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Structure Constrained Controller Design for Power Plants and EV Aggregator in Frequency Regulation Considering Time Delays

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Abstract

Frequency control is the major concern for the integration of renewable energy into power systems. Electric vehicles (EV) are suggested to mitigate the system frequency deviation due to its vehicle-to-grid (V2G) capability and quick response characteristic. In this paper, the EVs are modeled by an EV aggregator and responded to the measureable states, such as system frequency, outputs of power plants and EV aggregator. Thus, a structure constrained feedback controller for the power plants and the EV aggregator is designed. However, the time delays during the transmission of control signal and state variable are inevitable. To deal with the time delays in the input and state variables, the Pade approximation is applied to construct the state space equations for the time delays. An equivalent augmented system without time delay is derived, in which the linear quadratic regulator (LQR) method is applied to derive the structure constrained feedback controller. Effectiveness and correctness of the proposed method are validated by a simple Great Britain power system in 2020.

Keywords: frequency control strategy; electrical vehicle (EV); time delay; pade approximation; linear quadratic regulator (LQR).

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1. Introduction

The integration of renewable electricity into the power systems has drawn great attention around the world to meet lower carbon emission target and implement climate change policy. For examples, in 2017, there was 40.5 GW of installed renewables capacity in the United Kingdom, where onshore wind have the most capacity, accounting for 32% (12.9 GW) of all renewables capacity, the capacities of solar PV and offshore wind were 12.8 GW and 7.0 GW, respectively [1]. However, the high penetration of renewable energies with the intermittent outputs often leads to system frequency variation, which limits the utilization of renewable electricity. As rapid development of demand response, the electric vehicles (EV) are suggested to participate in the load frequency control due to its vehicle-to-grid (V2G) capability [2].

The control of EVs in the frequency control has gained increasing interests by researchers in recent years. With the frequency response from EV aggregator, the frequency deviations and power plant output variations can be reduced [3], [4]. A coordinated control strategy for EVs and power plants in frequency regulation is presented in [5], in which the EV aggregator has a higher participant priority. Both centralized and decentralized control strategies have been applied for EVs to participate in system frequency regulation. Although the decentralized control strategy for small-scale charging facilities needs no communication infrastructure support, the centralized control strategy for large-scale charging facilities can realize feedback control through communication systems, which could be more efficient and accurate in the frequency control [6], [7]. In this paper, a feedback controller based on the centralized control strategy will be designed for the power plants and EV aggregator. Considering the unavailable states of frequency regulation, the design of feedback controller is only derived from the variation of power plant output, EV aggregator output and system frequency, instead of full state feedback. As a result, a structure constrained controller for the frequency control need to be solved according to the different priority of power plants and EVs.

However, the time delays exist widely in the frequency control loops especially when some low-cost and heterogeneous communication techniques are utilized to measure EVs' states or transmit control signals [5], [8], which cannot be neglected. To cope with such delays, the Pade approximation could be employed to describe the delays, which will be represented by state space equations. An augmented system without time delay is then constructed to incorporate the whole controller dynamics.

The paper is organized as follows. The frequency control model of power plants and EV aggregator with time-delay issues is reviewed in Section 2. Structure constrained feedback controller of frequency regulation is designed based on measureable variables in Section 3. Case studies are analyzed in Section 4. Finally, Section 5 concludes this paper.

2. Frequency control model of power system with time delays

In this section, the frequency control model of the power system including the traditional power plants and the EV aggregator is proposed. Considering the time delays of state and control signal, the state space model of the frequency control system is constructed.

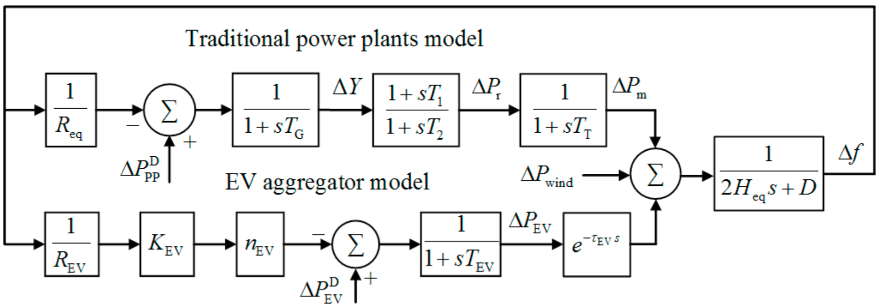


Fig. 1. Model of power system in frequency control.

A transfer-function model of traditional power plants is adopted in this paper as shown in Fig. 1, which was widely used in the frequency control studies. In this model, the dynamics of the whole system are given by (1).

$$\begin{cases} \dot{\boldsymbol{x}}(t) = \boldsymbol{A}_0\boldsymbol{x}(t) + \boldsymbol{A}_1\boldsymbol{x}(t-\tau_{\text{EV}}) + \boldsymbol{B}\boldsymbol{u}(t-\tau_{\text{c}}) \\ \boldsymbol{x}(\xi) = \boldsymbol{h}(\xi),\ \xi \in [-\tau_{\max}, 0] \end{cases} \tag{1}$$

where, $\boldsymbol{x}(t) = [\Delta Y, \Delta P_{\text{r}}, \Delta P_{\text{m}}, \Delta P_{\text{EV}}, \Delta f]^{\text{T}} \in \mathbb{R}^{5\times1}$ is the state variable vector; ΔY, ΔP_{r}, ΔP_{m} are state variables of power plants; ΔP_{EV} is the output deviation of EV aggregator; Δf is the system frequency; $\boldsymbol{u}(t) = [\Delta P_{\text{PP}}^{\text{D}}, \Delta P_{\text{EV}}^{\text{D}}]^{\text{T}} \in \mathbb{R}^{2\times1}$ is the input vector, which denotes the control signals of traditional power plants and EV aggregator and derives from the system measureable states; τ_{EV} is the time delay caused by EV aggregator output, τ_{c} is the time delay caused by the control signal transmission, and $\tau_{\max} = \max(\tau_{\text{EV}}, \tau_{\text{c}})$; $\boldsymbol{h}$ represents the system historical trajectory. More details about the models of traditional power plant and EV aggregator can be referred to [5], [9]. The system (1) represents a class of linear systems with time delays of state and input vectors. The system matrices $\boldsymbol{A}_0$, $\boldsymbol{A}_1$, input matrix $\boldsymbol{B}$ are given as follows.

$$\boldsymbol{A}_0 = \begin{bmatrix} \frac{-1}{T_{\text{G}}} & 0 & 0 & 0 & \frac{-1}{R_{\text{eq}}T_{\text{G}}} \\ \frac{1}{T_2}(1-\frac{T_1}{T_{\text{G}}}) & \frac{-1}{T_2} & 0 & 0 & \frac{-T_1}{R_{\text{eq}}T_{\text{G}}T_2} \\ 0 & \frac{1}{T_{\text{T}}} & \frac{-1}{T_{\text{T}}} & 0 & 0 \\ 0 & 0 & 0 & \frac{-1}{T_{\text{EV}}} & \frac{-K_{\text{EV}}n_{\text{EV}}}{R_{\text{EV}}T_{\text{EV}}} \\ 0 & 0 & \frac{1}{2H_{\text{eq}}} & 0 & \frac{-D}{2H_{\text{eq}}} \end{bmatrix},\ \boldsymbol{A}_1 = \begin{bmatrix} 0&0&0&0&0 \\ 0&0&0&0&0 \\ 0&0&0&0&0 \\ 0&0&0&0&0 \\ 0&0&0&\frac{1}{2H_{\text{eq}}}&0 \end{bmatrix},\ \boldsymbol{B} = \begin{bmatrix} \frac{1}{T_{\text{G}}} & 0 \\ \frac{T_1}{T_{\text{G}}T_2} & 0 \\ 0 & 0 \\ 0 & \frac{1}{T_{\text{EV}}} \\ 0 & 0 \end{bmatrix}.$$

3. Structure constrained controller for frequency regulation based on measureable variables

In this section, the structure constrained feedback controller for the traditional power plants and EV aggregator based on linear quadratic regulator (LQR) method is designed. Since the state vector and the input vector are both time-delayed, the delay are first modeled by p-order Pade approximation [10]. And then, the frequency control system with state and input time delays are modeled by an augmented system which incorporates the controller dynamics. Finally, the controller takes the measureable state variables into account, and the states of power plants output deviation, EV aggregator output deviation, system frequency deviation are used to construct the state feedback.

3.1. Time-delay model using Pade approximation

The state space representation of the time delay in the state vector and input vector is derived as following:

$$\begin{cases} \dot{\hat{\boldsymbol{x}}}_i(t) = \hat{\boldsymbol{A}}_i\hat{\boldsymbol{x}}_i(t) + \hat{\boldsymbol{B}}_i\hat{\boldsymbol{u}}_i(t) \\ \hat{\boldsymbol{y}}_i(t) = \hat{\boldsymbol{C}}_i\hat{\boldsymbol{x}}_i(t) + \hat{\boldsymbol{D}}_i\hat{\boldsymbol{u}}_i(t) \end{cases} \tag{2}$$

where, $\hat{\boldsymbol{x}}_i$ is the state variable vector introduced by the p-order Pade approximation, $i = 1, 2$, for the state time delay, $i = 1$, otherwise, $i = 2$. $\hat{\boldsymbol{x}}_1 \in \mathbb{R}^{5p\times1}$, $\hat{\boldsymbol{x}}_2 \in \mathbb{R}^{2p\times1}$. And, $\hat{\boldsymbol{u}}_1(t) = \boldsymbol{x}(t)$, $\hat{\boldsymbol{y}}_1(t) = \boldsymbol{x}(t-\tau_{\text{EV}})$; $\hat{\boldsymbol{u}}_2(t) = \boldsymbol{u}(t)$, $\hat{\boldsymbol{y}}_2(t) = \boldsymbol{u}(t-\tau_{\text{c}})$. The system matrices are given as:

$$\hat{\boldsymbol{A}}_i = \begin{bmatrix} \bar{\boldsymbol{A}} & \boldsymbol{0} & \cdots & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{0} & \bar{\boldsymbol{A}} & \cdots & \cdots & \boldsymbol{0} \\ \vdots & \ddots & \ddots & \ddots & \vdots \\ \boldsymbol{0} & \boldsymbol{0} & \ddots & \bar{\boldsymbol{A}} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} & \cdots & \boldsymbol{0} & \bar{\boldsymbol{A}} \end{bmatrix}_{kp\times kp},\ \hat{\boldsymbol{B}}_i = \begin{bmatrix} \bar{\boldsymbol{B}} & \boldsymbol{0} & \cdots & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{0} & \bar{\boldsymbol{B}} & \ddots & \ddots & \boldsymbol{0} \\ \vdots & \ddots & \ddots & \ddots & \vdots \\ \boldsymbol{0} & \ddots & \ddots & \bar{\boldsymbol{B}} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} & \cdots & \boldsymbol{0} & \bar{\boldsymbol{B}} \end{bmatrix}_{kp\times k},\ \hat{\boldsymbol{C}}_i = \begin{bmatrix} \bar{\boldsymbol{C}} & \boldsymbol{0} & \cdots & \boldsymbol{0} & \boldsymbol{0} \\ \boldsymbol{0} & \bar{\boldsymbol{C}} & \ddots & \boldsymbol{0} & \boldsymbol{0} \\ \vdots & \ddots & \ddots & \ddots & \vdots \\ \boldsymbol{0} & \ddots & \ddots & \bar{\boldsymbol{C}} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{0} & \cdots & \boldsymbol{0} & \bar{\boldsymbol{C}} \end{bmatrix}_{k\times kp},\ \hat{\boldsymbol{D}}_i = \begin{bmatrix} \frac{a_p}{b_p} & 0 & \cdots & 0 \\ 0 & \frac{a_p}{b_p} & \ddots & 0 \\ \vdots & \ddots & \ddots & \vdots \\ 0 & 0 & \ddots & \frac{a_p}{b_p} \end{bmatrix}_{5\times5},$$

where, $k=5$ (state time delay) or $k=2$ (input time delay); a_i, b_i, $i=0,1,\cdots,p$ are coefficients of p-order Pade approximation.

$$\bar{A}=\begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ \vdots & \vdots & \cdots & \ddots \\ -\dfrac{b_0}{b_p} & -\dfrac{b_1}{b_p} & \cdots & -\dfrac{b_{p-1}}{b_p} \end{bmatrix}_{p\times p},\ \bar{B}=\begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ \dfrac{1}{b_p} \end{bmatrix}_{p\times 1},\ \bar{C}=\begin{bmatrix} a_0-\dfrac{a_p b_0}{b_p} & a_1-\dfrac{a_p b_1}{b_p} & \cdots & a_{p-1}-\dfrac{a_p b_{p-1}}{b_p} \end{bmatrix}_{1\times p}.$$

3.2. Augmented frequency control system

Based on the dynamic model of power system (1) and the time-delay approximation (2), the time-delay frequency control system is represented by the closed-looped augmented state space model:

$$\dot{\tilde{x}}(t)=\tilde{A}\tilde{x}(t)+\tilde{B}u(t) \tag{3}$$

where, $\tilde{x}(t)=[x^{\mathrm{T}}(t),\hat{x}_1^{\mathrm{T}}(t),\hat{x}_2^{\mathrm{T}}(t)]^{\mathrm{T}}\in\mathbb{R}^{(5+7p)\times 1}$; $\tilde{A}=\begin{bmatrix} A_0+A_1\hat{D}_1 & A_1\hat{C}_1 & B\hat{C}_2 \\ \hat{B}_1 & \hat{A}_1 & O \\ O & O & \hat{A}_2 \end{bmatrix}$, $\tilde{B}=\begin{bmatrix} B\hat{D}_2 \\ O \\ \hat{B}_2 \end{bmatrix}$.

3.3. Structure constrained controller design

Based on the fact that most of the states in (3) cannot be available and measureable for the frequency control, the control strategy is designed only with the variables which are measurable, i.e., ΔP_{m}, ΔP_{EV} and Δf. Thus, the structure of state feedback controller gain is shown as follows:

$$u(t)=-\tilde{K}x(t) \tag{4}$$

$$\tilde{K}=\begin{bmatrix} K_{2\times 5} & O_{2\times 7p} \end{bmatrix} \tag{5}$$

$$K=\begin{bmatrix} 0 & 0 & K_{13} & K_{14} & K_{15} \\ 0 & 0 & K_{23} & K_{24} & K_{25} \end{bmatrix} \tag{6}$$

Such practical structural restricted controller can be obtained by a structurally constrained optimal problem [11], which minimizes a quadratic performance index and so-called LQR problem:

$$J(\tilde{x},u)=\frac{1}{2}\int_0^\infty (\tilde{x}^{\mathrm{T}}Q\tilde{x}+u^{\mathrm{T}}Ru)\,\mathrm{d}t \tag{7}$$

where, the semi-definite positive matrix Q and the positive definite matrix R are weighting matrices. Since the higher weights for the state and the input signal strongly represent higher damping, the diagonal element associated to desired high damping states are more strongly weighted. In this paper, the goal of frequency control is to mitigate system frequency deviation as much as possible. Furthermore, the EV aggregator is controlled to have higher priority in frequency regulation due to its V2G capability and quick response characteristic, so the state weighting matrices are chosen as follows:

$$Q=diag(0,0,0,0,100,\underbrace{0,0,\cdots,0}_{7p}) \tag{8}$$

$$R=diag(0.1,0.02) \tag{9}$$

4. Case studies

In this section, the simplified GB power system model related to frequency control in 2020 is used to verify the correctness of proposed structure constrained controller. The typical values of the parameters are listed in Table I [1], [3]. The parameters of EV aggregator are listed in Table 2, where the EV quantity is estimated to reach 500,000 in 2020 according to the UK Department for Business Innovation and Skills [4].

Table 1. Parameters of the GB power system

Parameter	Value	Parameter	Value
R_{eq} (p.u.)	0.09	T_T (s)	0.3
T_G (s)	0.2	H_{eq} (s)	4.44
T_1 (s)	2	D (p.u.)	1
T_2 (s)	12	S_B (GW)	30
f_B (Hz)	50	-	-

Table 2. Parameters of EV aggregator

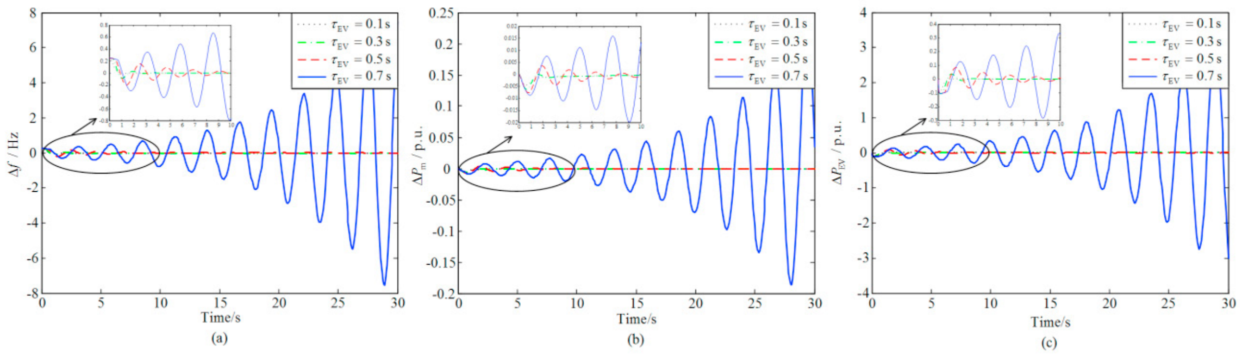
Parameter	Value	Parameter	Value
R_{EV} (p.u.)	0.09	K_{EV} (p.u.)	4×10^{-6}
T_{EV} (s)	0.035	n_{EV} (万)	50

Without state feedback controller, the system states are shown in Fig. 3 (a)-(c) with τ_{EV} growing from 0.1 to 0.7 s. It is clear that the frequency deviation loses its stability with the increasing of the time delay, as well as the power output of power plants and EV aggregator.

The structure feedback constrained controller is designed to control the inputs of power plants and EV aggregator just using the system output and frequency deviation, and the transmission of control signals will introduce time delays. It is assumed that the time delays of state variable and input signal transmission satisfy $\tau_{EV} = 0.7$ s and $\tau_c = 0.7$ s. A proper second order approximation for the time delays is used to obtain the augmented control system (3). By using the LQR technology, the controller gain $\boldsymbol{K}$ can be obtained, in which

$$\boldsymbol{K} = \begin{bmatrix} 0 & 0 & 0.5400 & 0.0262 & 16.0130 \\ 0 & 0 & 0.9778 & 1.0163 & 7.1119 \end{bmatrix} \tag{10}$$

The obtained controller is used in system (1), and the simulation results are shown in Fig. 3 (d)-(f). It can be seen that the deviation of system frequency, output of traditional power plants and EV aggregator are converged to 0 in about 15s, and oscillations are damped greatly.



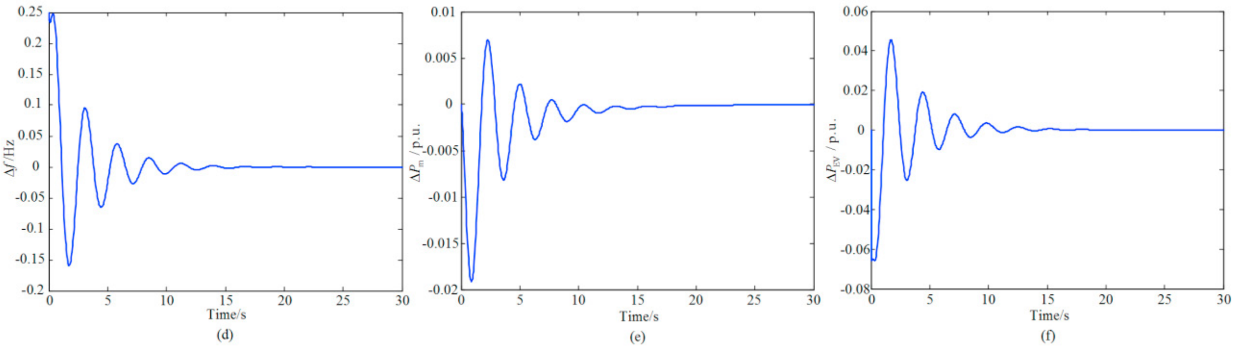


Fig. 2. Deviation of system frequency, power plants output, and EV aggregator output without and with structure constrained controller.

5. Conclusions

This paper presents a structure constrained controller for the power plants and the EV aggregator considering the time delays. Based on the models of power plants and EV aggregator, a time delay state space model of frequency control model of power system is established. State space models with delayed state and input are derived from the Pade approximation. Besides, an augmented system without time delay for the controller design is developed. Furthermore, the optimal control with structural constraints based on the LQR method is carried out, which considers the participant priority in the frequency control. With the designed controller, the system can be stabilized and the system frequency deviation is damped well even in the large time delays.

Acknowledgements

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