International Conference on Applied Energy 2019
Aug 12-15, 2019, Västerås, Sweden
Paper ID: 1008

DELAY INDUCED OSCILLATION IN FREQUENCY REGULATION SYSTEMS WITH ELECTRIC VEHICLE AGGREGATION

Zhang Yimei[1], Dong Chaoyu[1*], Dai Liye[2], Xiao Qian[1], Jia Hongjie[1]
1 School of Electrical and Information Engineering, Tianjin University, Tianjin, China
2 The 54th Research Institute of China Electronics Technology Group Corporation, Hebei, China

ABSTRACT

With the participating of electric vehicle (EV) aggregators in frequency regulation (FR) services, inevitable time delays are penetrating into power systems due to the open communication infrastructure and scheduling, which may lead to poor performance or even instability.

The models of traditional FR system without EVs, FR system including EV aggregators without delay and FR system including EV aggregators consider-ing time delays are deduced and compared. And an effective damping ratio extraction method based on solution operator transformation is then presented for FR systems including EV aggregators with time delays. And by utilizing the proposed method, the dominant oscillation frequency and the minimum damping ratio are obtained. In consideration of time delays, we evaluate the effect of EV aggregators on the performance and stability of the frequency regulation system of the power system. Relationship between time delays, the gains of the PI controller and the dominant oscillation frequency and the minimum damping ratio of the FR scheme are explored. The model differences between time-delay and non-delay systems are revealed. Through comparisons, it is found that the mass utilization of electric vehicles in the frequency control might result in instability due to the aggregation delay, which induces oscillation for the whole system.

Keywords: renewable energy resources, time delays, solution operator discretization, electric vehicle.

1. INTRODUCTION

Nowadays, EV aggregators participating in frequency regulation service would aggregate a large number of EVs, and communication infrastructure is needed to control their EVs, which may cause signals transmission delay[1][2]. The delay may lead to degradation of the fr performance, or even instability. Hence, the time-delay impacts should be evaluated in frequency regulation[3]. However, most methods assume that time delays are negligible, which introduces risks in system stability and controller performance[4][5].

The time delay induced to the power system due to the participating of EV aggregators will affect the FR performance and then affect the indication signals required to compensate for frequency errors. Identification of oscillation frequency, damping ratio, oscillation mode, and other parameters play a vital role in the management of dynamic characteristics[6], especially considering the large-scale EV aggregation.

To solve these problems, the models of traditional FR system without EVs, FR system including EV aggregators without delay and FR system including EV aggregators considering time delays are deduced. The comparative analyses of the three modelS is carried out. Then a damping ratio extraction method based on the solution operator transformation for delayed frequency regulation systems is proposed, which structures a simple approximate matrix based on the solution operator. According to the Spectral Mapping Principle, the eigenvalues and the corresponding eigenvectors of the delayed system can be obtained by computing the nonzero eigenvalues of the approximate matrix, which reflects the time delay stability of the power system considering the EV aggregation.

2. SYSTEM MODELING

In order to investigate the effect of delays in EV aggregators' domain on regulation performance, the dynamics of FR system including multiple EV aggregators with time delays should be modeled first.

2.1 EV Aggregator

An EV aggregator including a large number of EVs with time delay considered can be modeled as the following first-order transfer function:

$$G_{EV(s)} = \frac{K_{EV}}{1+sT_{EV}} \tag{1}$$

where K_{EV} is the gain of the EV and T_{EV} is the time constant of the EV battery system. The communication delay from an EV aggregator to the EV and the scheduling delay in the EV aggregator are modeled by an exponential transfer function of $e^{-s\tau}$, where τ is the delay time taken for receiving control signals from the EV aggregator.

2.2 Frequency Regulation Model Including Multiple EV Aggregators with Delays

We consider a single-area frequency regulation model including multiple EV aggregators to focus on the effect of delays in EV aggregators on power systems, as shown in Fig 1.

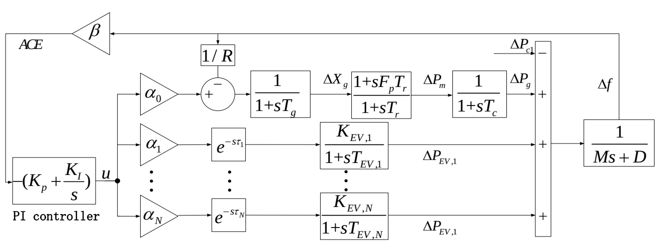


Fig 1 Modified FR model including EV aggregators with delays

For a one-area FR system, all generation units in each control area are simplified as an equivalent generation unit. And synchronous generators are assumed to have reheat thermal turbines. We adopt a PI-type controller as a frequency regulator controller. The output of the PI controller is distributed to the reheat thermal generator and *N* EV aggregators depending on the participation ratios α_0 , α_1 ,...,α_N , where α_0 denotes the participation ratio of an aggregated thermal generator and α_i denotes the participation ratio of EV aggregator *i* for *i* = 1,...,N.

The dynamics of one-area frequency regulation system are described as:

$$\Delta\dot{f} = -\frac{D}{M}\Delta f + \frac{1}{M}\Delta P_g + \frac{1}{M}\sum_{k=1}^{N}\Delta P_{EV,k} - \frac{1}{M}\Delta P_L \tag{2}$$

$$\Delta\dot{P}_g = \frac{1}{T_c}\Delta P_m - \frac{1}{T_c}\Delta P_g \tag{3}$$

$$\Delta\dot{P}_m = \frac{-F_p}{RT_g}\Delta f - \frac{1}{T_r}\Delta P_m + \frac{T_g - F_pT_r}{T_rT_g}\Delta X_g + \frac{F_p\alpha_0}{T_g}u \tag{4}$$

$$\Delta\dot{X}_g = -\frac{1}{RT_g}\Delta f - \frac{1}{T_g}\Delta X_g + \frac{\alpha_0}{T_g}u \tag{5}$$

$$\Delta\dot{P}_{EV,k} = \frac{-1}{T_{EV,k}}\Delta P_{EV,k} + \frac{\alpha_k K_{EV,k}}{T_{EV,k}}u(t-\tau_k)(k=1,\dots,N) \tag{6}$$

where Δf_i , ΔP_g , ΔP_m , $\Delta\dot{X}_g$, ΔP_{L_i} are the deviations of the frequency, generator power output, generator mechanical output, turbine valve position, and load respectively. $\Delta P_{EV,k}(k=1,\dots,N)$ is the deviation of the power output in the *k*-th EV aggregator; ΔP_c is load reference set-point, M is the moment of inertia of generator; D is damping coefficient of generator *i*; T_g is time constant of governor *i*; T_c is time constant of turbine i; R is speed droop coefficient.

The area control error *ACE* in a multi-area FR is defined as

$$ACE = \beta\Delta f \tag{7}$$

For each area, the dispatch center is designed as

$$u(t) = -K_p ACE - K_I \int ACE \tag{8}$$

Based on the dynamic equation above, the state-space model can be obtained

$$\begin{cases} \dot{\boldsymbol{x}}(t) = \boldsymbol{A}\boldsymbol{x}(t) + \boldsymbol{B}_0 u(t) + \sum_{k=1}^{N}\boldsymbol{B}_k u(t-\tau_k) + \boldsymbol{F}\Delta P_L \\ \boldsymbol{y}(t) = \boldsymbol{C}\boldsymbol{x}(t) \end{cases} \tag{9}$$

where $\boldsymbol{x}(t) = [\Delta f \ \ \Delta P_g \ \ \Delta P_m \ \ \Delta X_g \ \ \Delta P_{EV,1} \cdots \Delta P_{EV,N} \ \ \int ACE]^T$, $\boldsymbol{y}(t) = \left[ACE \quad \int ACE\right]^T$

$$\boldsymbol{A} = \begin{bmatrix} \frac{-D}{M} & \frac{1}{M} & 0 & 0 & \frac{1}{M} & \cdots & \frac{1}{M} & 0 \\ 0 & \frac{-1}{T_c} & \frac{1}{T_c} & 0 & 0 & \cdots & 0 & 0 \\ \frac{-F_p}{RT_g} & 0 & \frac{-1}{T_r} & \frac{T_g - F_pT_r}{T_rT_g} & 0 & \cdots & 0 & 0 \\ \frac{-1}{RT_g} & 0 & 0 & \frac{-1}{T_g} & 0 & \cdots & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{-1}{T_{EV,1}} & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \ddots & \cdots & \vdots & 0 \\ 0 & 0 & 0 & 0 & 0 & \cdots & \frac{-1}{T_{EV,N}} & 0 \\ \beta & 0 & 0 & 0 & 0 & \cdots & 0 & 0 \end{bmatrix} \tag{10}$$

$$\boldsymbol{B}_0 = \left[0 \quad 0 \quad F_p\alpha_0/T_g \quad \alpha_0/T_g \quad 0 \quad \dots \quad 0 \quad 0\right]^T \tag{11}$$

$$\boldsymbol{B}_k = \frac{\alpha_k K_{EV,k}}{T_{EV,k}}e_{4+k}(k=1,\dots,N) \tag{12}$$

$$\boldsymbol{C}=\begin{bmatrix}\beta & 0 & 0 & 0 & 0 & \dots & 0 & 0\\ 0 & 0 & 0 & 0 & 0 & \dots & 0 & 1\end{bmatrix} \tag{13}$$

$$\boldsymbol{F}=\begin{bmatrix}-1/M & 0 & 0 & 0 & 0 & \dots & 0 & 0\end{bmatrix}^T \tag{14}$$

To simply the subsequent analysis and lessen the calculative burden, the delays for all EVs are assumed to be equal as τ. Then the time-delay model of the multi-area power system can be described by following delayed differential equations.

$$\begin{cases}\dot{\boldsymbol{x}}(t)=\tilde{\boldsymbol{A}}\boldsymbol{x}(t)+\tilde{\boldsymbol{A}}_d\boldsymbol{x}(t-\tau), t\geq 0\\ x(t)=\Delta x_0 \triangleq \varphi, t\in[-\tau_{\max},0]\end{cases} \tag{15}$$

where φ is the initial system state.

Table I Comparisons of No-EV and EV Components in the modified frequency regulation system Model

(a)

Traditional FR system (no EVs)				EV-FR system (including EVs)		
			$\boldsymbol{A}$			
$-\frac{D}{M}$	$-\frac{1}{M}$			$\frac{1}{M}$	$\cdots$	$\frac{1}{M}$
	$-\frac{1}{T_c}$	$\frac{1}{T_c}$			$\cdots$	
$\frac{-F_p}{RT_g}$		$\frac{-1}{T_c}$	$\frac{F_g-F_pT_r}{T_rT_g}$		$\cdots$	
$-\frac{1}{RT_g}$			$-\frac{1}{T_g}$		$\cdots$	
				$\frac{-1}{T_{EV,1}}$	$\cdots$	
$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\ddots$	$\ddots$	$\vdots$
					$\cdots$	$\frac{-1}{T_{EV,N}}$
β						

(b)

Traditional (no EVs)	EV-FR system (including EVs)				
	no delay	with delays			
$\boldsymbol{B}_0$	$\boldsymbol{B}$	$\boldsymbol{B}_0$	$\boldsymbol{B}_k$		
$F_p\alpha_0/T_g$	$F_p\alpha_0/T_g$	$F_p\alpha_0/T_g$			
α_0/T_g	α_0/T_g	α_0/T_g			
	$\frac{\alpha_1K_{EV,1}}{T_{EV,1}}$		$\frac{\alpha_1K_{EV,1}}{T_{EV,1}}$		
	$\vdots$			$\ddots$	
	$\frac{\alpha_NK_{EV,N}}{T_{EV,N}}$				$\frac{\alpha_NK_{EV,N}}{T_{EV,N}}$

$$\tilde{\boldsymbol{A}}=\boldsymbol{A}-\boldsymbol{B}_0\boldsymbol{KC} \tag{16}$$

$$\tilde{\boldsymbol{A}}_d=-\sum_{k=1}^{N}\boldsymbol{B}_k\boldsymbol{KC} \tag{17}$$

The characteristic equation of (14) the system is

$$(\tilde{\boldsymbol{A}}+\tilde{\boldsymbol{A}}_d e^{-\lambda\tau_i})v=\lambda v \tag{18}$$

where λ is an eigenvalue and v is the corresponding eigenvector.

Table I presents the comparison between traditional FR system without EVs, FR system including EV aggregators without delay and FR system including EV aggregators considering delays.

3. TIME-DELAY DISCRETIZATION

The solution operator $T(h)$ maps the initial condition φ at t into the system state at $t + h$, where h is the transfer step length satisfying $0\leq h\leq\tau_{\max}$

$$(\boldsymbol{T}(h)\boldsymbol{\varphi})(t)=\Delta\boldsymbol{x}_h(t)=\Delta\boldsymbol{x}(t+h) \tag{19}$$

Eigenvalues μ of $T(h)$ can be obtained from eigenvalues λ of multi-area frequency regulation

$$\mu=e^{\lambda h},\quad \mu\in\sigma(\boldsymbol{T}(h))\setminus\{0\} \tag{20}$$

The problem is transformed into computing μ from $T(h)$, which is an infinite-dimensional problem. To reduce the complexity, the operator $T(h)$ could be discretized by implicit Runge-Kutta methods first.

By applying implicit Runge-Kutta and using the shift property to assess system states at the points of Ω_{Ns}, the approximate matrix $\boldsymbol{T}_{Ns}$ to $\boldsymbol{T}(h)$ is obtained.

$$\boldsymbol{T}_{Ns}=\begin{bmatrix}\boldsymbol{R}_{Ns}^{-1}\boldsymbol{\Sigma}_{Ns}\\ \boldsymbol{\Gamma}_{Ns}\end{bmatrix}\quad \boldsymbol{\Gamma}_{Ns}=\begin{bmatrix}\boldsymbol{I}_{(N-1)sn}\\ \boldsymbol{0}_{(N-1)sn\times sn}\end{bmatrix} \tag{21}$$

$$\begin{cases}\boldsymbol{R}_{Ns}=\boldsymbol{I}_{sn}-h\boldsymbol{A}\otimes\tilde{\boldsymbol{A}}\\ \boldsymbol{\Sigma}_{Ns}=\boldsymbol{L}_0^T\otimes\boldsymbol{I}_n+h(\boldsymbol{AL}_1^T)\otimes\tilde{\boldsymbol{A}}_d\end{cases} \tag{22}$$

where $\boldsymbol{A}\in\mathbf{R}^{s\times s}$ is formed by Butcher tableau elements, $\boldsymbol{L}_1\in\mathbf{R}^{Ns\times s}$ is the constant Lagrange interpolation matrices.

A space conversion technique is presented to shift the desirable eigenvalues to improve computing efficiency.

Eigenvalues λ are first rotated by $\theta(=\arcsin(\zeta))$ in counterclockwise direction, which is then amplified by α times to increase the relative distance between them.

$$\mu'=e^{\lambda' h}\qquad \lambda'=\alpha e^{-j\theta}\lambda \tag{23}$$

After space transformation, the discretized matrix of the solution operator $\boldsymbol{T}_{Ns}$ turns to $\boldsymbol{T}_{N's}$

$$\boldsymbol{T}_{N's}=\begin{bmatrix}\boldsymbol{R}_{N's}^{-1}\boldsymbol{\Sigma}_{N's}\\ \boldsymbol{\Gamma}_{N's}\end{bmatrix},\begin{cases}\boldsymbol{R}_{N's}=\boldsymbol{I}_{sn}-h\boldsymbol{A}\otimes\tilde{\boldsymbol{A}}_0{}'\\ \boldsymbol{\Sigma}_{Ns}=\boldsymbol{L}_0^T\otimes\boldsymbol{I}_n+h(\boldsymbol{AL}_1^T)\otimes\tilde{\boldsymbol{A}}_d{}'\end{cases} \tag{24}$$

An Arnoldi method is used to generate an orthonormal basis $\boldsymbol{V}_m$ of the projection subspace to obtain a reduced-dimension matrix

$$\begin{aligned}\boldsymbol{T}_{N's}\boldsymbol{V}_m &= \boldsymbol{V}_m\boldsymbol{H}_m + h_{m+1,m}v_{m+1}e_m^T \\ &= \boldsymbol{V}_m\boldsymbol{H}_m + f_m e_m^T = \boldsymbol{V}_{m+1}\tilde{\boldsymbol{H}}_m\end{aligned} \tag{25}$$

The corresponding minimum damping ratio and dominant oscillation frequency can be obtained by calculating the critical eigenvalue of reduced-dimension matrix $\boldsymbol{H}_m$. The oscillation frequency is determined by the imaginary part of the eigenvalue, and the magnitude is $f = \omega / 2\pi$. The minimum damping ratio is determined by the real part of eigenvalue

$$\xi = -\sigma / \sqrt{\sigma^2 + \omega^2} \tag{26}$$

4. CASE STUDIES

Case studies are carried out based on a one-area frequency regulation system in which a single EV aggregator with α1 = 0.4 has a time delay. Parameters are listed in [2]. First, to investigate how EV aggregators with time delay affect the FR performance, the dominant oscillation frequency and the minimum damping ratio of traditional FR system without EVs and EV-FR system including EVs are calculated based on the extraction method proposed. And then time delay in EV aggregator is changed to investigate how time delay affects the system performance. And different gains of the PI controller (K_P, K_I) are set to investigate how gains affect the result. The features of the system after encompassing a large number of EVs are extracted.

The relationship between time delay and system damping are summarized in Fig 2 and Fig 3, respectively. It can be found that, with the increase of the time delay τ, the dominant oscillation frequency presents clear cyclical fluctuation, and the waveform within each period is sawtooth. In the meantime, the minimum damping ratio doesn't linearly decrease with τ. As time delay increases, the damping ratio may even increases, which means the system becomes more stable. And the changing curves both have tipping points, which are different with respect to the different PI controllers. Under smaller K_P and K_I, a relatively larger minimum damping ratio is obtained, but bigger K_P and K_I lead to sharply ξ reduction. According to Fig 2 and Fig 3, the design and tuning of the controller, a trade-off between the delay margin and dynamic control should be achieved.

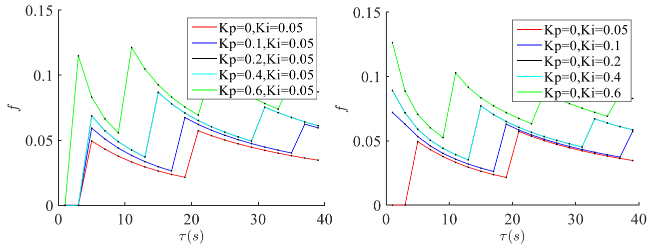


Fig 2 Dominant oscillation frequency $f \propto \tau$

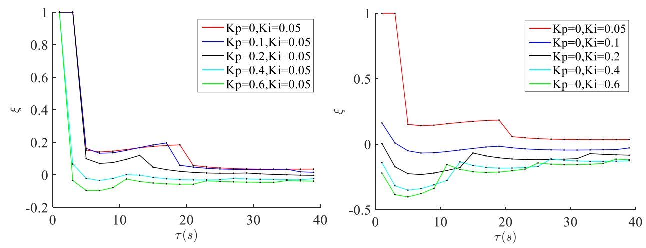


Fig 3 Minimum damping ratio $\xi \propto \tau$

The frequency deviation error of the FR system is simulated including a single EV aggregator when (K_P,K_I) is set to (0, 0.1) and τ is set to 0s, 3s and 5s. The corresponding simulation is carried out on the FR system without EVs.

Table II Dominant oscillation frequency $f \propto \tau$

(Comparisons of no-EV and EV, no delay and different τ)

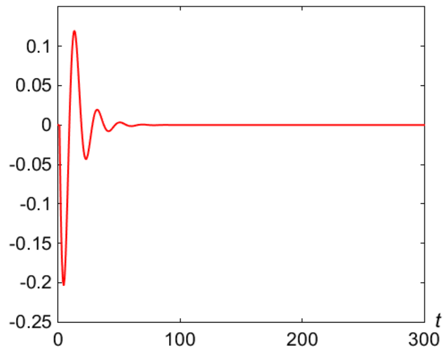
f						
(K_P,K_I)	no EV	no delay	τ=5s	τ=10s	τ=20s	τ=40s
(0,0.05)	0	0	0.049	0.035	0.059	0.034
(0,0.1)	0	0	0.053	0.038	0.061	0.056
(0.1,0.1)	0	0	0.059	0.041	0.064	0.058
(0.2,0.4)	0	0	0.070	0.048	0.068	0.061
(1,1)	0	0	0.087	0.129	0.116	0.109

Table III Minimum damping ratio $\xi \propto \tau$

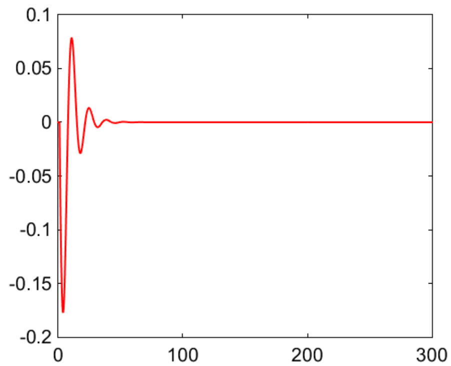
(Comparisons of no-EV and EV, no delay and different τ)

ξ						
(K_P,K_I)	no EV	no delay	τ=5s	τ=10s	τ=20s	τ=40s
(0,0.05)	1	1	0.153	0.151	0.064	0.036
(0,0.1)	1	1	-0.050	-0.061	-0.022	-0.030
(0.1,0.1)	1	1	-0.019	-0.041	-0.017	-0.027
(0.2,0.4)	1	1	-0.323	-0.274	-0.164	-0.112
(1,1)	1	1	-0.390	-0.178	-0.134	-0.088

The accuracy of the result is verified by the comparisons between Table II, Table III and Fig 4, Fig 5. The result also shows that mass use of electric vehicles in load frequency control results in instability is due to the penetrating of EVs brings time delay, which causes the system oscillation due to damping loss.

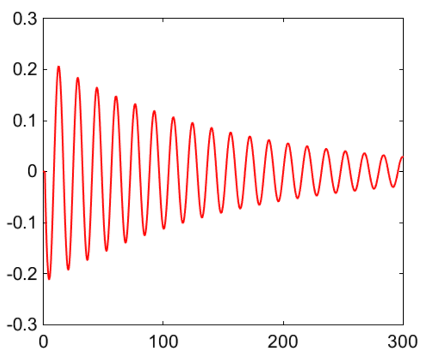


a. No EV

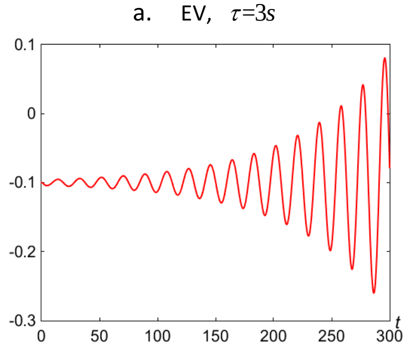


b. EV, no delay

Fig 4 Frequency variation $\Delta f \propto t$ (K_P=0,K_I =0.1)



a. EV, τ=3s



b. EV, τ=5s

Fig 5 Frequency variation $\Delta f \propto t$ (K_P=0,K_I =0.1)

5. CONCLUSIONS

With the participating of electric vehicle (EV) aggregators in frequency regulation services, inevitable time delays are penetrating into power systems. The time delays have negative effects on the performance and may even cause the frequency instability. To solve these problems, the model of traditional FR system without EVs, FR system including EV aggregators without delay and FR system including EV aggregators considering time delays are deduced in this paper. And the comparative analyses of the three model is carried out. Then an effective damping ratio extraction method based on solution operator transformation is presented for FR systems considering time delays. And the dominant oscillation frequency and the minimum damping ratio are obtained by the proposed method. It should be noted especially that the frequency regulator needs careful design when a large number of EVs participate in frequency regulation service.

The coupling of controller and time delay is revealed influencing the dominant oscillation frequency and the minimum damping ratio. Due to the time delay, a small increment of the controller gains may lead to a significant decrement of the damping ratio. It is also shown that the time delay during the EV aggregation is one of the oscillation sources for the whole system, which causes nonlinear variations in the system damping and oscillation frequency.

REFERENCE

[1] H. Ameli, M. Qadrdan, Strbac. Coordinated Operation Strategies for Natural Gas and Power Systems in presence of Gas-related Flexibilities[J]. Energy Systems Integration 2019, 1: 3-13.
[2] K. S. Ko, D. K. Sung. The Effect of EV Aggregators with Time-Varying Delays on the Stability of a Load Frequency Control System[J]. IEEE Transactions on Power Systems, 2017:1-1.
[3] X. M. Li, X. D. Yu, H. J. Jia, et al. Structure Constrained Controller Design for Power Plants and EV Aggregator in Frequency Regulation Considering Time Delays[J]. Applied Energy, Energy Procedia, 2019, 158: 2966-2971.
[4] C. Y. Dong, F. H. Guo,H. J. Jia, et al. DC Microgrid Stability Analysis Considering Time Delay in the Distributed Control[J]. Energy Procedia, 2017, 142:2126-2131.
[5] L. Wang, C. Y. Dong, H. J. Jia, et al. Diversity-based Quantitative Evaluation Method of Conservatism of Time-delay Stability Criteria for Power Systems[J]. Automation of Electric Power Systems, 2017, 4:22-28.
[6] C. Y. Dong, H. J. Jia, T. Jiang, et al. Effective Method to Determine Time-delay Stability Margin and Its Application to Power Systems[J]. IET Generation, Transmission & Distribution, 2017, 11:1661-1670.