EV aggregator gains on the delay margins. The related parameters of the system are shown in **Table 1**.

4.1 Comparison With the Existing Research

The method proposed by Jiang et al. (2012) is used to verify the advantage of the proposed method. Set $h_1 = 0$, $\alpha = 0$, $K_d = 0$, and $k_{EV} = 1$, and the system can be considered asymptotically stable if the conditions in **Theorem 1** are true. Then, the delay margins of the method proposed in this paper are compared with the delay margins of time-varying delay ($\mu = 0.9$) in the study of Jiang et al. (2012). It is clear from **Table 2** that the results of the proposed method are less conservative.

4.2 Effect of PID Controller and EV Aggregator Gains

The gains of the PID controller and EV aggregator have an important effect on the delay margins of the LFC for power systems with an EV aggregator. Firstly, let $h_1 = 0$, $\alpha = 0.01$, $k_{EV} =$

1, and PID controller parameters K be different; the delay margins of the system are obtained, and the related results are shown in **Tables 3–5**.

As shown in **Table 3**, when $K_d = 0$ (PI controllers), for fixed K_p, the delay margins decrease gradually with the increase of K_i. For fixed K_i, with the increase of K_p, the delay margins decrease gradually. As can be seen from **Tables 3–5**, when K_d is not 0 (PID controllers), the delay margins gradually become smaller with the gradual increase of K_d. For fixed K_p, the delay margins increase gradually with the increase of K_i; for fixed K_i, the delay margins decrease as K_p increases. To sum up, the delay margins under PI controllers are larger than that under the PID controller. The larger K_p or K_d is, the smaller delay margins are.

Then, the frequency deviations of LFC for power systems with an EV aggregator under the delay of 5.15s and different PID controller gains are simulated. It is assumed that the power deviations of load and WTG fluctuate randomly in the range of 0.19–0.21 p. u. and 0.49–0.51 p. u., respectively. As shown in **Figure 2**, when K = [0.2 0.2 0], the system is stable. When K_p and K_i decrease (K = [0.1 0.1 0]), the frequency deviation also tends to zero. But when K_p and K_i are increased (K = [0.4 0.4 0]), or K_d is increased (K = [0.2 0.2 0.5]), it is clear that the frequency deviations do not converge in these cases. Therefore, **Figure 2** validates the analysis in **Tables 3–5**, and appropriate selection of PID controller gains K is very important for the stability of LFC for power systems with an EV aggregator.

Finally, the gain of the EV aggregator K_{EV} is also an important factor affecting the delay margins of LFC for power systems with an EV aggregator. As shown in **Table 6**, regardless of how the gains of the PID controller change, the delay margins of the delayed LFC system with an EV aggregator and intermittent wind energy decrease with the increase of K_{EV}.

5 CONCLUSION

In this paper, the LFC stability of delayed power systems with an EV aggregator was studied. The LFC of the power system was modeled as a delayed linear system with an EV aggregator. Based on Lyapunov stability theory and the linear matrix inequality approach, a new stability criterion was proposed by using Wirtinger inequality and improved inverse convex matrix inequality. Finally, the influence of EV aggregator gains and PID controller gains on the delay margins was studied, and some case studies have shown the advantage of the results. The research of this paper can solve the delay margins more accurately and guide the design of PID controllers of LFC for power systems with an EV aggregator effectively.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, and further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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