The stability control for isolated wind-diesel power system based on the cross coupling effect model

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Abstract
In the isolated wind-diesel hybrid power system, the system voltage and frequency may be affected simultaneously by the fluctuated wind turbine output power and variable load, which can make the system crash in extreme cases without control strategy. Therefore, in order to reduce the voltage and frequency deviation caused by system power fluctuation, both the battery and super twisting algorithm sliding mode state observer (STATCOM) are equipped to adjust the active power and reactive power for load power demand in the isolated small-scale power system. Then, the system mathematical model is established which considers the cross-coupling effect exist in the small-scale power system. In order to improve the control effect of battery and STATCOM, the unified control strategy is designed for battery and STATCOM by using the super twisting sliding mode state observer and the adaptive sliding mode controller according to the constructed cross-coupling effect model. Furthermore, the parameters of controller are further optimized by using the fuzzy method. Finally, the simulation experiments are performed by the real-time digital simulator to validate the effectiveness of the proposed control strategy under different operation points.

1 INTRODUCTION

The wind-diesel hybrid power system is widely applied to solve the insufficient power transmission for the topographical and economic factors [1–3]. However, due to the randomness of the wind power and the fluctuation of load, the safe operation of the power system may be challenged by the deviation of voltage and frequency [4–6], which can threaten the personal safety and property damage [7–9]. Therefore, it is necessary to take some measures for the stability of the wind-diesel power system.

The frequency control of the isolated hybrid power system has been researched for a long time. In [10], the energy storage is equipped to ensure the stability and power supply for the isolated wind-diesel hybrid power system. Doolla and Bhatti [11] considered the tidal power plant in the load frequency control (LFC) design, and then the capacitive energy storage is added to reduce the frequency deviation. In [12], an adaptive LFC is applied for an uncertain power system, but the system states are

assumed measurable completely, then it is imprecise for the controller design. In [13], the pitch angle control for the windmill and the charge or discharge control for the battery is designed to reduce the frequency deviation in the low- and high-frequency domain, but the load disturbance and different working situation are not considered for the system operation. The sliding mode (SM) method is used to design the stability control strategy because of fast response and good robustness according to the system disturbances and parameter uncertainties, and it is widely used in LFC researches. In [14], the LFC is designed by using the SM method to reduce the frequency deviation for a multi-area time-delay hybrid power system. In [15], the neural-network-based integral SM controller is employed to ensure the frequency stability, but this control algorithm depends on complex calculation for real-time work.

There are also many studies about voltage deviation control. In [16], the super twisting algorithm SM state observer (STATCOM) and permanent-magnet induction generator are used to
regulate the system reactive power for the stability of wind-diesel power system. In [17], the opposition-based gravitational search algorithm and Sugeno fuzzy logic are used to optimize the static var compensator parameters, so the system voltage can be adaptively recovered.

In a large-scale power system, the interaction of active power fluctuation for the voltage and reactive power fluctuation for the frequency is small because the line resistance can be ignored, so the active power and reactive power can be decoupled for the model construction. But it cannot be completely decoupled in the small-scale power system because of the line resistance influence, so the cross-coupling needs to be considered for improving the model construction accuracy as described in [20]. However, this can make the system model more complex for voltage and frequency control. Therefore, the cross-coupling effect must be considered for the whole mathematical model construction. In [18], the dynamic model of the wind-biogas hybrid system is developed, and the synchronous generator (SG) in biogas-genset is used to control the voltage and frequency of the system simultaneously. In [19], the voltage and frequency control strategy is designed by using disturbance observer and adaptive SM method to reduce the fluctuation of system, but the system states are assumed measurable completely, and the cross-coupling effect existed in small-scale power system of system active and reactive power is not considered for the system model.

Based on the analysis, the main contribution can be given as follows.

1. The mathematical model with cross-coupling effect is constructed for the small-scale isolated power system to improve the hybrid power system model accuracy.
2. The battery and STATCOM are both equipped to ensure the stability of isolated wind-diesel hybrid systems to reduce the deviation of voltage and frequency caused by the system’s active and reactive power fluctuation.
3. In order to improve the adjustment effect of the battery and STATCOM, the adaptive voltage and frequency unified controller is designed by using SM and fuzzy methods. At the same time, the super twisting SM state observer is constructed to estimate the state variable for improving the accuracy of the adaptive controller.
4. Finally, the effectiveness of the proposed controller can be tested by using the real-time digital simulator (RTDS) considering the fluctuated renewable source, the parameter uncertainties together with the load disturbances for the hybrid power system. The simulation results show that the presented control strategy has a better effect according to other control methods.

The rest of the paper is organized as follows: Section 2 introduces the mathematical model of the isolated hybrid power system with a cross-coupling effect. The state observer and coordinated control strategy are designed in Section 3. The experiment results based on RTDS are shown in Section 4. Finally, the results are concluded in Section 5.

2  |  MODEL OF WIND-DIESEL MICRO-GRID

The isolated wind-diesel hybrid power system can be shown in Figure 1.

Where $P_{IG}$ and $Q_{IG}$ are the real power and reactive power output of induction generator (IG), respectively. $P_{SG}$ and $Q_{SG}$ are the output real power and reactive power of SG, respectively. The active load and reactive load are represented by $P_L$ and $Q_L$, respectively. $P_B$ is the active power output of battery and $Q_{COM}$ is reactive power output of STATCOM. The battery and STATCOM are connected to the AC grid through the power conversion system, respectively. The voltage and frequency may be affected by the fluctuated wind power and changed load [22]. Therefore, the system deviation of voltage and frequency can be written as

$$
\Delta f(t) = \frac{K_p}{1 + sT_p} [\Delta P_{IG}(t) + \Delta P_{SG}(t) + \Delta P_L(t) - \Delta P_B(t)] \quad (1)
$$

$$
\Delta U(t) = \frac{K_f}{1 + sT_f} [\Delta Q_{IG}(t) + \Delta Q_{SG}(t) + \Delta Q_{COM}(t) - \Delta Q_L(t)]
$$

where $K_p$ and $K_f$ are system gains and $T_p$ and $T_f$ are the time constant.

2.1  |  Mathematical model of IG

Wind generator usually consists of fan and IG. The wind energy can be transferred to mechanical power by the wind energy conversion system. And then, the electromagnetic power can be output through the IG. The active power of IG output can be given as [19]

$$
\Delta P_{IG}(t) = K_4 \Delta U(t) + K_3 \Delta P_{IG}(t) \quad (3)
$$

$$
K_4 = -\frac{2UR_f^2}{(R_f^2 + X_{IG}^2)} \times \left(1 + \frac{U^2(R_f/R_f)(R_f^2 - X_{IG}^2)}{(R_f^2 + X_{IG}^2)[-2R_fU/R_f + U^2/(R_f^2 + X_{IG}^2) + U^2]}\right) \quad (4)
$$
FIGURE 2  The block diagram of diesel generator

\[ K_3 = \frac{U^2(R_y^2 - X_{eq}^2)}{(R_y^2 + X_{eq}^2)][-2R_yR_pU^2/(R_y^2 + X_{eq}^2) + U^2]} \]  

\[ R_T = R_p + R_{eq} R_p = \frac{r_1'}{s_1} (1 - s_1) \]  

\[ R_{eq} = r_1 + r_2', X_{eq} = x_1 + x_2' \]  

where \( U \) is the system terminal voltage, \( r_1, r_2' \) \( x_1, x_2' \) are the stator resistance, rotor resistance, state reactance and rotor reactance of IG, respectively. \( s_1 \) is the slip ratio of IG. \( R_{eq} \) and \( X_{eq} \) are equivalent resistance and reactance of IG, respectively.

And the reactive power output of IG can be given as

\[ \Delta Q_{IG}(s) = K_a \Delta U(i) + K_r \Delta P_{av}(s) \]  

\[ K_a = -\frac{2UX_{eq}}{K_1 \left[ 1 + \left( 2U^2R_pR_y \right) \right]} \left[ -2R_yR_pU^2/(R_y^2 + X_{eq}^2) + U^2 \right] \]  

\[ K_r = -\frac{2X_{eq}R_y U^2}{K_1 \left[ 1 + \left( 2U^2R_pR_y \right) \right]} \left[ -2R_yR_pU^2/(R_y^2 + X_{eq}^2) + U^2 \right] \]  

2.2 Mathematical model of IG

The small-signal model of diesel generator with cross-coupling can be represented as following.

From Figure 2, the active output power \([21]\) can be written as

\[ \Delta R_{SG}(s) = \frac{1}{1 + sT_{ch}} \Delta P_f(s) \]  

\[ \Delta P_f(s) = \frac{1}{1 + sT_A} \left( \frac{K_{f1}}{s} + \frac{1}{R} \right) \Delta f \]  

where \( \Delta P_f \) is the control valve position increment, \( R \) is the rate adjustment caused by governor action, \( T_{ch} \) and \( T_A \) are time constants, \( K_{f1} \) is the integral control gain.

The reactive power \([22]\) output from Figure 3 can be given as

\[ \Delta Q_{SG}(s) = K_i \Delta U(i) + K_r \Delta E_q'(s) + K_2 \Delta \delta(s) \]  

\[ K_1 = \frac{E_q' \cos \delta - 2U}{X_{d}'}, K_2 = \frac{U \cos \delta}{X_{d}'}, K_3 = \frac{-UE_q'}{X_{d}'} \sin \delta \]  

where \( E_q' \) is transient voltage change, \( \delta \) is the angle between armature internal voltage and system voltage. \( X_{d}' \) and \( X_{d}'' \) are direct-axis reactance under steady-state and transient-state conditions, respectively. The flux linkage equation \( \Delta E_d'' \) from equation (13) can be described as

\[ \Delta E_d''(s) = \frac{1}{(1 + sT_C)} \left( K_0 \Delta E_{a}(s) + K_3 \Delta U(i) + K_1 \Delta \delta(s) \right) sT \]  

\[ T_C = \frac{X_{d}''}{X_{d}''}, K_1 = \frac{X_{d}''U \sin \delta}{X_{d}''}, K_2 = \frac{(X_{d} - X_{d}'' \cos \delta) \cos \delta}{X_{d}''} \]  

where the exciter voltage deviation is represented by \( \Delta E_{a} \) and \( T_{ch} \) is time constant. And \( \Delta E_{d} \) is the output of IEEE type-I excitation system, so it can be given as

\[ \Delta E_{d}(s) = \frac{1}{K_E + sT_E} \Delta U_d(s) \]  

\[ \Delta U_d = \frac{K_A}{1 + sT_A} \left( \Delta U_{ref}(s) - \Delta U(i) - \Delta U_f(s) \right) \]  

\[ \Delta U_f(s) = \frac{sK_E}{1 + sT_E} \Delta E_{a}(s) \]  

where \( K_E, K_A, K_F \) are constants, \( T_E, T_A, T_F \) are time constants.
2.3 Mathematical model of battery and STATCOM

In order to ensure the stability of voltage and frequency control at the same time, the battery and STATCOM are both equipped for the power system. The battery is used to provide a part of the active power support for the system. And the mathematical model can be described by a first-order inertia link [23] as shown in Figure 3, where the $K_B$ is battery unit power factor, $T_B$ is the time constant, $K_{P3}$ and $K_{I2}$ are gains of the regulator.

The STATCOM is used to supply the reactive power support [24], and the mathematical model can be given in Figure 4, where the $\Delta \alpha$ is the deviation of IGBT firing angle, $T_a$ is the time constant of IGBT firing delay phase, $T_d$ is the time constant of phase sequence delay, $K_d$ is firing gain constant. $K_{P3}$ and $K_{I3}$ are the gains of regulator. The STATCOM output reactive power can be given in Figure 5.

From Figure 5, the reactive power deviation of STATCOM can be described as

$$ \Delta Q_{\text{COM}}(s) = K_{11} \Delta U(s) + K_{10} \Delta \alpha(s) $$

$$ K_{11} = -k_d U_{dc}B \cos \alpha, K_{10} = k_d U_{dc} UB \sin \alpha $$

where $k_d$ is constant, $U_{dc}$ is the voltage of DC side, $B$ is output susceptance, $\alpha$ is the phase angle of the converter output voltage.

3 THE ADAPTIVE VOLTAGE AND FREQUENCY CONTROL STRATEGY DESIGN

Based on the above mathematical model of a hybrid power system with cross-coupling effect, the voltage and frequency unified control strategy is designed for the battery and STATCOM. Due to the state variables cannot be obtained directly, the improved super twisting second-order SM state observer is designed. And in order to improve the control performance, an adaptive SM control method is used to design the voltage and frequency controller. The block diagram of the proposed control strategy is depicted as following.

In Figure 6, $u_1(t)$ and $u_2(t)$ are the designed adaptive control signal, $y_1(t)$ and $y_2(t)$ are incremental in the phase angle of STATCOM and output power of battery, respectively, $d_1(t)$ and $d_2(t)$ are the disturbance vector of STATCOM and battery, respectively. Then the dynamic models including battery and STATCOM can be established. Because of the load variation and wind power fluctuation, the system operation points may be affected [24], so the model can be given as

$$ \dot{x}(t) = (A + \Delta A)x(t) + Bu(t) + (G + \Delta G)d(t) $$

$$ y(t) = Cx(t) $$

(24)

Defining $x(t) = [\Delta \alpha(t) \Delta \alpha_1(t) \Delta \alpha_2(t) \Delta P_b(t) \Delta P_1(t)]^T$ as the system state vector, $u(t) = [u_1(t) u_2(t)]^T$ as the control output vector, $d(t) = [d_1(t) d_2(t)]^T$ as the disturbance vector and $y(t) = [\Delta \alpha(t) \Delta P_b(t) \Delta P_1(t)]^T$ as system output vector. The parameter matrix $A, B, C, G$ are the system matrix, control matrix, output matrix and disturbance matrix, respectively. And the $\Delta A$ and $\Delta G$ are parameter uncertainties matrix. These matrices are given in Tables 1 to 4. Then the uncertainties can be defined as
TABLE 2 Parameters of IG, SG, excitation system and load

| Parameter | Value |
|-----------|-------|
| $P_{IG}$  | 0.4 p.u. |
| $Q_{IG}$  | 0.2 p.u. |
| $E_{IG}$  | 1.1136 p.u. |
| $\delta$  | 21.66° |
| $P_{IG}$  | 0.6 p.u. |
| $Q_{IG}$  | 0.189 p.u. |
| $T_f$     | 0.05 s |
| $P_f$     | 1.0 p.u. |
| $\eta$    | 80% |
| $T_f'$    | 0.715 s |
| $\gamma$  | 0.15 p.u. |

TABLE 3 Parameters of observer and adaptive sliding mode controller

| Parameter | Value |
|-----------|-------|
| $K_{F1}$  | 40 |
| $K_{F2}$  | 0.5 |
| $P_f$     | 0.8 |
| $R_e'$    | 0.05 Hz/pu.kW |
| $T_d$     | 5 s |
| $R$       | 0.05 Hz/pu.kW |
| $K_f$     | 0.6229 |
| $K_{F1}$  | 100 |
| $K_{F2}$  | 12700 |
| $K_{F3}$  | 0.4542 |
| $K_{F4}$  | 2.1079 |
| $K_{F5}$  | -0.9482 |
| $K_{F6}$  | 0.15 |
| $K_{F7}$  | 0.7933 |
| $K_{F8}$  | -0.3053 |
| $K_{F9}$  | -2.2995 |
| $P_f'$    | 0.9 |

TABLE 4 Design parameters of the observer and adaptive sliding mode controller

| Parameter | Value |
|-----------|-------|
| $K_{F1}$  | 5 |
| $K_{F2}$  | 10.5 |
| $K_{F3}$  | 6 |
| $K_{F4}$  | 0.0019 |
| $T_d$     | 0.12 |
| $T_f$     | 0.00167 |

3.1 Previous siding mode voltage and frequency control strategy

For the system represented by (26), the state variables are unmeasurable, so the system state variables need to be estimated by the observer, and then the controller is designed by using the estimated state variables. The SM state observer can be designed as

$$\dot{\hat{x}}(t) = A\hat{x}(t) + Bu(t) + m(x; t) + G\text{sign}(\bar{y}) + H(t) \tag{28}$$

where $\hat{x}(t)$ is the estimated state variables, $\bar{y}(t) = y(t) - C\hat{x}(t)$ is the error between estimated and actual output variables. $G$ and $H$ are the designed gain matrix.

Then, the switching surface and the control law are designed by taking advantage of the estimated state variables. The switching function is designed as [25, 26]

$$\gamma(t) = D\dot{\hat{x}}(t) \tag{29}$$

where $D$ is the designed constant matrix, and $DB$ is nonsingular. So the controller $u_c(t)$ can be given as

$$u_c(t) = -(DB)^{-1}[DA\dot{\hat{x}} + Dm(x; t)]. \tag{30}$$

The exponential reaching law is designed as

$$\dot{\hat{y}} = -p\text{sign}(y) - qy. \tag{31}$$

So the controller is designed as

$$u(t) = -(DB)^{-1}[DA\dot{\hat{x}} + Dm(x; t) + p\text{sign}(y) + qy]. \tag{32}$$

3.2 Improved voltage and frequency control strategy

3.2.1 Super twisting algorithm state observer design

In order to improve the accuracy of the observer, the super twisting algorithm (STA) is used to improve the SM observer [27]. The basic STA is described as

$$\frac{d\xi_1}{dt} = -r_1|\xi_1|^{1/2}\text{sign}(\xi_1) + \xi_2 + p_1(\xi_1, t) \tag{33}$$

where $f$ is the known Lipschitz constant.
Table 4  Parameters of observer and adaptive sliding mode controller

| Observer | Controller |
|----------|------------|
| $L_k_2 = \begin{bmatrix} 1000 & 590 & 1000 & 0 & 0 \\ 0 & 0 & 0 & 1240 & 191 \end{bmatrix}$ | $D = \begin{bmatrix} 2.8145 & 1.2555 & -0.1428 & -0.0139 & 0.0826 \\ -4.0933 & -1.6382 & 0.2132 & 88.562 & -527.57 \end{bmatrix}$ |
| $F_{k_1} = \begin{bmatrix} 0.0012 & 0.0018 & 0.0024 & 0 & 0 \\ 0 & 0 & 0 & 0.0015 & 0.001 \end{bmatrix}$ | $T$ |

$A = \begin{bmatrix} -1/T_d & 1/T_d & 0 & 0 & 0 \\ -1/T_d & K_p & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1/T_B & K_p \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$

$C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$

$B = \begin{bmatrix} K_p & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$

$G = \begin{bmatrix} 0.1 \sin(2\pi t) & \sin(2\pi t) & 0 & 0 & 0 \\ 0 & -0.5 \sin(\pi t) & 0.2 \sin(2\pi t) & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2 \cos(2\pi t) & 0.5 \sin(\pi t) \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$

$\Delta A = \begin{bmatrix} 0 & 0.1 \sin(2\pi t) & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2 \cos(0.5\pi t) & \sin(\pi t) \end{bmatrix}$

So the system SM observer based on STA can be constructed as

$$\frac{d\xi}{dt} = -v_2 \text{sign} (\xi_1) + \rho_2 (\xi_2, t)$$

where $\xi_1, \xi_2, v_1$ and $\rho_1$ are the state variable, estimate error, constant and perturbation terms, respectively. From [28, 29], the stable condition of the STA has been proved. And from [30], the constant and perturbation terms of STA should be satisfied as

$v_1 > 2\tau, v_2 > v_1 \left( \frac{5v_1 + 4\tau^2}{2(v_1 - 2\tau)} \right)$

$$|\rho_1| \leq \tau |\xi_1|^{1/2}, |\rho_2| = 0$$

where $\tau$ is a positive constant.
where $a$ is the positive constant, so the (37) can be changed as

$$\begin{align*}
\dot{x}(t) &= Ax(t) + Bu(t) + m(\hat{x}, t) + Fk_1|y(t)|^{1/2}n(y(t)) + \hat{b}(t) \\
\dot{\hat{b}}(t) &= Lk_2n(y(t))
\end{align*}$$

(39)

**Lemma 1.** [25] Suppose that the perturbation terms are globally bounded by

$$\begin{align*}
|\rho_1(x)| &= |Ax(t) + Bu(t) + m(\hat{x}, t)| \leq \xi|x|^{1/2} \\
|\rho_2(x)| &= 0
\end{align*}$$

(40)

and constant $\xi \geq 0$, then the observer is strongly globally asymptotically stable if the gains satisfy

$$k_1 > 2\xi, k_2 > k_1\left(\frac{4k_2 + k_1^2}{2(k_1 - 2\xi)}\right)$$

(41)

**Proof.** Construct Lyapunov function as following:

$$V_1 = 2k_2\|y\| + \frac{1}{2}b^2 + \frac{1}{2}(k_1\|y\|^{1/2}n(y) - b)^2$$

(42)

The Lyapunov function can be written as a quadratic form

$$V_1 = \sigma^T P\sigma$$

(43)

$$\sigma^T = \|y\|^{1/2}n(y), P = \frac{1}{2}\begin{bmatrix} 4k_2 + k_1^2 & -k_1 \\ -k_1 & 2 \end{bmatrix}$$

(44)

Using the bounds on the (40), it can be shown that

$$\dot{V}_1 \leq -\frac{1}{\|y\|^{1/2}}\sigma^T Q\sigma$$

(45)

where $Q = \frac{k_1}{2}\begin{bmatrix} 2k_2 + k_1^2 & -\frac{4k_2}{k_1} + k_1\xi - (k_1 + 2\xi) \\ -(k_1 + 2\xi) & 1 \end{bmatrix}$. $\dot{V}_1$ is negative definite if $Q > 0$. So it can be seen if the $k_1$ and $k_2$ are satisfied in (41), the STA SM observer is stable.

### 3.2.2 Adaptive SM voltage and frequency controller design

In order to improve the robustness of the controller, an adaptive SM voltage and frequency controller is designed by using the fuzzy method. In the reaching law of the SM method, the parameters $p$ can be selected to shorten the approach time and reduce the chattering effect. The fuzzy rule as in Table 5 can adjust adaptively the parameters of reaching law (33) of SM voltage and frequency controller.

Based on the proposed adaptive rules, the reaching law (31) can be described as

$$\dot{\gamma} = -\bar{p}n(\gamma) - q\gamma$$

(46)

where $\bar{p}$ is the adaptive constant. The following theorem can be given as follows.

**Theorem 1.** If the system satisfies the assumptions together with (32) and (46), the adaptive SM voltage and frequency controller can be given as

$$u(t) = -(DB)^{-1}[D\dot{Ax} + Dm(\hat{x}, t) + \bar{p}n(\gamma) + q\gamma]$$

(47)

So the system (28) can reach the SM in finite time by using the adaptive controller (47).

**Proof.** Construct Lyapunov function $V_2 = \frac{1}{2}\gamma^2$, so the derivative of $V_2$ can be given as

$$\dot{V}_2 = \gamma \dot{\gamma}$$

(48)

As the system (26) satisfies assumptions and based on (29) and (47), the $\dot{\gamma}$ can be written by

$$\dot{\gamma} = D\dot{x}(t) = D(\dot{Ax}(t) + m(\hat{x}(t), t)) - DB(\frac{DB}{-1}[D\dot{Ax}(t) + Dm(\hat{x}(t), t) + \bar{p}n(\gamma) + q\gamma] = D\dot{Ax}(t) - \tilde{x}(t)) + D[m(\hat{x}(t), t) - m(\hat{x}(t), t)] - \bar{p}n(\gamma) - q\gamma$$

(49)

Therefore, (48) can be given as

$$\dot{V}_2 = \gamma D\dot{Ax}(t) - \tilde{x}(t) + \gamma D[m(\hat{x}(t), t) - m(\hat{x}(t), t)] - \bar{p}n(\gamma) - q\gamma$$

$$\leq \|\gamma D\| \|\dot{x}(t) - \tilde{x}(t)\| + \|\gamma D\|\|m(\hat{x}(t), t) - m(\hat{x}(t), t)\| - \bar{p}n(\gamma) - q\gamma^2$$

$$\leq -\bar{p}n(\gamma) - q\gamma^2 < 0$$

(50)

Thus, the system can be driven to the sliding surface by the proposed approach law and to ensure that the sliding condition is locally bounded and stable under the designed SM controller.

| IF | THEN | $\dot{p}$ |
|----|------|---------|
| Positive big | Positive big |
| Middle | Middle |
| Positive small | Positive small |

**TABLE 5** The rules of fuzzy controller
In order to verify the effectiveness of the proposed voltage and frequency control strategy, the simulation experiment is tested by using RTDS for the isolated wind-diesel power system. The system model is compiled by RSCAD, and then the simulation data is transferred to the RTDS by the router. The mathematical model is simulated under the 20-kHz sampling frequency, which means the controllers provide the updated control setpoints every 50 μs. The designed control strategy can run by a digital signal processor microcontroller which may simulate the isolated hybrid power system in real-time. The simulation experiments are based on SG, IG, STATCOM, battery and load in RTDS. Finally, the system simulation is done in the RTDS under different working conditions, and the result is feedback to the RSCAD by the router. [15]. The structure diagram of the RTDS experimental platform is shown in Figure 7.

In order to test the designed controller, five cases are proposed to test the performance. In case one, the cross-coupling effect between reactive power and active power in the small isolated power system is verified. At \( t = 1 \) s, \( \Delta P_L = 0.4 \) p.u., \( \Delta Q_L = 0.03 \) p.u., \( \Delta P_W = 0.1 \) p.u., the simulation result of only step active load fluctuation is depicted in Figure 9.

From Figure 8, it can be seen that when there is active load fluctuation, both the output active and reactive power of SG are changed, so the system frequency and voltage deviation may exist. In Figure 9, when the system has reactive load fluctuation, the output active power of SG does not change with the change of reactive power of SG; the system frequency deviation is only affected by the wind generator. And the result suits with the changes in the operation of SG under the constant excitation. So in the small hybrid power system, the cross-coupling cannot be ignored. And the feasibility of the mathematical model is verified.

### 4.2 Case 2

In this case, the simulation is performed to verify the SM voltage and frequency control strategy under the step disturbance. At \( t = 1 \) s, \( \Delta P_L = 0.4 \) p.u., \( \Delta Q_L = 0.03 \) p.u., \( \Delta P_W = 0.1 \) p.u. And the simulation results of the system are depicted in Figure 10.

From Figure 10(a) and (c), when the battery and STATCOM are not equipped in the system, the frequency and voltage may have a large deviation. And the battery and STATCOM can appropriately reduce the output power variation of the SG, so the system voltage and frequency deviation may decrease. Moreover, the SM control strategy can improve the robustness of the
wind-diesel system, the frequency and voltage deviation can be minimal in this comparison case.

4.3 Case 3

In order to verify the effectiveness of the designed STASMO together with traditional SM controller, the random disturbance of wind output power and load are considered in this case. And the random disturbance is shown in Figure 11.

The simulation results of different observers with a control strategy for small wind-diesel hybrid system are depicted in Figure 12.

From the simulation results shown in Figure 12, the improved STASMO can estimate all the state variables with high accuracy compared with traditional SMO under the random power fluctuation in the system. So the actual value can be approximately estimated by the STASMO, and the observed value can be utilized by the controller in practical situations. And the accuracy of the controller can be higher.

4.4 Case 4

In order to verify the effectiveness of the proposed adaptive SM controller (ASMC), the random system fluctuation of wind power and load may be considered in this case too. The simulation results of the different controllers are shown in Figure 13.

As the simulation results of Figure 13, the system voltage and frequency deviation may be higher when the system used the PI controller. The SMC can appropriately reduce the frequency and voltage deviation, which can be retained smaller fluctuation using ASMC than the other two control strategy. So the results given as the proposed controller have better effectiveness.
4.5 | Case 5

In order to verify the effectiveness of the proposed adaptive SM controller based on the proposed super twisting SM state observer, the ASMC and SMC are compared by using different observers under random system disturbance. And the simulation results of this case are shown in Figure 14.

From Figure 14, under the SMC, the STASMO with SMC has a better control effect than SMO with SMC. Under the ASMC, the STASMO with ASMC has a better control effect than SMO with ASMC. So the STASMO with ASMC can make system voltage and frequency have less deviation than other controllers. And it is shown that ASMC with STASMO can improve the voltage and frequency stability of isolated small wind-diesel hybrid power system to the utmost extent.

5 | CONCLUSION

In this paper, the whole mathematical model with the cross-coupling effect is established for the small isolated wind-diesel hybrid power system, the battery and STATCOM are equipped to ensure the system stability. Then the adaptive SM unified control strategy is proposed to reduce the system voltage and frequency deviation. But the state variables of battery and STATCOM are unmeasured, so the super twisting SM state observer is designed to estimate the system state of battery and STATCOM. Based on the estimated state variables, the adaptive SM controller is constructed for battery and STATCOM to improve the power compensation performance. Here, the saturation function is used instead of the sign function in the proposed SM control strategy to reduce the chattering. And the fuzzy method is applied to adaptively select the control law parameters of the adaptive SM controller. Finally, the simulation results show that the proposed control strategy can improve the voltage and frequency stability of the isolated small hybrid power system than other control strategies.
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