

Robust Load Frequency Control for Isolated Microgrids Based on Double-loop Compensation

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Abstract—Frequency is an important indicator for the operation of microgrids. However, the randomness and uncertainty of renewable energy and load variability may lead to frequency undulation. So, a robust load frequency control (LFC) is proposed for isolated wind–diesel microgrids considering time delay and parameter uncertainty. The control strategy can suppress frequency fluctuation and optimize frequency dynamic response. First, the double compensation loop, including feedforward control and integral sliding mode control (SMC), is devised to provide anti-disturbance compensation for the diesel generator system and ameliorate the frequency stability of independent microgrids. Secondly, a dynamic fuzzy controller, composed of wind speed and load demand, is designed to provide real-time response reference power for doubly fed induction generator systems (DFIGs), which can promote the effective participation of a wind turbine system for frequency regulation. Then, the proportional differential (PD) parameters of a dynamic fuzzy controller and the frequency adjustment compensation of DFIGs can be obtained by using a particle swarm optimization (PSO) algorithm. Thirdly, load demand is an important index of the robust dynamic load frequency control method; the radial basis function (RBF) neural network observer (NNO) based on the LFC model is presented to obtain more accurate load deviations and improve the control precision of LFC. The performance of the proposed LFC method is tested under different operation cases.

Index Terms—Load frequency control, microgrid, neural network observer, sliding mode, time delay and parameter uncertainty.

I. INTRODUCTION

RENEWABLE energy, may play an active role in solving the shortage of fossil energy and global warming [1], [2]. However, the power generated by renewable energy may be random and uncertain, which can increase the frequency instability and deteriorate the operating state of the microgrid [3], [4]. Unfortunately, both random load fluctuation and

time delay of the open communication network structure may exist in practical microgrid systems. The load fluctuation can also affect the accuracy of frequency control. Time delay may not only degrade the performance of LFC, but also cause the closed-loop control system instability. Therefore, the frequency control of isolated microgrids has attracted a lot of attention in recent years [5]–[7].

A diesel generator is often equipped to the isolated microgrid because of its stable power output. It is necessary to design effective LFC to improve dynamic performance and robustness. In [8], [9], LFC based on adaptive control and fuzzy control is combined to smooth the system undulation. In [10]–[15], different LFCs may be designed to optimize frequency regulation for the power system considering communication delay. Then the proportional integral (PI) LFC is developed to get better frequency regulation effects, which can benefit from the gains of the PI controller and the delay margin of the LFC scheme [10]. In [12], the proportional integral differentiation (PID) method for LFC is proposed to provide a robust frequency control. In [14], the linear matrix inequality method is studied to fix the characteristic of LFC under different uncertainties and special time-varying conditions.

As a typical robust control method, SMC is concerned about its rapidity and extensive engineering applications [16]–[25]. The SMC is also insensitive to external disturbance, and the controller parameters can be adjusted according to the system dynamic state. Therefore, LFC based on the sliding model algorithm may greatly improve system robustness and transient performance. In [19], [20], LFC is proposed for interconnected systems with uncertainties based on SMC. The presented controller can assure the stable operations over a wide range. Sliding mode LFC is designed by using adaptive dynamic programming for the parameter optimization [21]. Compared with the PI LFC, both frequency characteristics and response speed are improved at the same time. In [22], the sliding mode LFC with disturbance observer is designed to improve the controller accuracy and overcome the frequency deviation. The sliding mode LFC is applied for the non-linear power system with time-delay [23], [24] to adjust the speed response and robustness. In [25], [26], the wind integration of the power system is modeled to analyze the influence of different wind energy permeabilities on LFC. In [27], it is verified that the adjustment characteristics of the WTG can assure stable wind farm operations. The pitch angle control [28] may adjust the output power of WTG for smoothing the frequency fluctuation

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in composite multilayer frequency controls. In [29], [30], the combined fuzzy-based speed controller and the auxiliary frequency controller for the DFIG are proposed to realize faster speed regulation and smaller frequency deviation. The integrated controller of WTG with both inertial response and primary frequency regulation is designed to provide dynamic frequency support [31], [32]. The above studies are carried out to assist the WTG to participate in frequency adjustment through controlling the inertia and pitch angle of the wind turbine. However, the hybrid microgrid can not only determine the generator controller design, but also need to coordinate the operation of various type generators.

According to the above analysis, the robust dynamic LFC strategy for an isolated wind-diesel microgrid with time delay and parameter uncertainty is proposed to improve the frequency performance. Based on the wind-diesel microgrid model, the main contributions of this paper are as follows: 1) the double compensation loop controller is designed for a diesel generator. The feedforward control is designed to suppress the frequency deviation directly of an isolated microgrid. The integral SM feedforward LFC is used to improve the dynamic robustness for the isolated microgrid including time delay, parameter uncertainties and source-load fluctuations. 2) For the DFIG side, the load response reference power of the rotor side converter (RSC) is obtained by the dynamic fuzzy controller, which can ensure DFIGs are fully controlled and joined in the change of the system frequency. The excellent feature of the global optimization of the PSO algorithm is used in the fuzzy controller in this part, the PD parameters of the dynamic fuzzy controller and the frequency adjustment compensation of DFIG are concluded as a multi-objective function which can be optimized by the PSO algorithm. 3) RBF NNO is created for load deviation, and NNO can improve the control precision of the proposed LFC method.

The remainder of this paper is organized as follows. The LFC model of a typical wind-diesel isolated microgrid is established in Section II. In Section III, the robust dynamic LFC method is proposed for an isolated microgrid, and the double compensation loop, dynamic fuzzy controller, RBF neural network observer and PSO with multi-objective function are designed in this section. In Section IV, simulation results are shown and analyzed by comparing the different LFC methods and operation modes. Conclusions are presented in Section V.

II. LFC MODEL OF ISOLATED WIND-DIESEL MICROGRID

A typical isolated wind-diesel microgrid model, which consists of WTG, diesel generator and load, is shown as Fig. 1.

In Fig. 1, Δf , ΔP_m , ΔP_v , ΔE , ΔP_L , ΔP_W , ΔP_{me} are the frequency offset value, output power of diesel generator, governor value position, voltage angle, load variable and output power of WTG, windmill mechanical output power, respectively [33]; T_p , T_{ch} , T_g are time constants of the system, diesel generator and governor, respectively. The power system here refers to the rotor equipment and load. K_p , K_ε are the gain of system, integral control, respectively. r is the governor speed governing coefficient; d_1 is the time delay; Δv_w , $\Delta\beta$, $\Delta\lambda$, $\Delta\omega$ are the changes of wind speed, blade pitch angle, tip

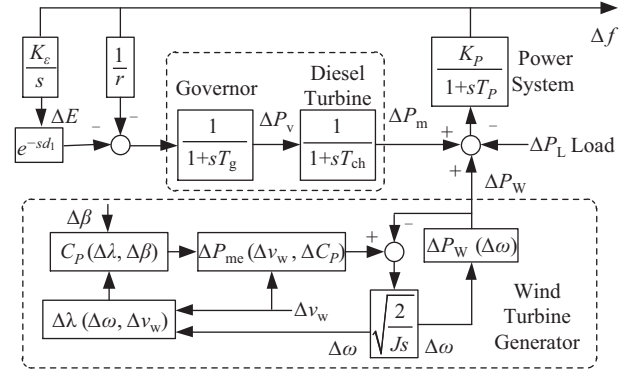


Fig. 1. Typical model of isolated wind-diesel microgrid.

speed ratio, angular rotor speed, respectively. C_p is the power coefficient, and J is the moment of inertia of WTG.

A. LFC Model of Isolated Wind-diesel Microgrid

The time-delay LFC equations of an isolated wind-diesel microgrid are determined from Fig. 1 as:

$$\Delta \dot{f}(t) = -\frac{1}{T_p} \Delta f(t) + \frac{K_p}{T_p} (\Delta P_m(t) + \Delta P_W(t)) - \frac{K_p}{T_p} \Delta P_L(t) \quad (1)$$

$$\Delta \dot{P}_m(t) = -\frac{1}{T_{ch}} \Delta P_m(t) + \frac{1}{T_{ch}} \Delta P_v(t) \quad (2)$$

$$\Delta \dot{P}_v(t) = -\frac{1}{T_g r} \Delta f(t) - \frac{1}{T_g} \Delta P_v(t) - \frac{1}{T_g} \Delta E(t - d_1) \quad (3)$$

$$\Delta \dot{E}(t) = K_\varepsilon \Delta f(t) \quad (4)$$

B. Model of WTG

In Fig. 1, the output power of windmill ΔP_{me} [34] is denoted as:

$$\Delta P_{me} = \frac{\Delta C_p(\Delta\lambda, \Delta\beta) \Delta v_w^3 \rho A_r}{2} \quad (5)$$

where ρ is air density, A_r is the sweep area of wind turbine.

Angular rotor speed $\Delta\omega$ is given by:

$$\Delta\omega^2 = \int \frac{2}{J} (\Delta P_W - \Delta P_{me}) dt \quad (6)$$

ω_0 is the synchronous angular velocity of the rotor, the WTG output power ΔP_W [36], [37] can be expressed as:

$$\Delta P_W = \frac{-3V^2(\Delta\omega - \omega_0)(1 + (\Delta\omega - \omega_0))R_2}{(R_2 - (\Delta\omega - \omega_0)R_1)^2 + (\Delta\omega - \omega_0)^2(X_1 + X_2)^2} \quad (7)$$

where V is the phase voltage, R_1 , R_2 are resistance of stator and rotor, X_1 and X_2 are the stator reactance, and the rotor reactance, respectively.

III. THE PROPOSED ROBUST LFC STRATEGY

In an isolated wind-diesel microgrid, the output of the DFIGs is influenced by the wind speed, however, its instantaneous active power support can be provided when operating above the rated wind speed [27], [31]. The dynamic fuzzy

controller is designed to take into account the load demand and wind speed for making full use of DFIGs. Then the diesel generator is the main part of the frequency regulation which can be controlled through the feedforward control and integral SMC method. The proposed robust dynamic LFC strategy can optimize the output of the wind-diesel microgrid and improve the dynamic performance of the frequency response. Furthermore, the LFC accuracy can be improved by using the designed RBF NNO.

A. The Double Compensation Loop Design for Diesel Generator

The double compensation loop is composed of the feedforward compensation loop and integral SMC compensation loop, which is designed as follows.

The feedforward control is added according to the frequency deviation. The output ΔS_g of the feedforward control is used to adjust the diesel generator considering the system time-delay.

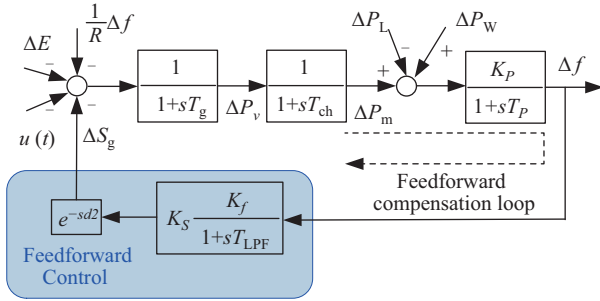


Fig. 2. The structure of feedforward control for diesel generator.

Where T_{LPF} is the time constant, K_f is the frequency coefficient, K_S is the feedforward coefficient. $u(t)$ is the output of the integral SMC. The value of the feedforward control and its derivative equation can be obtained by:

$$\Delta S_g(t) = K_S \Delta P_{ML}(t) = K_S \frac{K_f}{1+sT_{LPF}} \Delta f(t) \quad (8)$$

$$\Delta \dot{S}_g(t) = K_S \frac{K_f}{T_{LPF}} \Delta f(t) - \frac{1}{T_{LPF}} \Delta S_g(t) \quad (9)$$

In the LFC model with the feedforward control, the system communication time delays d_1 and d_2 are considered, and parameter uncertainties, such as source-load disturbance, are also added for the practical power system. Therefore, an integral SMC based on the LFC model shown in Fig. 2 is devised to improve the robustness of the frequency regulation and restrain the frequency deterioration caused by uncertain disturbances.

The state vector equations of (1)–(4) and (9) can be determined and rewritten as:

$$\dot{x}(t) = Ax(t) + Bu(t) + A_{di}x(t-d_i) + Fm(t) \quad (10)$$

where $x(t)$ is the state vector, $x(t) = [\Delta f, \Delta P_m, \Delta P_v, \Delta E, \Delta S_g]^T$, $i = 1, 2$, $m(t) = \begin{bmatrix} \Delta P_L & 0 \\ 0 & \Delta P_W \end{bmatrix}$. A , A_{di} , B , F are the matrix, time-delay parameter matrix, control matrix, and disturbance matrix, respectively. In an isolated microgrid,

the operating point is transformed by the constantly varying load demand and the fluctuating wind energy, which lead to system parameter uncertainties. So, the state equation (10) is rewritten as:

$$\dot{x}(t) = (A + \Delta A)x(t) + (B + \Delta B)u(t) + (A_{di} + \Delta A_{di})x(t-d_i) + (F + \Delta F)m(t) \quad (11)$$

where ΔA , ΔB , ΔA_{di} and ΔF represent the parameter uncertainties. For the convenience of designing the integral SMC, the parameter uncertainties can be described as:

$$w(t) = \Delta Ax(t) + \Delta Bu(t) + \Delta A_{di}x(t-d_i) + (F + \Delta F)m(t) \quad (12)$$

So, the state equation (11) can be denoted by:

$$\dot{x}(t) = Ax(t) + Bu(t) + A_{di}x(t-d_i) + w(t) \quad (13)$$

For designing the integral SMC, the assumptions have been given in [38]–[40].

Assumption 1 (A, B) is completely controllable.

Assumption 2 The $w(t)$ is bounded, and a known constant ξ with $\|w(t)\| \leq \xi$, $\|\cdot\|$ represents the Euclidean norm.

Assumption 3 The time delay state vector satisfies the condition $\|x(t-d_i)\| \leq x_{\max i}$, $x_{\max i} = \max \|x(t-d_i)\|$.

Assumption 4 The matrix A_{di} is bounded, there exists known constants ς_i such as $\|A_{di}\| \leq \varsigma_i$.

An integral sliding surface $\sigma(t)$ is designed as:

$$\sigma(t) = E_s x(t) - \int_0^t E_s (A - BH)x(\tau) d\tau \quad (14)$$

where matrix E_s is constant and full rank, which is chosen to ensure that matrix $E_s B$ is non-singular. Matrix H is a constant matrix and it is designed by pole assignment to satisfy: $\lambda(A - BH) < 0$.

When the dynamic trajectory finally come into contact with the sliding surface, the conditions $\sigma(t) = 0$ and $\dot{\sigma}(t) = 0$ are satisfied, so the equivalent controller $u_{eq}(t)$ is determined by (13)–(14) as:

$$u_{eq}(t) = -Hx(t) - (E_s B)^{-1} E_s A_{di} x(t-d_i) - (E_s B)^{-1} E_s w(t) \quad (15)$$

Substituting (15) into (13), the SM dynamic equation can be determined by:

$$\dot{x}(t) = \hat{A}x(t) + \hat{A}_{di}x(t-d_i) + \hat{w}(t) \quad (16)$$

where $\hat{A}_{di} = (I - B(E_s B)^{-1} E_s) A_{di}$, $\hat{w}(t) = (I - B(E_s B)^{-1} E_s) w(t)$, $\hat{A} = (A - BH)$.

Theorem 1 the sliding model dynamic (16) is bounded stability when the state vector satisfies by:

$$\|x(t)\| > \frac{2(\xi + \varsigma_1 + \varsigma_2) \|P\|}{\lambda_{\min}(Q)} \quad (17)$$

Proof Construct the Lyapunov function as $V(t) = x^T P x$, where P is the solution of $\hat{A}^T P + P \hat{A} = -Q$, Q is the positive definite symmetric matrix.

Substituting (16) into $\dot{V}(t)$, the $\dot{V}(t)$ can be written as:

$$\dot{V}(t) \leq -\lambda_{\min}(Q)\|x(t)\|^2 + 2\xi\|P\|\|x(t)\| + 2\zeta_i\|P\|x_{\max i} \quad (18)$$

When the state vector meets (17), the Lyapunov function satisfies $\dot{V}(t) < 0$, and the system (16) is stable.

The integral SMC also needs to meet the reaching condition [25]. The reaching law is designed as follows:

$$\dot{\sigma}(t) = -\tilde{k}|\sigma|^\alpha \arctan(\sigma) \quad (19)$$

where $\tilde{k} > 0$, $\alpha > 0$, $\arctan()$ is the arctangent function. In order to change the reaching time of the state trajectory and improve the robustness of the SMC, the adaptive law is adopted and $\tilde{k}$ satisfies $\tilde{k} = h|\sigma(t)|$ where h is an adaptive positive constant.

Theorem 2 the designed SMC is constructed as:

$$u(t) = -Hx - (E_s B)^{-1}\|E_s\|(\xi + (\zeta_i x_{\max i} + \tilde{k}|\sigma|^\alpha \arctan(\sigma))) \quad (20)$$

Proof Construct Lyapunov function as $V(t) = \|\sigma(t)\|$, and substituting (14) into the derivative of $V(t) = \|\sigma(t)\|$, the following equation can be derived as:

$$\begin{aligned} \dot{V}(t) &= \frac{\sigma^T(t)}{\|\sigma(t)\|} E_s (BHx(t) + Bu(t) + E_s w(t) \\ &\quad + E_s A_{di} x(t - d_i)) \\ &= \frac{\sigma^T(t)}{\|\sigma(t)\|} E_s BHx(t) + \frac{\sigma^T(t)}{\|\sigma(t)\|} E_s [-BHx \\ &\quad - B(E_s B)^{-1}(\tilde{k}|\sigma|^\alpha \arctan(\sigma)) + E_s(w(t) - \xi) \\ &\quad + E_s(A_{di}x(t - d_i) - \zeta_i x_{\max i})] \\ &\leq -\frac{\sigma^T(t)}{\|\sigma(t)\|} \|E_s\| \tilde{k} |\sigma|^\alpha \arctan(\sigma) < 0 \end{aligned} \quad (21)$$

Therefore, when the control law is used, system (13) can reach the surface of the sliding model. And prove that the system is stable under the switching surface of the design.

The designed integral SMC is shown in Fig. 3.

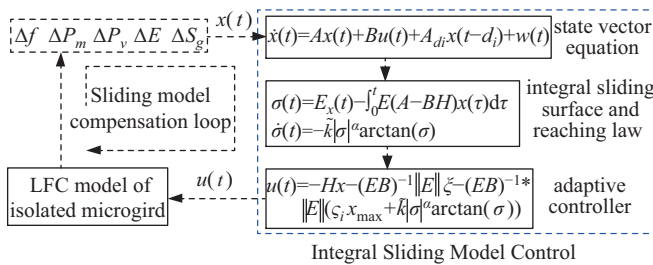


Fig. 3. The structure of an integral SMC compensation loop for diesel generator.

B. The Dynamic Fuzzy Controller Design for DFIGs

Because DFIGs can rapidly provide additional power compensation in a short time [27], [40], the dynamic fuzzy controller for RSC composed of fuzzy rules and dynamically adjusted PD parameters is designed by using wind speed and load demand to provide real-time load response reference

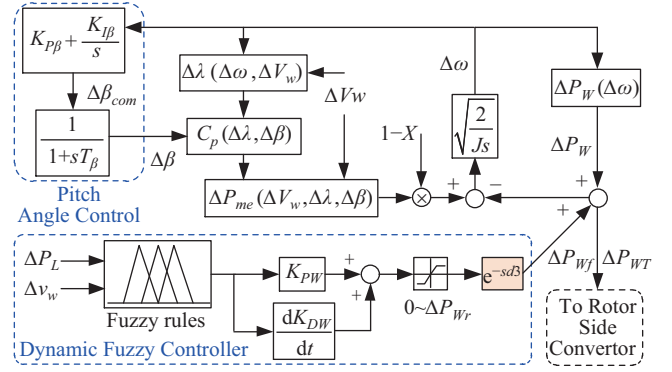


Fig. 4. The structure of dynamic fuzzy controller for RSC of DFIG.

power and promote effective participation of DFIGs in frequency regulation. The dynamic fuzzy controller is shown in Fig. 4.

Where $K_{P\beta}$, $K_{I\beta}$ and T_β are the PI parameters and the time constant of the pitch angle control. K_{PW} , K_{DW} and d_3 are the PD parameters and the time delay of the dynamic fuzzy controller. X is the adjustment factor. ΔP_{Wr} , ΔP_{Wf} and ΔP_{WT} are the frequency adjustment compensation changes of DFIGs, the output of the dynamic fuzzy controller and the reference power of RSC, respectively.

The frequency adjustment compensation ΔP_{Wr} can be expressed as:

$$\begin{cases} \Delta P_{Wr} = X \Delta P_{me}, & \omega_{th-} < \omega < \omega_{th+} \quad 0 < X < 1 \\ \Delta P_{Wr} = 0, & \omega \leq \omega_{th-} \quad X = 0 \end{cases} \quad (22)$$

where ω_{th+} and ω_{th-} are the maximum rotor speed and minimum rotor speed at the rated output power of DFIGs. An adjustment factor X is determined by the magnitude of the frequency adjustment compensation, and its value is affected by frequency deviation.

According to Fig. 4, the reference power of RSC is determined as:

$$\Delta P_{WT} = \Delta P_W + \Delta P_{Wf} \quad (23)$$

The output power of the dynamic fuzzy controller P_{Wf} is decided by using the fuzzy method together with the PD algorithm, the fuzzy rules are shown in Fig. 5.

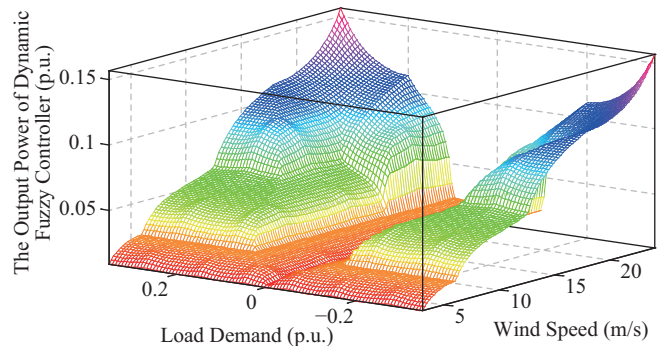


Fig. 5. The fuzzy rules of dynamic fuzzy controller.

The parameters X , K_{PW} and K_{DW} being adjusted dynamically according to load estimation, wind speed and frequency adjustment compensation of DFIGs need to minimize the time delay microgrid frequency offset. Therefore, the multi-objective function including the frequency and time-delay is constructed as:

$$f(X, K_{PW}, K_{DW}) = \alpha_p \int |\Delta f|^2 dt + \beta_p d_3 \quad (24)$$

where α_p , β_p are the coefficients of the multi-objective function, d_3 is the settling time-delay. The parameters of the multi-objective function satisfy the following conditions:

$$\begin{cases} 0 \leq X \leq 0.2 \\ 0 \leq K_{PW} \leq 600 \\ 0 \leq K_{DW} \leq 800 \end{cases} \quad (25)$$

The PSO algorithm is a global stochastic optimization algorithm based on the swarm intelligence heuristic. The algorithm can refer to the individual currently in the optimal position of the group and the optimal position reached before, which can adjust the direction and size of the next search.

According to the proposed multi-objective function (24), the PSO algorithm is used in this paper to optimize the fuzzy controller and obtain the optimal parameter values. The speed vector of the PSO algorithm is defined as:

$$\begin{aligned} V_l^{j+1} = & w_s V_l^j + c_1 \cdot \text{rand}_1 \cdot (g_{\text{best}l}^j - g_l^j) \\ & + c_2 \cdot \text{rand}_2 \cdot (z_{\text{best}l}^j - g_l^j) \end{aligned} \quad (26)$$

where w_s is the inertia factor, c_1 and c_2 are the acceleration constant, V_l^j is the velocity of individual l at iteration j , rand_1 and rand_2 are the rand numbers between 0 and 1, $g_{\text{best}l}^j$ is the best position of individual l until iteration j , g_l^j is the position of individual l , $z_{\text{best}l}^j$ is the best site of the group until iteration j . The location update is shown as:

$$g^{j+1} = g^j + V_{\text{step}}^{j+1} \quad (27)$$

The gearbox torque of DFIGs can be described as:

$$T_{\text{me}} = \frac{C_P(\lambda, \beta) v_w^3 \rho A_r}{2\omega} \quad (28)$$

Equation (28) is calculated by Taylor's expansion, ignoring higher-order terms, and the small signal model is:

$$T_{\text{me}} - T_{\text{mop}} = \bar{A}\Delta\omega + \bar{B}\Delta\beta + \bar{C}\Delta v_w \quad (29)$$

where T_{mop} is the power at the rated operation point, $\bar{A}$, $\bar{B}$, $\bar{C}$ are the first-order derivative of the rotor speed, the pitch angle and the wind speed, respectively. The constant Δv_w is ignored, and when DFIG is working at the rated point (β_{opt} , V_{opt}), (29) can be expressed as:

$$\Delta T_w = \bar{A}|_{\text{op}} \Delta\omega + \bar{B}|_{\text{op}} \Delta\beta \quad (30)$$

where ΔT_w is the gearbox torque deviation. Combine (30) with: $J \frac{d\omega}{dt} = T_{\text{me}} - T_e$, T_e is the electric torque, then the command of the variable pitch angle is derived as:

$$\Delta\beta_{\text{com}} = K_{P\beta} \Delta\dot{\omega} - K_{I\beta} \Delta\omega \quad (31)$$

where $K_{P\beta} = \frac{J}{\bar{B}|_{\text{op}}}$, $K_{I\beta} = \frac{\bar{A}|_{\text{op}}}{\bar{B}|_{\text{op}}}$, and $\Delta\beta = \frac{1}{1+sT_\beta} \Delta\beta_{\text{com}}$.

C. The RBF NNO Design

The RBF neural network observer (NNO) dynamically approximates the nonlinear part, and observes the output and disturbance of the system through the traditional observer reconstruction method, then corrects the weights dynamically through the dynamic error between the neural network output value and the system output value. In this way, the effect of the neural network approximation is better.

Based on the above advantages, the RBF NNO is designed based on the proposed model to improve the accuracy of the proposed LFC method. In the state equation (10), the load deviation is often replaced by a boundary constant. Define the load deviation as $n(t) = F_L \Delta P_L(t)$, $F_L = \begin{bmatrix} -\frac{K_P}{T_P} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}^T$. The load deviation is approximated by the RBF neural network (NN).

$$n(t) = W^T g(x) + e(x) \quad (32)$$

where $g(x)$ is the gauss function, W is the weight matrix between the hidden layer and output layer of the RBF neural network, $e(x)$ is the approximation error. The estimated value $\hat{n}(t)$ is approximately expressed as $\hat{n}(t) = \hat{W}^T g(\hat{x})$.

Because of the state vector equation (10), the NNO can be designed. The structure of RBF NNO is given in Fig. 6.

$$\begin{cases} \dot{\hat{x}}(t) = A\hat{x}(t) + Bu(t) + A_{di}\hat{x}(t - d_i) + f_W \\ \quad + \hat{n}(t) + L(y(t) - \hat{y}(t)) \\ \hat{y}(t) = G_o \hat{x}(t) \end{cases} \quad (33)$$

where $i = 1, 2$, L is the gain matrix of observer, $\hat{y}(t)$ is the output of the RBF NNO, $f_W = F_W \Delta P_W$, $F_W = \begin{bmatrix} \frac{K_P}{T_P} & 0 & 0 & 0 & 0 \end{bmatrix}^T$. Define state error $\tilde{x}(t) = x(t) - \hat{x}(t)$, $\tilde{x}(t - d_i) = x(t - d_i) - \hat{x}(t - d_i)$, output error $\tilde{y}(t) = y(t) - \hat{y}(t)$, and gauss function error $g(x, \hat{x}) = g(x) - g(\hat{x})$. According to (10), (32) and (33), the error system is described as:

$$\begin{cases} \dot{\tilde{x}}(t) = A_L \tilde{x}(t) + A_{di} \tilde{x}(t - d_i) + \tilde{W}^T g(\hat{x}) + \theta(x) \\ \tilde{y}(t) = G_o \tilde{x}(t) \end{cases} \quad (34)$$

where $\tilde{W} = W - \hat{W}$, $A_L = A - LG_o$ is an asymptotically stable Hurwitz matrix, $\theta(x) = W^T g(x, \hat{x}) + \tau(x)$ is bounded disturbance and it satisfies $\|\theta(x)\| \leq \psi$, $\psi > 0$.

In order to prove the stability of the error system, formula (34) is transformed into:

$$\begin{cases} s\tilde{x}(t) = A_L \tilde{x}(t) + A_{di} \tilde{x}(t - d_i) + \tilde{W}^T g(\hat{x}) + \theta(x) \\ \tilde{y}(t) = H_o(s)(A_{di} \tilde{x}(t - d_i) + \tilde{W}^T g(\hat{x}) + \theta(x)) \end{cases} \quad (35)$$

where $H_o(s) = \frac{E}{sI - A_L}$. Define $\bar{\theta}(x) = L^{-1}(s)\theta(x)$, filter $L^{-1}(s)$ is a transfer function with stable pole. $\delta(t) = L^{-1}(s)\tilde{W}^T g(\hat{x}) - \tilde{W}^T L^{-1}(s)g(\hat{x})$, $\|\delta(t)\| \leq c_r \|\tilde{W}\|_F$, c_r is a positive real number, $\tau(t - d_i) = L^{-1}(s)A_{di}\tilde{x}(t - d_i)$, $\|\tau(t - d_i)\| \leq \varsigma_i x_{\text{max}i}$. The (36) can be given as:

$$\begin{aligned} \tilde{y}(t) = & H_o(s)L(s)(\tau(t - d_i) + \delta(t) + \bar{\theta}(x) \\ & + \tilde{W}^T L^{-1}(s)g(\hat{x})) \end{aligned} \quad (36)$$

TABLE I
THE PARAMETERS OF ISOLATED WIND-DIESEL MICROGRID

Parameter	Value	Parameter	Value	Parameter	Value
K_p	120	T_p	15	r	0.49
T_{ch}	0.0728	T_g	0.273	K_e	0.3
K_f	1	T_{LPF}	0.05	K_s	0.25
A_r	14	J	62993	ρ	1.225
V	230.94	R_1	0.00397	R_2	0.00443
X_1	0.00376	X_2	0.0534	T_β	0.2

In case 1, four different LFC methods for a diesel generator are used to verify the improvement of frequency dynamic performance by double compensation loops. Case 2 is designed to verify that the dynamic fuzzy controller can effectively improve the frequency response performance. In case 3, different time-delay and uncertain parameters are tested for the isolated microgrid by using the proposed robust dynamic LFC method. In addition, it is verified that using the designed RBF NNO in case 4 can improve the control accuracy of the proposed method. Case 1 Different LFC Methods for Diesel Generator

To verify the improvement of the frequency dynamic performance of the diesel generator by the proposed double compensation loop, the PI control, the feedforward control, the SMC and the double compensation loop control are used to provide dynamic compensation for the governor of the diesel generator, and the frequency deviation and power output fluctuation of the diesel generator caused by different LFC methods are shown in Figs. 10 and 11. The active load power fluctuation and wind speed variety curve are shown in Fig. 9.

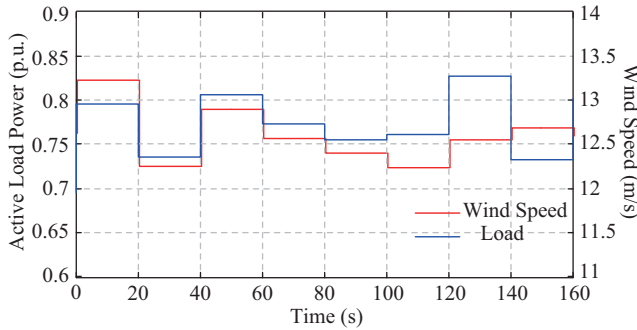


Fig. 9. Wind speed and load fluctuation curve.

As exhibited in Fig. 10, the dynamic performance of frequency response under the control of the double compensation loop for the diesel generator has significant advantages. First, the amplitude of frequency deviation produced by the double compensation loop control is the smallest, there is no overshoot, and the frequency dynamic stability time is the shortest. PI control produces the largest frequency deviation, obvious overshoot and longer frequency stabilization time. The performance of the frequency dynamic response generated by the feedforward control or SMC is between the PI control and double compensation loop control. In Fig. 11, the output of the diesel generator responds fastest, overshoot is smallest and stabilization time is shortest when controlled by the double compensation loop, while the dynamic performance of the output power is relatively poor with the other three LFC methods.

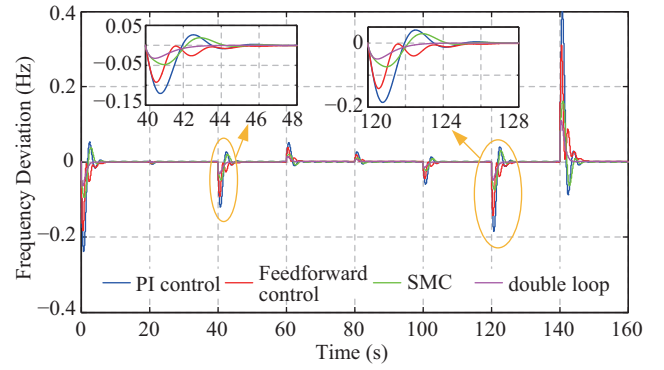


Fig. 10. The frequency deviation based on different LFC methods.

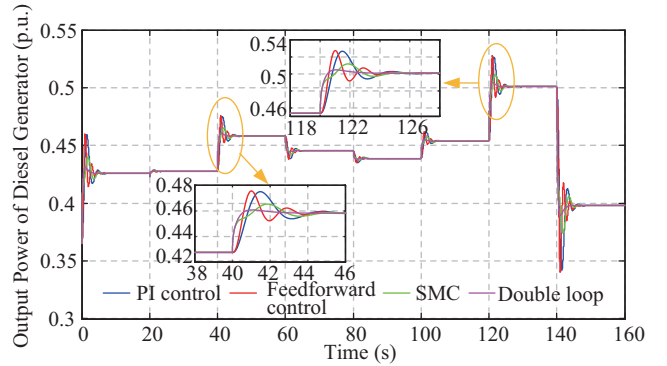


Fig. 11. The output power of diesel generator based on different LFC methods.

A. Case 2 Dynamic Fuzzy Controller for DFIGs

To give full play to the advantages of DFIGs, the dynamic fuzzy controller is used to directly respond to load demand in the microgrid. In this case, the PSO algorithm with particle swarm sizes of 5, 10, and 30 is used to optimize the parameters, and the computer simulation with the processor is an Intel i7, and the solution time of the algorithm is 8–20 minutes. Two working scenarios of DFIGs are compared. One working scenario is that the wind turbine is only used as a source of output power, and the other is that the wind turbine can take part in system frequency regulation. The double compensation loop for the diesel generator is used in this case. The frequency deviation and the output of the diesel generator and DFIGs are shown in Figs. 12–14.

When the dynamic fuzzy controller is used, Fig. 12 shows that the frequency dynamic response speed and frequency deviation are significantly reduced. Although the frequency deviation is an overshoot, it is still smaller than the frequency deviation produced by the non-dynamic fuzzy controller. In different load and wind speed changes, the dynamic performance of frequency response is also improved, as shown in Fig. 12, with the frequency changes at 120 s. Figs. 13 and 14 show that the output power of both the diesel generator and DFIGs are effectively improved and become more stable, when the dynamic fuzzy controller is used. Moreover, the blue curve in Fig. 13 can show that DFIGs can release energy rapidly in each fluctuation, which causes the operation of the microgrid to be more stable.

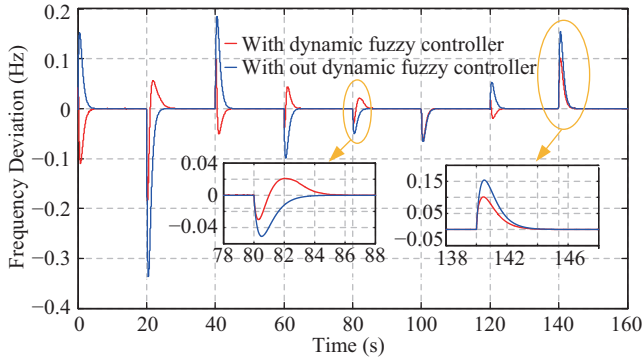


Fig. 12. The frequency deviations with or without dynamic fuzzy controller.

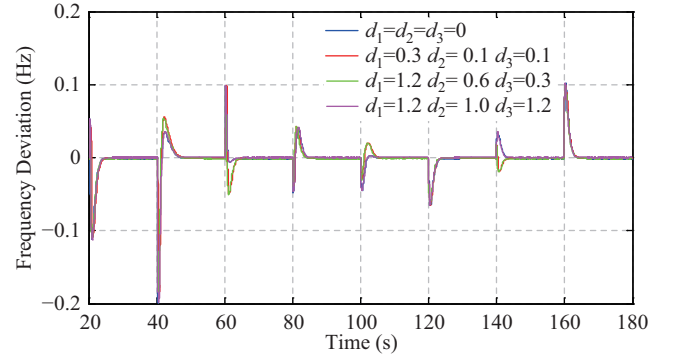


Fig. 15. The frequency deviations of proposed LFC with different time delay.

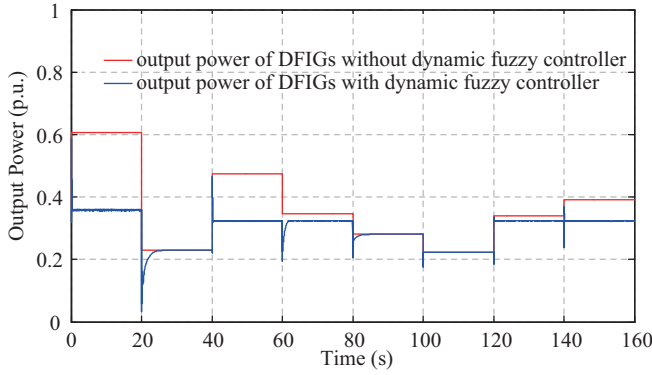


Fig. 13. The output power of DFIGs with dynamic fuzzy controller.

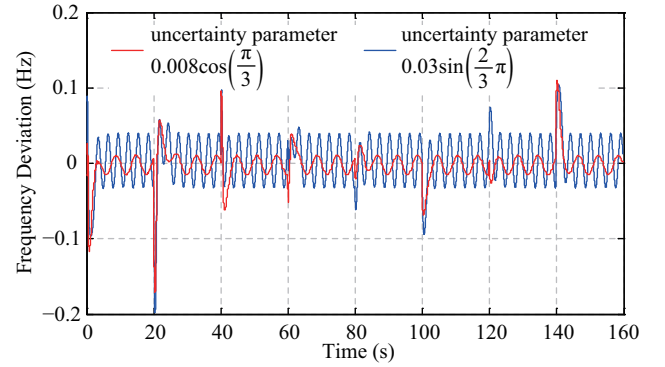


Fig. 16. The frequency deviations of proposed LFC with uncertain parameter.

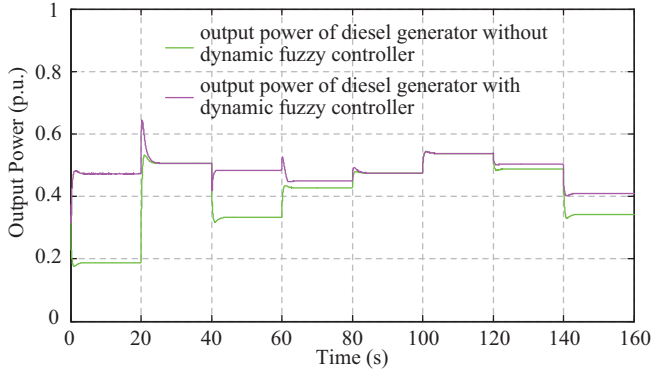


Fig. 14. The output power of diesel generator with dynamic fuzzy controller.

B. Case 3 Different Time Delay and Uncertainty Parameter for the Proposed Robust Dynamic LFC Method

In Case 3, the stability and robustness of the proposed robust dynamic LFC method is verified by using different time delay and uncertainty parameter values. The time delay d_1 , d_2 , d_3 involved in the secondary frequency control, feedforward control, and dynamic fuzzy control are given different delays, and sine function $0.008\cos(\frac{\pi}{3})$ and $0.03\sin(\frac{2}{3}\pi)$ are added to the proposed LFC method as the uncertainty parameters. The frequency deviations of the proposed robust dynamic LFC method with different time delays and uncertainty parameters are shown in Figs. 15 and 16.

In Figs. 15 and 16, the proposed dynamic robust LFC method can enhance the robustness of the microgrid operation

under different time delays and uncertainty parameters. Although the time delay and uncertain parameter will deteriorate the frequency dynamic performance, the proposed method can still ensure that the frequency dynamic performance is within a reasonable range.

C. Case 4 RBF NNO for the Proposed Robust Dynamic LFC Method

In order to test the better observation accuracy of the designed RBF NNO, the observational effects of the step change of the load and the frequency deviation produced by the NNO and the disturbance observer in [19] are compared in this case. The 3×100 sample sizes are used to train the weight matrix W , and W is updated. The observed values of the different observers are shown in Fig. 17, and the frequency deviations produced by different observers are shown in Fig. 18.

The characteristics of the RBF NNO can guarantee its autonomous learning of the observed values, and then continuously adjust to improve the observation accuracy. Fig. 17 shows that the designed observer can accurately track the actual load value, while the designed observer in [19] has relatively poor tracking accuracy. The inaccurate load tracking further may lead to inaccurate frequency regulation in the microgrid. Results are shown in Fig. 18, the frequency curve generated by the load is observed according to the designed observer, which may coincide with the frequency curve generated by the actual load value.

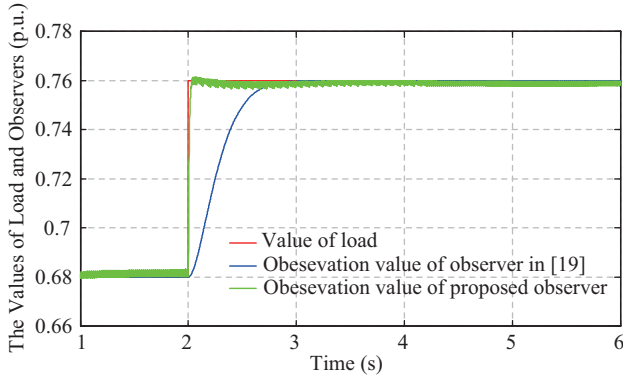


Fig. 17. The observation values of load with different observer.

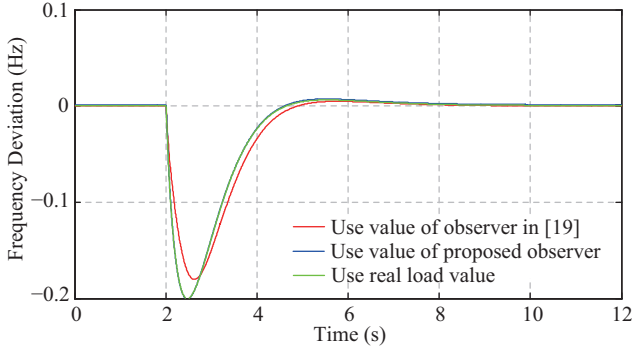


Fig. 18. The frequency deviations with different observer.

V. CONCLUSION

In this paper, a robust dynamic LFC method is proposed for the isolated wind-diesel microgrid with time delay and parameter uncertainty. This method designs a double compensation loop and dynamic fuzzy controller for the diesel generator and DFIGs, respectively. By using the proposed control strategy and considering the wind speed and uncertainty parameter, the frequency can be dynamically adjusted and the frequency dynamic response performance can be effectively improved. Meanwhile, the dynamic fuzzy controller is designed for DFIGs to dynamically respond to the load demand and improve frequency performance. The simulation results of the different operation cases show that the proposed method can effectively decrease the frequency deviation, shorten the frequency dynamic stability time, make the output of the wind-diesel more stable, and enhance the robustness of the microgrid.

APPENDIX

$$A = \begin{bmatrix} -\frac{1}{T_P} & \frac{K_P}{T_P} & 0 & 0 & 0 \\ 0 & -\frac{1}{T_{ch}} & \frac{1}{T_{ch}} & 0 & 0 \\ -\frac{1}{T_g R} & 0 & -\frac{1}{T_g} & 0 & 0 \\ K_e & 0 & 0 & 0 & 0 \\ \frac{K_S K_f}{T_{LPF}} & 0 & 0 & 0 & -\frac{1}{T_{LPF}} \end{bmatrix}, B = \begin{bmatrix} 0 \\ 0 \\ \frac{1}{T_g} \\ 0 \\ 0 \end{bmatrix}$$

$$F = \begin{bmatrix} -\frac{K_P}{T_P} & \frac{K_P}{T_P} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}, A_{d1} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{T_g} & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$A_{d2} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\frac{1}{T_g} \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

REFERENCES

- [1] C. Byers and A. Botterud, "Additional capacity value from synergy of variable renewable energy and energy storage," *IEEE Transactions on Sustainable Energy*, vol. 11, no. 2, pp. 1106–1109, Apr. 2020.
- [2] J. T. Chen and Q. Y. Zhu, "A game-theoretic framework for resilient and distributed generation control of renewable energies in microgrids," *IEEE Transactions on Smart Grid*, vol. 8, no. 1, pp. 285–295, Jan. 2017.
- [3] R. Wang, Q. Y. Sun, X. R. Liu, and D. Z. Ma, "Power flow calculation based on local controller impedance features for the AC microgrid with distributed generations," *IET Energy Systems Integration*, vol. 1, no. 3, pp. 202–209, Sep. 2019.
- [4] B. Fan, S. L. Guo, J. K. Peng, Q. M. Yang, W. X. Liu, and L. M. Liu, "A consensus-based algorithm for power sharing and voltage regulation in DC microgrids," *IEEE Transactions on Industrial Informatics*, vol. 16, no. 6, pp. 3987–3996, Jun. 2020.
- [5] M. H. Khooban, "Secondary load frequency control of time-delay stand-alone microgrids with electric vehicles," *IEEE Transactions on Industrial Electronics*, vol. 65, no. 9, pp. 7416–7422, Sep. 2018.
- [6] A. Annamraju and S. Nandiraju, "Coordinated control of conventional power sources and PHEVs using Jaya algorithm optimized PID controller for frequency control of a renewable penetrated power system," *Protection and Control of Modern Power Systems*, vol. 4, no. 1, pp. 28, Dec. 2019.
- [7] M. H. Khooban, T. Dragicevic, F. Blaabjerg, and M. Delimar, "Ship-board microgrids: a novel approach to load frequency control," *IEEE Transactions on Sustainable Energy*, vol. 9, no. 2, pp. 843–852, Apr. 2018.
- [8] M. Zribi, M. Al-Rashed, and M. Alrifai, "Adaptive decentralized load frequency control of multi-area power systems," *International Journal of Electrical Power & Energy Systems*, vol. 27, no. 8, pp. 575–583, Oct. 2005.
- [9] D. K. Chaturvedi, R. Umrao, and O. P. Malik, "Adaptive polar fuzzy logic based load frequency controller," *International Journal of Electrical Power & Energy Systems*, vol. 66, pp. 154–159, Mar. 2015.
- [10] L. Jiang, W. Yao, Q. H. Wu, J. Y. Wen, and S. J. Cheng, "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, May 2012.
- [11] C. K. Zhang, L. Jiang, Q. H. Wu, Y. He, and M. Wu, "Delay-dependent robust load frequency control for time delay power systems," *IEEE Transactions on Power Systems*, vol. 28, no. 3, pp. 2192–2201, Aug. 2013.
- [12] H. Y. Li, X. H. Wang, and J. M. Xiao, "Adaptive event-triggered load frequency control for interconnected microgrids by observer-based sliding mode control," *IEEE Access*, vol. 7, pp. 68271–68280, May 2019.
- [13] H. Bevrani and T. Hiyama, "On load-frequency regulation with time delays: design and real-time implementation," *IEEE Transactions on Energy Conversion*, vol. 24, no. 1, pp. 292–300, Mar. 2009.
- [14] P. Ojaghi and M. Rahmani, "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, Sep. 2017.
- [15] P. Babahajani, Q. Shafiee, and H. Bevrani, "Intelligent demand response contribution in frequency control of multi-area power systems," *IEEE Transactions on Smart Grid*, vol. 9, no. 2, pp. 1282–1291, Mar. 2018.
- [16] A. Y. Sivaramakrishnan, M. V. Hariharan, and M. C. Srisailem, "Design of variable-structure load-frequency controller using pole assignment technique," *International Journal of Control*, vol. 40, no. 3, pp. 487–498, Sep. 1984.
- [17] K. Vrdoljak, N. Perić, and I. Petrović, "Sliding mode based load-frequency control in power systems," *Electric Power Systems Research*, vol. 80, no. 5, pp. 514–527, May 2010.

- [18] S. Prasad, S. Purwar, and N. Kishor, "Non-linear sliding mode load frequency control in multi-area power system," *Control Engineering Practice*, vol. 61, pp. 81–92, Apr. 2017.
- [19] M. S. Yang and H. C. Lu, "Sliding mode load-frequency controller design for dynamic stability enhancement of large-scale interconnected power systems," in *Proceedings of the IEEE International Symposium on Industrial Electronics (Cat. No.99TH8465)*, Bled, Slovenia, Jul. 1999, pp. 1316–1321.
- [20] Y. Mi, Y. Fu, C. S. Wang, and P. Wang, "Decentralized sliding mode load frequency control for multi-area power systems," *IEEE Transactions on Power Systems*, vol. 28, no. 4, pp. 4301–4309, Nov. 2013.
- [21] C. X. Mu, Y. F. Tang, and H. B. He, "Improved sliding mode design for load frequency control of power system integrated an adaptive learning strategy," *IEEE Transactions on Industrial Electronics*, vol. 64, no. 8, pp. 6742–6751, Aug. 2017.
- [22] Y. Mi, Y. Fu, D. D. Li, C. S. Wang, P. C. Loh, and P. Wang, "The sliding mode frequency control for hybrid power system based on disturbance observer," *International Journal of Electrical Power & Energy Systems*, vol. 74, pp. 446–452, Jan. 2016.
- [23] Y. H. Sun, Y. X. Wang, Z. N. Wei, G. Q. Sun, and X. P. Wu, "Robust H_∞ load frequency control of multi-area power system with time delay: A sliding mode control approach," *IEEE/CAA Journal of Automatica Sinica*, vol. 5, no. 2, pp. 610–617, Mar. 2018.
- [24] Y. Mi, X. Z. Hao, Y. J. Liu, Y. Fu, C. S. Wang, P. Wang, and P. C. Loh, "Sliding mode load frequency control for multi-area time-delay power system with wind power integration," *IET Generation, Transmission & Distribution*, vol. 11, no. 18, pp. 4644–4653, Dec. 2017.
- [25] N. Nguyen and J. Mitra, "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, Jan. 2015.
- [26] V. Gevorgian, Y. C. Zhang, and E. Ela, "Investigating the impacts of wind generation participation in interconnection frequency response," *IEEE Transactions on Sustainable Energy*, vol. 6, no. 3, pp. 1004–1012, Jul. 2017.
- [27] N. R. Ullah, T. Thiringer, and D. Karlsson, "Temporary primary frequency control support by variable speed wind turbines—potential and applications," *IEEE Transactions on Power Systems*, vol. 23, no. 2, pp. 601–612, May 2008.
- [28] M. Wang-Hansen, R. Josefsson, and H. Mehmedovic, "Frequency controlling wind power modeling of control strategies," *IEEE Transactions on Sustainable Energy*, vol. 4, no. 4, pp. 954–959, Oct. 2013.
- [29] A. Ashouri-Zadeh, M. Toulabi, and A. M. Ranjbar, "Coordinated design of fuzzy-based speed controller and auxiliary controllers in a variable speed wind turbine to enhance frequency control," *IET Renewable Power Generation*, vol. 10, no. 9, pp. 1298–1308, Oct. 2016.
- [30] A. Ashouri-Zadeh, M. Toulabi, S. Bahrami, and A. M. Ranjbar, "Modification of DFIG's active power control loop for speed control enhancement and inertial frequency response," *IEEE Transactions on Sustainable Energy*, vol. 8, no. 4, pp. 1772–1782, Oct. 2017.
- [31] Y. Fu, Y. Wang, and X. Y. Zhang, "Integrated wind turbine controller with virtual inertia and primary frequency responses for grid dynamic frequency support," *IET Renewable Power Generation*, vol. 11, no. 8, pp. 1129–1137, Jun. 2017.
- [32] V. Gholamrezaie, M. G. Dozein, H. Monsef, and B. Wu, "An optimal frequency control method through a dynamic load frequency control (LFC) model incorporating wind farm," *IEEE Systems Journal*, vol. 12, no. 1, pp. 392–401, Mar. 2018.
- [33] Y. Wang, R. Zhou, and C. Wen, "Robust load-frequency controller design for power systems," *IEEE Proceedings C (Generation, Transmission and Distribution)*, vol. 140, no. 1, pp. 11–16, Jan. 1993.
- [34] T. Senjyu, R. Sakamoto, N. Urasaki, T. Funabashi, H. Fujita, and H. Sekine, "Output power leveling of wind turbine generator for all operating regions by pitch angle control," *IEEE Transactions on Energy Conversion*, vol. 21, no. 2, pp. 467–475, Jun. 2006.
- [35] A. Uehara, T. Senjyu, A. Yona, and T. Funabashi, "A frequency control method by wind farm & battery using load estimation in isolated power system," *International Journal of Emerging Electric Power Systems*, vol. 11, no. 2, pp. 1–20, Mar. 2010.
- [36] C. S. Wang, Y. Mi, Y. Fu, and P. Wang, "Frequency control of an isolated micro-grid using double sliding mode controllers and disturbance observer," *IEEE Transactions on Smart Grid*, vol. 9, no. 2, pp. 923–930, Mar. 2018.
- [37] W. B. Gao, Y. F. Wang, and A. Homaifa, "Discrete-time variable structure control systems," *IEEE Transactions on Industrial Electronics*, vol. 42, no. 2, pp. 117–122, Apr. 1995.
- [38] X. G. Yan, C. Edwards, S. K. Spurgeon, and J. A. M. Bleijs, "Decentralised sliding-mode control for multimachine power systems using only output information," *IEEE Proceedings-Control Theory and Applications*, vol. 151, no. 5, pp. 627–635, Sep. 2004.
- [39] X. G. Yan, S. K. Spurgeon, and C. Edwards, "Global decentralised static output feedback sliding-mode control for interconnected time-delay systems," *IET Control Theory & Applications*, vol. 6, no. 2, pp. 192–202, Jan. 2012.
- [40] J. Ekanayake and N. Jenkins, "Comparison of the response of doubly fed and fixed-speed induction generator wind turbines to changes in network frequency," *IEEE Transactions on Energy Conversion*, vol. 19, no. 4, pp. 800–802, Dec. 2004.



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