

Robust exponential load frequency control for time delay power system considering wind power ^{*}

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Abstract: The injection of intermittent wind power reduces the equivalent inertia of power systems, and therefore, the change rate of frequency deviation for the load frequency control (LFC) schemes is increased. LFC schemes employ communication channels to transmit signals, which introduces time delays resulting in badly dynamic performance. This paper presents a delay-dependent approach to obtain the robust load frequency controllers based on decay rate for a multi-area LFC scheme integrated with wind power. An index of decay rate related to settling time is introduced. For a preset delay upper bound, controller gains are optimized by maximizing the decay rate. Also, the controller gains can be designed under the desired decay rate while obtaining the allowable maximum delay margins. Case studies are based on the deregulated multi-area LFC system to verify the robustness of developed controller against inertia reduction. Moreover, the proposed method enables the frequency deviation to be restrained and eliminated within a few seconds.

Keywords: Load frequency control, wind power, communication delay, decay rate.

1. INTRODUCTION

Recently, air pollutants generated by fossil fuel lead to serious environmental problems such as acid rain, global warming, etc. (Dong *et al.*, 2015). In the US, for example, fossil fuel power plants emit about 2.2 billion tons of carbon dioxide annually. Also, the nonrenewable fossil fuel is decreasingly reserved. As an alternative method, renewable energy sources have drawn attention from all over the world (Tungadio *et al.*, 2019). Over the past decade, the cost of wind generators has been gradually competitive in comparison with solar energy. The replacement of conventional generators with wind generators will reduce the total inertia of the power system while increasing the equivalent regulation constant (Dehghanpour *et al.*, 2015). That is, the high penetration of wind power with inherent intermittent and non-dispatchable features will endanger the stable operation of the system or even make the whole system collapse (Han *et al.*, 2014). Therefore, researchers made an effort to identify the allowable maximum penetration level of wind power based on thermal limit or constraint on frequency deviation (Dai *et al.*, 2019). The effect of wind integration on the area control error (ACE) and tie-line interchanges is investigated

under the interconnected system (Nguyen *et al.*, 2016). Moreover, the virtual synchronous machine (VSM) was introduced, whose parameters can be adjusted freely to compensate for the decrease in inertia (Beck *et al.* 2007). The self-tuning algorithms are employed to continuously search for optimal parameters during the operation of the VSM in order to minimize the amplitude and change rate of the frequency variations (Torres *et al.* 2014). Based on the VSM, the adaptive sliding mode control is to enhance inertia in microgrids and grid stability while ensuring the speed of frequency response (Afshar *et al.* 2018).

On the other hand, load frequency control (LFC) has been applied in a power system to maintain frequency and power interchanges at scheduled values (Bhowmik *et al.*, 2004). Deregulated LFC tends to use open communication networks to transmit control and measurement signals with low-cost and high-flexibility. Time delays will be introduced from such networks due to sensor faults, data packet dropouts, etc. (Jiang *et al.*, 2009). In order to evaluate the influence of time delay on system stability, some delay-dependent results are presented relying on the truncated second-order Bessel-Legendre inequality (Yang *et al.*, 2018a) or the infinite-series-based inequality (Yang *et al.*, 2018b) or the augmented Lyapunov-Krasovskii functional (Jin *et al.*, 2019). These delays will degrade the dynamic performance of controllers that are designed without considering time delays. Hence, by regarding the time delays as the model uncertainty, a suboptimal static output feedback controller is developed (Bevrani *et al.*,

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2008) through the mixed H_2/H_∞ theory. Based on the H_∞ theory, controllers are developed to have increased robustness to time delays (Zhang *et al.*, 2013b). A robust predictive LFC is obtained in (Ojaghi *et al.*, 2017), which is robust to both model uncertainties and time delays. To reject large disturbances and drive the frequency error to a designed tolerable band, a fuzzy H_∞ iterative learning technique is developed (Ramlal *et al.*, 2019).

This paper concentrates on designing robust load frequency controllers based on the decay rate and time delay. In order to deal with inertia reduction (IR) in the power system caused by integrating wind power, existing research aims to test the allowable integration of wind power or to find the proper parameter for the VSM. Little work aims to design a robust controller against IR so that the increased change rate of frequency deviation can be directly suppressed based on the original model with wind power penetrated. The investigation of time-varying system claims that an index of decay rate related to settling time helps restore the system to equilibrium within a few seconds (Chilali *et al.*, 1996). Hence, the method proposed in this paper is able to depress the amplitude of frequency deviation occurring due to the intermittency of wind power, and then eliminate it using a few seconds despite of the IR at different levels. When the wind power is introduced into the power system, it should be controlled as a state instead of a disturbance being ignored when the system's internal stability is analyzed (Bevrani *et al.*, 2016). Although the controllers in (Zhang *et al.*, 2013b) are robust to both time delays and disturbance, they cannot ensure the frequency stability due to the high penetration of wind power. Therefore, this paper demonstrates how to design the delay-dependent load frequency controllers with decay rate, which have robustness against IR. With a preset delay upper bound, the robust load frequency controllers can be developed by maximizing the decay rate. Also, under the desired decay rate, the optimal controllers are obtained with allowable maximum delay margins.

The remainder of this paper is organized as follows. The second part presents the model of deregulated multi-area LFC scheme considering the wind power. In the third section, a stability criterion is established in terms of linear matrix inequality techniques (LMIs), based on which the relationship between time delays and decay rate is shown, and then a transformed result enables to solve controller gains. In the fourth part, case studies are carried out under deregulated multi-area LFC schemes to verify the effectiveness of presented method. The last section makes conclusions.

2. DYNAMIC MODEL OF MULTI-AREA DEREGULATED LFC

This section describes the model of deregulated multi-area LFC scheme integrating with wind power, based on which the object of this paper is clarified.

2.1 Multi-area LFC scheme considering wind power

The multi-area LFC scheme considering wind power is presented in Fig. 1. Area i includes n Gencos, and time delays arisen from the open communication networks, for simplicity, are seen as an exponential block $e^{-sd(t)}$. In a

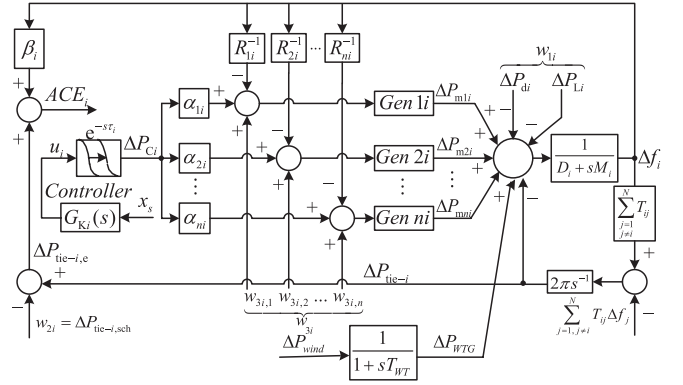


Fig. 1. Deregulated LFC scheme

deregulated multi-area LFC scheme including N areas, area i can be modeled as

$$\dot{\tilde{x}}_i(t) = \tilde{A}_i \tilde{x}_i(t) + \tilde{B}_i K_i \tilde{x}_i(t - d(t)) + F_i w_i \quad (1)$$

$$\tilde{x}_i(t) = [\Delta f_i, \Delta P_{tie-i,e}, \Delta P_{m1i}, \dots, \Delta P_{mni}, \Delta P_{v1i}, \dots,$$

$$\Delta P_{vni}, \Delta P_{WTG}, \int ACE_i]^T,$$

$$w_i^T = [w_{1i}, w_{2i}, w_{3i}, \Delta P_{wind}, \sum_{j=1, j \neq i}^N T_{ij} \Delta f_j]$$

$$\tilde{A}_i = \begin{bmatrix} A_i & \frac{1}{M_i} & 0 \\ 0 & -\frac{1}{T_{WT}} & 0 \\ \beta_i & 1 & 0 \end{bmatrix}, F_{3i} = \text{diag}\left\{\frac{1}{T_{g1i}}, \frac{1}{T_{g2i}}, \dots, \frac{1}{T_{gni}}\right\}$$

$$\tilde{B}_i = \begin{bmatrix} B_i \\ 0 \end{bmatrix}, F_i = \begin{bmatrix} -\frac{1}{M_i} & 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 & -2\pi \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & F_{3i} & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{T_{WT}} & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix},$$

where ΔP_{WTG} , ΔP_{wind} , T_{WT} are wind turbine generator output power change, wind power change and wind turbine generator time constants respectively, and other parameters and their meanings are given in (Zhang *et al.*, 2013b). $d(t)$ is a time-varying differentiable function that satisfies

$$0 \leq d(t) \leq h \quad \dot{d}(t) \leq \mu \leq 1 \quad (2)$$

Note that, in order to eliminate frequency deviation, the integral of ACE_i is used as an additional state variable.

The inherent intermittent and non-dispatchable features of wind power reduce the inertia instant of system, which decreases frequency stability when there exist disturbances. The practical LFC requires controllers to let power interchange and frequency go back scheduled values quickly. Hence, an index of decay rate α , related to settling time is introduced, i.e., setting $x_i(t) = e^{\alpha t} \tilde{x}_i$, then system (1) is transformed into

$$\dot{x}_i(t) = (\alpha I + \tilde{A}_i) x_i + e^{\alpha d(t)} \tilde{B}_i K_i x_i(t - d(t)) \quad (3)$$

Definition 1 (He *et al.* 2006) System (1) is said to be robustly exponentially stable with a decay rate α , if the trivial solution $\tilde{x}_i(t) \equiv 0$ is exponentially stable with a decay rate α for all admissible uncertainties, i.e., if there exist $\alpha > 0$ and $H > 1$ such that

$$\|\tilde{x}_i(t)\| \leq H \phi e^{-\alpha t}, \quad \phi = \sup_{0 \leq \theta \leq h} \|\tilde{x}_i(\theta)\|, \forall t > 0 \quad (4)$$

2.2 Object of this paper

This paper aims to develop a delay-dependent exponential criterion, based on which the robust load frequency controllers with decay rate can be designed. These controllers are robust to IR in power systems. Also, if load fluctuations emerge, within a few seconds, these controllers are able to stabilize the power system with different penetration levels of wind power.

3. ROBUST LOAD FREQUENCY CONTROLLER BASED ON DECAY RATE

In this part, to develop robust load frequency controllers based on decay rate and time delay, a delay-dependent exponential criterion with those two indexes will be derived, which guarantees the system stability. Then, this condition is transformed into LMIs for solving controller gains. When the delay upper bound is given, the optimal load frequency controllers can be determined by maximizing decay rate α . Also, for a desired α , controller gains can be obtained with allowable maximum delay margins.

3.1 Robust exponential performance analysis

First, suppose gain matrix K_i is given. The following theorem is developed in terms of LMIs for guaranteeing the robustly exponential stability of system (1), which presents the relationship between the time delay and decay rate.

Theorem 1. Given scalars h, μ and α , system (1) is robustly exponentially stable if there exist symmetric matrices $P > 0, Q_i > 0, R > 0, i = 1, 2$, and any matrices S and H such that the following LMI holds

$$\Pi < 0 \quad (5)$$

where

$$\begin{aligned} \Pi = & 2E_1^T P E_2 + e_1^T (Q_1 + Q_2) e_1 - (1 - \mu) e_2 Q_1 e_2 \\ & - e_3 Q_2 e_3 + h^2 e_6^T R e_6 - E_3^T \begin{bmatrix} R_1 & S \\ * & R_1 \end{bmatrix} E_3 \\ & + [e_1^T e_2^T e_6^T] H \left[e_6 - (\alpha I + \tilde{A}_i) e_1 - e^{\alpha d(t)} \tilde{B}_i K_i e_2 \right] \end{aligned}$$

and $R_1 = \begin{bmatrix} R & 0 \\ 0 & 3R \end{bmatrix}$, $E_1 = \text{col} \{e_1, d(t)e_4, d(t)e_4 + (h - d(t))e_5\}$,

$E_2 = \text{col} \{e_6, e_1 - (1 - \mu)e_2, e_1 - e_3\}$,
 $E_3 = \text{col} \{e_1 - e_2, e_1 + e_2 - 2e_4, e_2 - e_3, e_2 + e_3 - 2e_5\}$,
 $e_i = [0_{n \times (i-1)n}, I_{n \times n}, 0_{n \times (6-i)n}]$, $i = 1, 2, \dots, 6$.

Proof. Firstly, construct the following Lyapunov-Krasovskii functional:

$$\begin{aligned} V(t) = & \varepsilon^T(t) P \varepsilon(t) + \int_{t-d(t)}^t x^T(s) Q_1 x(s) ds + \int_{t-h}^t x^T(s) Q_2 x(s) ds \\ & + h \int_{-h}^0 \int_{t+\theta}^t \dot{x}^T(s) R \dot{x}(s) ds d\theta. \end{aligned}$$

where $\varepsilon(t) = \text{col} \{x(t), \int_{t-d(t)}^t x(s) ds, \int_{t-h}^t x(s) ds\}$ and $P > 0, Q_i > 0, i = 1, 2, R > 0$ are symmetric positive definite matrices.

Secondly, define notations $\xi(t) = \text{col} \{x(t), x(t-d(t)), x(t-h), \int_{t-d(t)}^t \frac{x(s)}{d(t)} ds, \int_{t-h}^{t-d(t)} \frac{x(s)}{h-d(t)} ds, \dot{x}(s)\}$ and $R_1 = \begin{bmatrix} R & 0 \\ 0 & 3R \end{bmatrix}$.

Calculate the derivative of the LKF along the solutions of system (3). Employing the Wirtinger-based inequality (Seuret *et al.*, 2013) combined with the reciprocally convex approach (Park *et al.*, 2011) to estimate the derivative of the LKF and then, considering that time-varying delay $d(t)$ satisfies condition (2), we have $\dot{V}(t) \leq \xi^T(t) \Pi \xi(t)$ where Π is defined in (5). Then, inequality $\dot{V}(t) < 0$ holds if LMI (5) holds and therefore, inequality $V(x(t)) < V(x(0))$ is obtained.

Thirdly, following the similar line in (He *et al.* 2006), we have

$$V(x(0)) \leq \Upsilon \|\phi\|^2 \quad (6)$$

where

$$\begin{aligned} \Upsilon = & \lambda_{\max}(P) + 2h^2 \lambda_{\max}(P) + h \lambda_{\max}(Q_1) + h \lambda_{\max}(Q_2) \\ & + 2h^2 \lambda_{\max}(R) \left[\lambda_{\max} \left((\alpha I + \tilde{A}_i)^T (\alpha I + \tilde{A}_i) \right) \right. \\ & \left. + \lambda_{\max} \left((e^{\alpha d(t)} \tilde{B}_i K_i)^T (e^{\alpha d(t)} \tilde{B}_i K_i) \right) \right] \end{aligned}$$

On the other hand

$$V(x(t)) \geq \lambda_{\min}(P) \|x(t)\|^2 = \lambda_{\min}(P) e^{2\alpha t} \|\tilde{x}(t)\|^2 \quad (7)$$

Combining inequalities (6),(7) and $V(x(t)) < V(x(0))$ yields

$$\|\tilde{x}(t)\| \leq \sqrt{\frac{\Upsilon}{\lambda_{\min}(P)}} \|\phi\| e^{-\alpha t}$$

Based on Definition 1, system (1) is robustly exponentially stable and has the exponential convergence rate α .

3.2 Controller design based on LMIs

When gain matrix K_i in Theorem 1 remains to be solved, inequality (5) in Theorem 1 is no longer a LMI. A transformation is needed to derive the following theorem in terms of LMI so that controller gains can be obtained.

Theorem 2. Given scalars h, μ and α , system (1) is robustly exponentially stable if there exist symmetric matrices $\hat{P} > 0, \hat{Q}_i > 0, \hat{R} > 0, i = 1, 2$, and any matrices \hat{S}, \hat{H}_1 and V such that the following LMI holds

$$\hat{\Pi} < 0 \quad (8)$$

where

$$\begin{aligned} \hat{\Pi} = & 2E_1^T \hat{P} E_2 + e_1^T (\hat{Q}_1 + \hat{Q}_2) e_1 - (1 - \mu) e_2 \hat{Q}_1 e_2 \\ & - e_3 \hat{Q}_2 e_3 + h^2 e_6^T \hat{R} e_6 - E_1^T \begin{bmatrix} \hat{R}_1 & \hat{S} \\ * & \hat{R}_1 \end{bmatrix} E_1 \\ & + [e_1^T e_2^T e_6^T] E_0 \left[\hat{H}_1^T e_6 - (\alpha I + \tilde{A}_i) \hat{H}_1^T e_1 - e^{\alpha d(t)} \tilde{B}_i V e_2 \right] \end{aligned}$$

and $E_i, i = 1, 2, 3$, and e_i are defined as Theorem 1; $E_0 = [I, aI, bI]$ with tuning parameters a and b ; the other parameters are given in Theorem 1 with superscript \wedge .

Proof. Pre- and post-multiplying inequality (5) by $\text{diag} \{\hat{H}_1, \hat{H}_1, \hat{H}_1, \hat{H}_1, \hat{H}_1\}$ and its transpose, respectively. Let $\hat{H}_1 = H_1^{-1}$, $H = [H_1^T, aH_1^T, bH_1^T]^T$, $\hat{P} = \text{diag} \{\hat{H}_1, \hat{H}_1, \hat{H}_1\}^T P \text{diag} \{\hat{H}_1, \hat{H}_1, \hat{H}_1\}$, $\hat{S} = \text{diag} \{\hat{H}_1, \hat{H}_1\}^T S \text{diag} \{\hat{H}_1, \hat{H}_1\}$, $\hat{Q}_1 = \hat{H}_1^T Q_1 \hat{H}_1$, $\hat{Q}_2 = \hat{H}_1^T Q_2 \hat{H}_1$, $\hat{R} = \hat{H}_1^T R \hat{H}_1$, $\hat{R}_1 = \text{diag} \{\hat{H}_1, \hat{H}_1\}^T R_1 \text{diag} \{\hat{H}_1, \hat{H}_1\}$, and $V = K_i \hat{H}_1$. Then,

inequality (8) holds and the closed-loop system is robustly exponential stable. The controller gain can be calculated by

$$K_i = V\hat{H}_1^{-1} \quad (9)$$

3.3 Summary of the presented method

The developed method is summarized as follows.

Step1. Model establishment. The state-space model is developed for area i under deregulated LFC scheme penetrated with wind power. Each area is equipped with a state-feedback controller.

Step2. Controller design. Based on Theorem 2 and the binary search technique, controller gains can be optimized through maximizing α for a preset delay upper bound by following the diagram in Fig. 2. Similarly, for the desired decay rate, the controller gains is determined while maximizing the delay upper bound.

Step3. Simulation verification. Case studies are carried out under deregulated environment to verify the effectiveness of designed controllers.

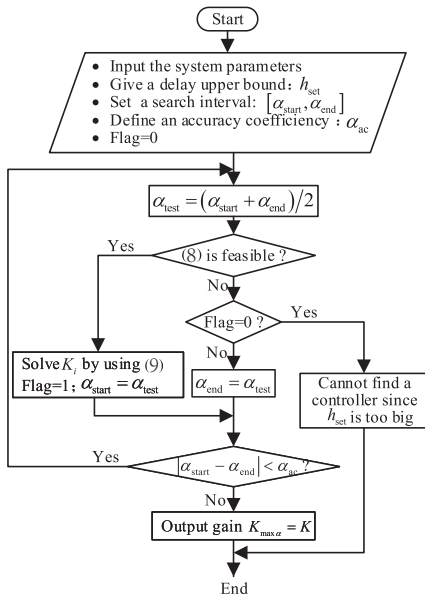


Fig. 2. Steps of optimizing controller gains for a preset delay upper bound.

4. CASE STUDIES

Based on multi-area LFC schemes, case studies are carried out under the deregulated environment. Firstly, the one-area scheme is considered to show how different penetrations of wind influence the frequency response of system when the load fluctuations are introduced. In order to verify the effectiveness of controllers designed, the deregulated three-area power system is considered, while in each area, two Gencos and two Discos are included. The parameter information refers to (Zhang *et al.*, 2013b). As a practical matter, the time-varying delays are considered as one special type of random delays, whose upper bounds in different areas are preset as the same value during the design of the controllers.

4.1 Controller design

Theorem 2 employs two tuning parameters a and b . For the deregulated three-area LFC scheme, assume the upper bound of time-varying delays equal to $3s$ and $\mu = 0.1$. We tuned a and b to find a feasible solution of LMI (8) by trial and error. Then, in order to obtain satisfactory robust control performance, we adjusted these parameters to obtain the maximum decay rate α following the flow chart Fig.2 via trial and error. Hence, we finally chose parameters $a = -0.4, b = 2$ in Theorem 2. The state-space model of each area has eight dimensions, and its state feedback controller has the same order. According to Theorem 2, the controller gains (K_1) are obtained in Table 1 together with other controllers developed in (Zhang *et al.*, 2013b) (C_1). Also, when some particular decay rates are required for shortening the settling time so as to stabilize the system, the related controllers can be calculated while obtaining the maximum delay margins. For decay rate $\alpha = 0.3$, controller K_2 is shown in Table 2 where h_1, h_2 and h_3 represent the delay upper bounds of area 1, area 2 and area 3 respectively.

4.2 Simulation verification

Firstly, in order to illustrate the aforementioned impacts of integrating wind power into the power system, the one-area deregulated LFC scheme is used, and its frequency regulation only resorts to the primary control. Different wind penetration level can be adjusted with the values of IR : 0%, 10%, 20%, 30%. When wind generators gradually substitute conventional generators, the total inertia of the system decreases while the equivalent regulation constant increases. The inertia and regulation constant of the system can be calculated by $M_{IR} = M_0(1 - IR)$ and $R_{IR} = R_0/(1 - IR)$, respectively (Nguyen *et al.*, 2016). System parameters are listed in Table 3.

When there appears a random change of wind power within $\pm 0.05pu$ plus a step load change of $0.28 pu$, Fig. 3 shows the frequency variations of the deregulated power system with various IRs. As can be seen, high percentages of IR can result in increasing fast and apparent frequency deviation. How to design controllers that have robustness against different IRs and are able to depress and eliminate the frequency deviation quickly is meaningful.

Secondly, the three-area deregulated LFC scheme is employed to check whether the controllers based on decay rate and time delay are effective. Provided that the generator rate constraint is $0.1 pu/min$. A step load disturbance of $0.1 pu$ amplitude is demanded by each Disco in three areas ($\Delta P_{Li} = 0.2pu$), and Disco 1 in area 1 and area 2, and Disco 2 in area 3 demand $0.05pu, 0.04pu$ and $0.03pu$ as uncontracted loads ($\Delta P_{d1} = 0.05pu, \Delta P_{d2} = 0.04pu, \Delta P_{d3} = 0.03pu$). The contract between the Discos and the Gencos is given as

$$AGPM = \begin{bmatrix} 0.25 & 0 & 0.25 & 0 & 0.5 & 0 \\ 0.5 & 0.25 & 0 & 0.25 & 0 & 0 \\ 0 & 0.5 & 0.25 & 0 & 0 & 0 \\ 0.25 & 0 & 0.5 & 0.75 & 0 & 0 \\ 0 & 0.25 & 0 & 0 & 0.5 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}. \quad (10)$$

Table 1. Controller gains determined by this paper and (Zhang *et al.*, 2013b)

area	K_1 ($h=3$ $\alpha_1 = 0.1391$ $\alpha_2 = 0.2025$ $\alpha_3 = 0.2025$)	C_1
1	[-0.0336 -0.0281 -0.0648 -0.0608 -0.0119 -0.0160 -0.3038 -0.2024]	[0.0473 -0.1456 -0.0137]
2	[-0.0422 -0.0503 -0.0607 -0.0648 -0.0121 -0.0142 -0.3037 -0.2025]	[0.0361 -0.1233 -0.0483]
3	[-0.0324 -0.0653 -0.0628 -0.0689 -0.0161 -0.0121 -0.3037 -0.2025]	[0.0779 -0.1040 -0.0259]

For scenario 1, the step disturbance of wind power with 0.1 pu amplitude appears in each area. The simulated results for the ACE of area 1 equipped with controllers K_1 or C_1 are shown in Fig. 4. Fig. 4 (a) describes the frequency responses for the deregulated three-area scheme having zero IR. The ACE controlled by K_1 is represented with the red line whose amplitude is always lower than that of blue line for controller C_1 , even though the time they spend on tending to zero is similar. However, when the LFC scheme has 30% IR, Fig. 4 (b) indicates that controller K_1 enables the system to be stable after 35s. By contrast, controller C_1 is unable to eliminate the ACE within finite time.

For scenario 2, the deregulated three-area LFC is integrated with random wind power of 0.1 pu in each area, and its simulation results are shown in Fig. 5. Fig. 5 (a) reveals that, for the normal power system, controller K_1 performances better than C_1 does within 7s, and then, they will behave the same. When the system inertia is reduced by 30%, from Fig. 5 (b), the dynamic performance of controller K_1 remains almost unchanged while C_1 leads to frequency instability. Here, the robustness and decreased settling time of design method can be verified.

For desired decay rates, the trajectory convergence speed can be estimated. Based on Fig. 6, as the decay rate becomes more significant, the amplitude of ACE will be smaller, and less settling time will be spent.

Table 2. Controller gains determined by this paper with decay rate $\alpha = 0.3$

area	K_2 ($\alpha = 0.3$ $h_1 = 0.2637$ $h_2 = h_3 = 2.0703$)
1	[0.4870 0.6171 -0.3475 -0.3193 0.0250 -0.0707 -0.9346 -0.2338]
2	[-0.0561 -0.0592 -0.0897 -0.0956 -0.0179 -0.0209 -0.4483 -0.2989]
3	[-0.0430 -0.0790 -0.0926 -0.1016 -0.0239 -0.0179 -0.4481 -0.2988]

Table 3. Simulation parameters for a deregulated standalone control area with wind effect

IR(%)	T_t	T_g	R	D	β	M
0 %	0.32	0.06	2.4	0.0084	0.4250	0.1667
10 %	0.32	0.06	2.6667	0.0084	0.4250	0.1500
20 %	0.32	0.06	3.0000	0.0084	0.4250	0.1334
30 %	0.32	0.06	3.4286	0.0084	0.4250	0.1167

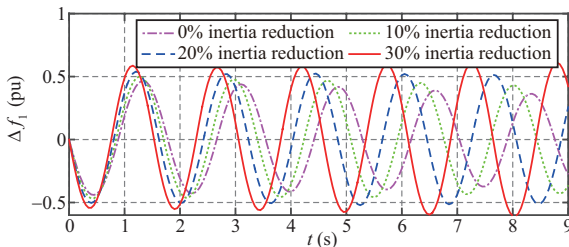


Fig. 3. Frequency deviations of deregulated standalone power system considering the effect of wind.

5. CONCLUSION

This paper has investigated the robust exponential LFC controller for the delayed power system considering the penetration of wind power. Based on the Lyapunov theory

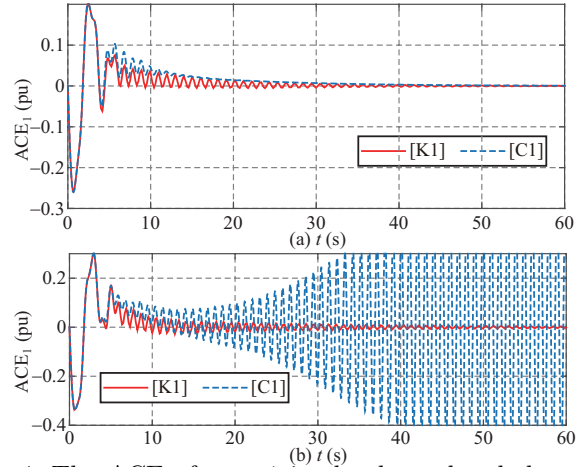


Fig. 4. The ACE of area 1 in the deregulated three-area LFC scheme with IRs (a)0%; (b) 30%.

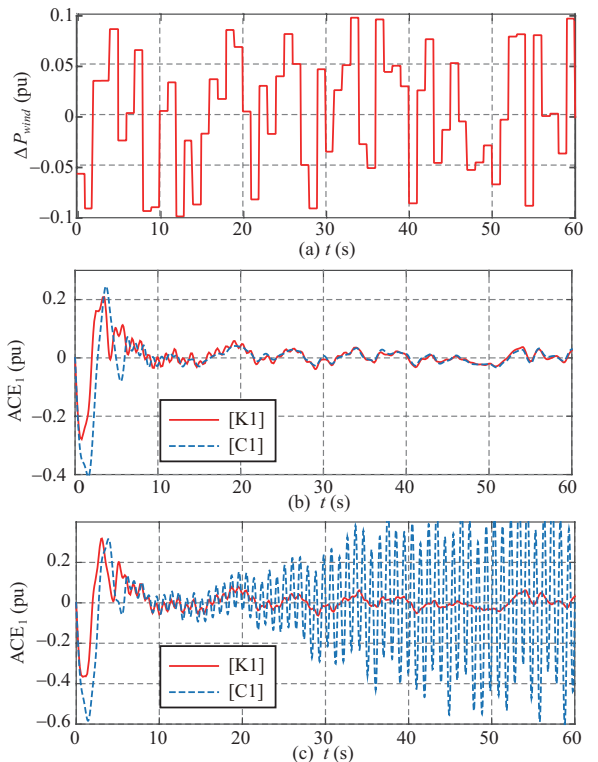


Fig. 5. The ACE of area 1 in the deregulated three-area LFC scheme with 30% IR.

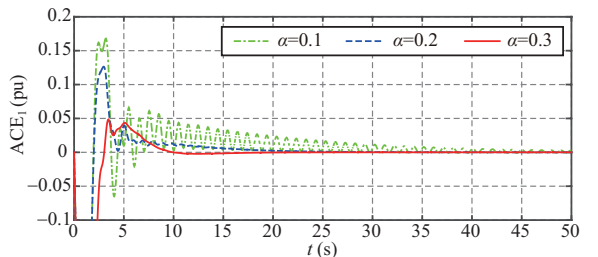


Fig. 6. The ACE of area 1 in the deregulated three-area LFC scheme with various decay rates.

and LMI techniques, a delay-dependent stability criterion has been established, which shows the relationship between decay rate and time-varying delay. When controller gains remain to be resolved, the theorem established no longer contains LMIs. A transformation is essential to turn the non-LMIs into LMIs. Then, for a preset delay upper bound, controller gains are optimized with the allowable maximum decay rate. Also, the information of controller can be determined for a required decay rate while maximizing the delay upper bound.

Case studies have been carried out on the deregulated multi-area LFC scheme. First, the deregulated one-area LFC scheme is employed to demonstrate that the IR leads to faster system response and increased frequency deviation. For simplicity, only the primary control is utilized for regulating frequency. Then, two scenarios including the step disturbance or random change of wind power integrated into each area of three-area LFC scheme, have been considered. Hence, the effectiveness of developed controllers has been verified in terms of being robust to IR and eliminating the frequency deviation. From a practical viewpoint, the method proposed in this paper can be applied to addressing the problem of parametric uncertainties in the smart grid, where there exist flexible demand response equipments. That is, the number of thermal loads and electric vehicles that participate in accommodating intermittent energy resources is varied according to the scheduling requirements.

REFERENCES

- Z. Afshar, N.T. Bazargani, S.M.T. Bathaee. (2018). "Virtual synchronous generator for frequency response improving and power damping in microgrids using adaptive sliding mode control," *Proceedings of the 10th International Conference and Exposition on Electrical and Power Engineering*, pp. 199-204.
- H.P. Beck, R. Hesse. (2007). "Virtual synchronous machine," *Proceedings of the 9th International Conference Electrical Power Quality and Utilisation*, pp. 1-6.
- H. Bevrani, M.R. Feizi, S. Ataei. (2016). "Robust frequency control in an islanded microgrid: H_∞ and μ -synthesis approaches," *IEEE Transactions on Smart Grid*, vol. 7, no. 2, pp. 706-717.
- H. Bevrani, T. Hiyama. (2008). "Robust decentralised PI based LFC design for time delay power systems," *Energy Conversion and Management*, vol. 49, no. 2, pp. 193-204.
- S. Bhowmik, K. Tomovic, A. Bose. (2004). "Communication models for third party load frequency control," *IEEE Transactions on Power Systems*, vol. 19, no. 1, pp. 543-548.
- M. Chilali, P. Gahinet. (1996). " H_∞ design with pole placement constraints: an LMI approach," *IEEE Transactions on Automatic Control*, vol. 41, no. 3, pp. 358-367.
- J.F. Dai, Y. Tang, Q. Wang. (2019). "Fast method to estimate Maximum penetration level of wind power considering frequency cumulative effect" *IET Generation, Transmission and Distribution*, vol. 13, no. 9, pp. 1726-1733.
- K. Dehghanpour, S. Afsharnia. (2015). "Electrical demand side contribution to frequency control in power systems: a review on technical aspects," *Renewable and Sustainable Energy Reviews*, vol. 41, pp. 1267-76.
- J. Dong, G. Xue, M. Dong, X. Xu. (2015). "Energy-saving power generation dispatching in China: regulations, pilot projects and policy recommendations a review," *Renewable and Sustainable Energy Reviews*, vol. 43, pp. 1285-300.
- S. Han, S. Han. (2014). "Development of short-term reliability criterion for frequency regulation under high penetration of wind power with vehicle-to-grid support," *Electric Power Systems Research*, vol. 107, pp. 258-267.
- Y. He, M. Wu, J.H. She. (2006). "Delay-dependent exponential stability of delayed neural networks with time-varying delay," *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 53, no. 7, pp. 553-557.
- L. Jiang, W. Yao, J.Y. Wen, S.J. Cheng, Q.H. Wu. (2009). "Delay-dependent stability for load frequency control with constant and time-varying delays," *IEEE Transactions on Power Systems*, vol. 27, no. 2, pp. 932-941.
- L. Jin, C.K. Zhang, Y. He, L. Jiang, M. Wu. (2019). "Delay-dependent stability analysis of multi-area load frequency control with enhanced accuracy and computation efficiency," *IEEE Transactions on Power Systems*, vol. 34, no. 5, pp. 3687-3696.
- N. Nguyen, J. Mitra. (2016). "An analysis of the effects and dependency of wind power penetration on system frequency regulation," *IEEE Transactions on Sustainable Energy*, vol. 7, no. 1, pp. 354-363.
- P. Ojaghi, M. Rahmani. (2017). "LMI-based robust predictive load frequency control for power systems with communication delays," *IEEE Transactions on Power Systems*, vol. 32, no. 5, pp. 4091-4100.
- P.G. Park, J.W. Ko, C. Jeong. (2011). "Reciprocally convex approach to stability of systems with time-varying delays," *Automatica*, vol. 47, pp. 235-238.
- C.J. Ramlal, A. Singh, S. Rocke, M. Sutherland. (2019). "Decentralized fuzzy H_∞ iterative learning LFC with time-varying communication delays and parametric uncertainties," *IEEE Transactions on Power Systems*, vol. 34, no. 6, pp. 4718-4727.
- A. Seuret, F. Gouaisbaut. (2013). "Wirtinger-based integral inequality: application to time-delay systems," *Automatica*, vol. 49, no. 9, pp. 2860-866.
- M.A. Torres L, L.a.C. Lopes, L.A. Moran T, J.R. Espinoza. (2014). "Self-tuning virtual synchronous machine: a control strategy for energy storage systems to support dynamic frequency control," *IEEE Transactions on Energy Conversion*, vol. 29, no. 4, pp. 833-840.
- D.H. Tungadio, Y.X. Sun. (2019). "Load frequency controllers considering renewable energy integration in power system," *Energy Reports*, vol. 5, pp. 436-453.
- F. Yang, J. He, Q. Pan. (2018a). "Further improvement on delay-dependent load frequency control of power systems via truncated B-L inequality," *IEEE Transactions on Power Systems*, vol. 33, no. 3, pp. 5062-5071.
- F. Yang, J. He, D. Wang. (2018b). "New stability criteria of delayed load frequency control systems via infinite-series-based inequality," *IEEE Transactions on Industrial Informatics*, vol. 14, no. 1, pp. 231-240.
- C.K. Zhang, L. Jiang, Q.H. Wu, Y. He, M. Wu. (2013b). "Delay-dependent robust load frequency control for time delay power systems," *IEEE Transactions on Power Systems*, vol. 28 no. 3, pp. 2192-2201.