Novel insight on temporary frequency support of variable speed wind energy conversion system

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Abstract
In the recent decade, temporary frequency support derived from variable speed wind turbine generator has been drawing increasing attention in the electronic-growing power system. Frequency nadir and rate of change of frequency are two key indicators temporary frequency support strives to improve. This paper proposes a novel insight on frequency regulation of wind power. Note that considerable part of load is shared by synchronous generators and wind turbine generator and the system frequency still will be dominated by the former for a period of time. Simultaneously taking the frequency regulation characteristic of synchronous and power balance into account, a novel frequency regulation scheme aiming at improving system's frequency regulation performance is proposed and tested in a 7-machine power system with an aggregated wind farm on MATLAB/Simulink to investigate what inherently determines the performance of frequency regulation. Results show that with differential cooperation of synchronous generator and doubly fed induction generator, frequency nadir and rate of change of frequency can be partially improved. Particularly, regarding to handling the issue of control delay, an appropriately slower action upon detecting a frequency event may not screw up it but contribute to a higher frequency nadir, which benefits from the spontaneous cooperation of synchronous generator and wind power with constraint of power balance.

KEYWORDS
cooperation control, doubly fed induction generator, inertia control, temporary frequency support, wind power

1 | INTRODUCTION

Conventionally, when a frequency event occurs, synchronous generators (SGs) intrinsically release kinetic energy (KE) as an inertial response; then, their primary and secondary controls can be used to restore the frequency. However, the KE of variable speed wind turbine generator (VSWTG) is completely hidden by the converter, and the wind power penetration (WPP) is increasing, reducing the installation of SG and frequency regulation capability of power system. If system frequency drops below the threshold of low-frequency load shedding relay, it will be activated to prevent frequency collapse. Energy storage system is suitable for suppressing fluctuating power and maintaining system frequency stability. While considering the high cost, it is not that economical for large-capacity configuration. Conversely, the response from a VSWTG can be several times more per megawatt than that is observed for the primary response from an SG. So it is promising to enhance the stable and economic operation of system by utilizing the rapid adjustable energy derived from rotor speed variation of wind turbine.
Typically, existing studies on the temporary frequency support (TFS) from wind power plant can be divided into two categories:

1. Frequency-based inertia control (FBIC). FBIC with fixed coefficients is directly coupled to the system frequency, including droop control and inertia control.\(^6\)–\(^9\) Droop control helps improve frequency deviation, while inertial control aims at improving the rate of change of frequency (ROCOF). It is flexible and practical. However, if the control parameters are not set appropriately, excessive KE will be released, causing rotor over deceleration (OD). In this situation, wind turbines will be cut subsequently, bringing about a secondary frequency fall (SFF). In contrast, inertia response speed and intensity may be insufficient, which contributes inadequately to system frequency regulation. In addition, due to the inherent hysteresis characteristics of relying on measured frequency as feedback control, the response is relatively slow. Therefore, FBIC with variable coefficients is proposed to counter this issue while the real-time calculation process for parameters is complicated.\(^10\)–\(^12\) Similarly, FBIC with time-varying control gains was proposed to shape the frequency response of wind power.\(^13\),\(^14\) At the onset of disturbance, inertial and droop gains are set large for generating a surge incremental power to support frequency. As time increases, the gains decrease to ensure that rotor speed of wind turbine generator (WTG) converges within the stable operating range. The initial parameters are dispatched according to the releasable KE stored in WTG before frequency event, and the final gains depend on the ratio of stored KE to the maximum amount of releasable KE, simultaneously preventing OD. However, the cooperation and selection of inertia and droop gains become more complicated, reducing the robustness and practicability for engineering.

2. Rotor speed-based inertia control (RSBIC). In order to overcome the shortcoming of slow response of FBIC and ensure avoiding OD, Hwang et al.,\(^15\) Yang et al.,\(^16\) and Kang et al.\(^17\),\(^18\) suggested applying reference trajectory designed control in the power-speed plane. Rotor speed-based power reference accurately ensures the rapidity, stability, effectiveness, and convergence stability without OD when releasing KE for VSWTG at various wind speeds. However, RSBIC essentially decouples wind turbine from system frequency, and the inertia response of VSWTG merely depends on the rotor speed, regardless of the severity of the frequency event. For large disturbance, KE of VSWTG can be fully released to improve frequency regulation characteristic. When it comes to small disturbance, overshooting frequency regulation is prone to occur for the decoupled rotor speed based inertia response, which may not only fail to improve frequency regulation characteristic but also lead to high frequency and trigger over-frequency generation shedding relay. Moreover, conventional frequency deviation-based event detector is rigid when cooperating with RSBIC, badly inhibiting the capability of system regarding handling back-to-back frequency events.

In addition, the assist of capacitor of DC link is introduced into inertia control to improve the frequency regulation performance of system.\(^19\) Considering the stable operation of DC link and simplification of control strategy, we do not superimpose additional inertia control on DC link; i.e., the grid side converter operates at a function to keep DC voltage stable.

Focus on the issue above and taking DFIG as the representative of VSWTGs, this paper proposes a novel strategy basing on RSBIC: when detecting a disturbance, power reference of DFIG is increased by adequately releasing KE along a rotor speed-based Sinusoidal Function Trajectory (SFT). Then, rotor speed recovery is accelerated through tracking a rotor speed based Quadratic Function Curve (QFC) as power reference without transiting control-state abruptly, together with staggering recovery to alleviate SFF. Considering upon improving the adaptability of inertia controls that are decoupled from system frequency after being triggered, a Frequency Event Detector and Output Suppressor (FEDOS) is complemented for RSBIC against back-to-back disturbances and overshooting output. With proposed power regulation behavior as “First repress then raise” to proceed rotor speed recovery, the frequency regulation intervention of wind power can be significantly smoothed and the process of rotor speed recovery can be effectively accelerated, which is verified by conducting case studies on a simulative power system with high WPP under different wind speeds and WPP levels on MATLAB/Simulink.

To this end, this paper is organized as follows: Section 2 explains the theoretical preparation; the proposed scheme is explained in Section 3, and the simulation model is built in Section 4; Section 5 conducts the case studies; and lastly, the conclusions are drawn in Section 6.

## 2 | THEORETICAL PREPARATION

### 2.1 | Operational characteristics of SG

Since the time scales for the withdrawal and restart of SG and the automatic generation control (AGC) are much larger than that of TFS provided by DFIG and the primary frequency regulation of SG, therefore, the operation characteristics of SG here are mainly analyzed on its inertia response and primary frequency regulation capability.

The primary frequency regulation of SG is based on the speed regulation control of generator unit. The function of the speed regulator is to prevent system frequency deviating from the rated. That is, when the power of the generation or the power of the load in the power system changes, the frequency of the power system will inevitably change; at this time, the energy stored in the electromagnetic field and rotating mass of the system will change to arrest the change of the system frequency. Specifically, if frequency changes beyond the dead-zone preset, the
The governor of the generator will act to change the valve position of the steam turbine and strive to eliminate the imbalance of the power. This characteristic of the prime mover governor is called the regulation coefficient and is typically expressed as

$$\delta = \frac{n_0 - n}{n_r} \times 100\%,$$

where $n_0$ is the static speed without load, $n$ is the static speed with full load, and $n_r$ is the rated speed. And the meaning of the adjustment rate is that if $\delta = 5\%$, when the system frequency changes by 5%, the prime mover valve position will change 100%.

Then, the integrated primary regulation characteristic of the power system is the summation of the primary regulation characteristics of all generators and loads in the system. The model of power system with primary frequency regulation function is shown as the following.

As can be seen from Figure 1, the existence of negative feedback adjustment link for speed plays a role in stabilizing the system frequency. However, under the constraint of instantaneous power balance, and the delay derived from transmission, control, and the rate of action of steam turbine valve, the electrical power and mechanical power SGs suffers during transient state are not consistent, resulting in inevitable frequency deviation. So the primary frequency regulation characteristic of system can be presented as shown in Figure 2.

Thus, unbalance power is undertaken by both droop control and inertia characteristics of the SGs. They participating in the primary frequency regulation have the following characteristics, of which the integration effect inherently determines the static and dynamic characteristic regarding frequency response of power system:

1. The primary frequency regulation is implemented by the speed regulation system of prime mover. Since the primary regulation of SG merely acts on the position of the steam valve of the prime mover, not the combustion system of the thermal power generating unit. When the valve opening increases, the heat stored in the boiler temporarily changes the power. Therefore, the inertia and primary frequency response are limited by the opening rate of steam valve.
2. For sudden variation of load under abnormal conditions, primary frequency regulation can play a buffering role while it cannot be relied on to regulate the system frequency alone for its characteristic of attenuation and static deviation.

### 2.2 Operational characteristics of DFIG

This subsection briefly describes the overall features of a DFIG model, which includes a DFIG controller, two-mass shaft model, and mechanical power model.\(^{20}\)

First, the DFIG controller consists of a rotor-side converter (RSC) and a grid-side converter (GSC). The RSC controls the active power and reactive power injected into the power system, where the MPPT operation control is conducted; the GSC is in charge with maintaining the DC-
link voltage and control the terminal voltage. In addition, a pitch controller is used to prevent the rotor speed from exceeding the maximum operating limit.

And the mechanical power extraction from the wind, $P_m$, is determined by

$$P_m = \frac{1}{2} \rho \pi C_p(\lambda, \beta) R^2 v^3,$$  \hspace{1cm} (2)

where $\rho$, $C_p$, $\lambda$, $\beta$, $R$, and $v$ are the air density, wind energy conversion coefficient, tip-speed ratio, pitch angle, rotor radius, and wind speed, respectively.

And the calculation of $C_p(\lambda, \beta)$ can be illustrated as the following:

$$C_p(\lambda, \beta) = 0.645 \left(0.00912 + \frac{-5-0.4(2.5+\beta+11.6i)}{e^{21\lambda}}\right),$$ \hspace{1cm} (3)

where

$$\lambda = \frac{1}{\lambda+0.08x} - \frac{0.035}{1+(2.5+\beta)^2}.$$ \hspace{1cm} (4)

Then, the reference power for MPPT operation, $P_{MPPT}$, can be further illustrated as the following:

$$P_{MPPT} = \frac{1}{2} \rho \pi C_{p,\text{max}}(\lambda_{\text{opt}}, \beta) R^2 \left(\frac{\omega R}{\lambda_{\text{opt}}}\right)^3 = k \omega^3,$$ \hspace{1cm} (5)

where $C_{p,\text{max}}$ is the maximum value of $C_p$ when $\beta = 0$ and the optimal tip-speed ratio $\lambda_{\text{opt}}$ is set to 9.95 in this paper$^{21}$; $k$ is an intermediate variable constant of the formulation, which is set to be 0.52.

Then, the two-mass shaft model showing the dynamics between the wind turbine and generator is represented as

$$\begin{align*}
2H_t \frac{d\omega_t}{dt} &= T_t - K_s \theta_s - D_s (\omega_t - \omega_r) - D_t \omega_t \\
2H_g \frac{d\omega_r}{dt} &= K_s \theta_s + D_s (\omega_t - \omega_r) - D_g \omega_r - T_g \\
\frac{d\theta_s}{dt} &= \omega (\omega_t - \omega_r)
\end{align*}$$ \hspace{1cm} (6)

where $H_t$, $\omega_t$, and $T_t$ are the inertia time constant, angular speed, and torque of a wind turbine mass, respectively; $K_s$, $\theta_s$, and $D_s$ are the shaft stiffness, torsional twist, and damping constant, respectively; $H_g$, $D_g$, and $T_g$ are the inertia time constant, damping constant, and torque of a generator mass, respectively; and $\omega$ is the base value of angular speed.$^{22}$

Considering that the rapid and excessive increase of output power, $P_e$, might result in the mechanical torsion of a wind turbine, the power limit and torque limit, $T_p$, are set to 1.1 p.u. (see brown curve in Figure 3) and 0.92 p.u. (see blue dotted curve in Figure 3, which is deduced from the relationship between power and torque as the following$^{7}$), respectively, to protect the mechanical transmission system.

$$P_e \leq P_{\text{lim}} = \alpha \omega \times T_p,$$ \hspace{1cm} (7)

**FIGURE 3** Operational features of DFIG
where $P_{\text{lim}}$ is the power limitation of WTG considering torque protection.

Further, the rate of change of power is limited within 0.45 p.u./s, as in Liu et al.\textsuperscript{19} And the stable rotor speed operation range of DFIG is typically set from 0.7 to 1.3 p.u. By now, the operational features of DFIG can be summarized as shown in Figure 3.

## 3 | DESCRIPTION OF PROPOSED SCHEME WITH NOVEL POWER REGULATION BEHAVIOR

For investigating how inertial wind turbines integrate with SG dominating system regarding frequency regulation, the characteristics of proposed schemes are described in detail in this session. The proposed scheme consists of two stages for deceleration and acceleration.

### 3.1 | Stage I

This stage aims to arrest the frequency decline by supplying prompt power to the power system for a period. Once detecting a frequency event, the power reference is switched to that of the proposed scheme, and it convergences to the mechanical power with the variation of rotor speed, as in

\[
\begin{align*}
A &= \frac{\left| P_{\text{lim}}(\omega_r) - P_m(\omega_r) \right| (\omega_r^2 - \omega_{\text{min}}^2)}{P_m(\omega_r)} + P_m(\omega_r), \\
\left\{ \begin{array}{l}
P_{\text{ref},1} = k_{\text{FEDOS}} \left[ A \sin \left( \frac{k_{\text{map}} - \omega_r + k_{\text{pan}} \omega_0}{\omega_0} \right) \right] \\
A = \frac{\left| P_{\text{lim}}(\omega_r) - P_m(\omega_r) \right| (\omega_r^2 - \omega_{\text{min}}^2)}{P_m(\omega_r)} + P_m(\omega_r),
\end{array} \right.
\end{align*}
\]

where $A$ is the power reference magnitude at the starting point of the proposed scheme for frequency regulation, dependent on the releasable KE stored in WTG\textsuperscript{11} when TFS is triggered. Different from that of variable droop control, $A$ is maintained unless TFS is triggered for another time. $k_{\text{map}}$ is the mapping factor, and $k_{\text{pan}}$ is the coefficient used to help adjust the starting point of $P_{\text{ref},1}$. Specifically, in this paper, $k_{\text{map}}$ is 2, and $k_{\text{pan}}$ is 0.25, considering the typical variation range of $\omega_r$ in p.u. is around 0.2 p.u. and

\[
P_{\text{ref},1}(\omega_0) = k_{\text{FEDOS}} \left[ A \sin \left( \frac{2\pi}{\omega_0} (\omega_0 + 0.25 \omega_0) \right) \right] = Ak_{\text{FEDOS}}.
\]

As shown in Figure 4, upon detecting an event, the proposed scheme instantly increases the power reference from $P_{\text{MPP}}(\omega_0)$ to $P_{\text{ref},1}(\omega_0)$. Then, since $P_e$ is larger than $P_m$, $\omega_r$ keeps decreasing until it converges to Point C, where $P_e = P_m$, $\omega_C$ as $\omega_{\text{min}}$ plus is ensured to be higher than $\omega_{\text{min}}$. Thus, the proposed $P_{\text{ref},1}$ ensures no OD because $\omega_r$ does not decrease below $\omega_{\text{min}}$ with the convergence of $P_e$ with $P_m$ before reaching $\omega_{\text{min}}$. During this stage, $d\omega_r/dt$ keeps decreasing, since $P_e - P_m$ continuously decreases with time. Note that there are two major features for the proposed scheme, which are the reasons for adopting Sinusoidal Function to set the structure of power reference as well.

![Figure 4](image-url)

**Figure 4** Operational features in the power-speed plane of the proposed scheme
First, based on Sinusoidal Function in power-speed plane, it provides a smooth power reference for WTG, simultaneously possessing similar support as Trapezoid reference and integral transition as Linear reference.

Second, as Sinusoidal Function is known to all, the setting of control parameters is brief. As can be seen from Figure 4, the only parameter needs predetermining is the magnitude of SFC, \( A \), which we set as \( P_{\text{TRlim}}(\omega_0) = 0.05 \text{ p.u.} \).

After \( \omega_r \) converges to Point C, the proposed scheme activates recovering rotor speed. To decide whether converges, the following judgment is used:

\[
|\Delta \omega_r| \leq 4.0 \times 10^{-7} \text{ p.u.}
\]  

### 3.2 Stage II

This stage aims to recover \( \omega_r \) for a higher efficiency to capture wind power, which eliminates the burden of SG and prepares for a possible subsequent event. Since \( \omega_r \) converges to \( \omega_C \), it allows for a small reduction for recovery activation, avoiding a significant SFF. The rotor speed and power at Point C are recorded and used to set the curve of \( P_{\text{ref,II}} \), which can be illustrated as the following:

\[
P_{\text{ref,II}} = P_{\text{MPP}}(\omega_0) + \frac{\partial P_{\text{MPP}}}{\partial \omega}(\omega_0) \cdot \Delta \omega - \frac{\partial^2 P_{\text{MPP}}}{\partial \omega^2}(\omega_0) \cdot \left( \frac{\omega_0 - \omega_r}{\omega_0 - \omega_C} \right)^2.
\]

where \( \Delta p \) is a positive constant, which is used for proceeding rotor speed recovery. It can be deduced from 12 that at the beginning of recovery, \( P_{\text{ref,II}} \) equals \( P_{\text{ref,II}}(\omega_C) \cdot \Delta \omega \) and with speed recovering, it spontaneously converges to \( P_{\text{MPP}}(\omega_0) \), following a brief Quadratic Concave Function based reference. The motivation for this design is to accelerate the recovery process while avoiding SFF.

In this paper, a FEDOS is applied to activate the RSBIC with complemented functions against back-to-back disturbances and overshooting output. The proposed reference is activated if the frequency deviation exceeds 0.02 Hz or ROCOF exceeds 0.3 Hz/s. \( k_{\text{FEDOS}} \) is the coefficient of FEDOS for arresting overshooting output, which can be obtained from the following:

\[
k_{\text{FEDOS}} = 1 - \left( \frac{P_{\text{ref, max}} - P_{\text{ref, min}}}{\Delta f_{\text{max}}} \right) \cdot \Delta f.
\]

where \( P_{\text{ref, min}} \) and \( P_{\text{ref, max}} \) are the minimal and maximum power of WTG, respectively. \( \Delta f_{\text{max}} \) is the threshold of high frequency load shedding relay. \( \Delta f \) is the deviation of system frequency. Signals of \( \Delta f \) are limited through Saturation Link (\( u \geq 0 \)) to avoid negative values, where \( u \) is the signal transmit through Saturation Link. Figure 5 shows the logic block diagram of the proposed scheme. Besides, considering that in Stage I, WTG will converge to a stable operation state as designed, where \( P_e \approx P_m \).

### 4 MODELING OF THE POWER SYSTEM

A typical 7-machine system with an aggregative DFIG-based wind farm is considered here, of which the topology is shown in Figure 6, where \( N \) is the number of 1.5-MW DFIG units. There is a static load of 480 MW totally in the system.
Specifically, to simulate a power system with a low ramping capability, each of the SGs is equipped with a speed regulator and an IEEE type 1 voltage regulator combined to an exciter. The dead-zone of SGs for frequency regulation is zero. The regulation coefficients are set to 5%, and there is no automatic generation control in the system. The inertia constants for the 200-MVA SGs, 150-MVA SGs, and 100-MVA SG are set to 5, 4.3, and 4 s, respectively.\(^\text{18}\)

The inertia gains of DFIGs in all cases are conservatively set to be 10.08 s. For torque protection, \(T_p\) is set to be 0.92 p.u. in this paper. And \(\Delta p\) is set to be 0.01 p.u. for activating the rotor speed recovery. In addition, the rate limiter and power limiter are considered here as 0.45 and 1.1 p.u., respectively.\(^\text{20}\) Regarding the specific parameters of the proposed scheme with different wind speeds, they are represented in Table 1.

5 \| CASE STUDIES AND RESULTS DISCUSSION

The performance of the proposed scheme is examined and compared in this session under the scenarios with varying wind speeds of 12 and 9 m/s and WPP levels of 18.75% and 37.50%. Studies for verifying its performance against frequency overshooting and back-to-back disturbances are also conducted.

In Cases 1–4, SG5 is tripped at 65.0 s as power disturbance. In comparison, an incremental power of 40 MW in static load at 65.0 s acts as the small disturbance in Case 5, and it together with another incremental 30 MW load at 85.0 s acts as the back-to-back disturbance in Case 6. The increasing of WPP reflects in incremental installed DFIGs replacing SG3, and specifically, \(N\) is increased from 100 to 162 units. The performances of the proposed schemes are compared with those of the Fixed PD Inertia Control (FPDC), Referenced Rotor Speed Control (RRSC),\(^\text{18}\) and MPPT control as well.

5.1 \| Effects of wind speeds

Different levels of KE restored in the DFIGs before power disturbance is affected by the wind speed, which results in the different performances of TFS schemes. This subsection validates the performance of the control schemes for the two cases with wind speeds of 12 and 9 m/s.

| Case | Regulation coefficient, \(\delta\) | Rated speed, \(\omega_0\) | Magnitude, A |
|------|---------------------------------|----------------|------------|
| 1    | 2%                              | 1.2 p.u.       | 1.05 p.u.  |
| 2    | 2%                              | 0.9 p.u.       | 0.775 p.u. |
| 3    | 2%                              | 1.2 p.u.       | 1.05 p.u.  |
| 4    | 2%                              | 0.9 p.u.       | 0.775 p.u. |
| 5    | 2%                              | 1.2 p.u.       | 1.05 p.u.  |
| 6    | 2%                              | 1.2 p.u.       | 1.05 p.u.  |
CASE 1. Wind speed of 12 m/s and WPP level of 18.75%: Figure 7 shows that the responses of RSBICs are faster than that of FPDC while controllable, i.e., response speed is decoupled from the magnitude against that overreact power of FPDC with large inertia gain. Comparing RRSC and the proposed scheme, the latter strives to shape a reference as “anti-S” to smoothly support frequency. Note that, with QFC-based recovery reference, output of the proposed scheme goes down smoothly and slowly at the onset of recovery and then rises up, which enables speed recovery compared to FPDC. Besides, by managing the kinetic energy of wind turbine in this way, the proposed scheme saves more rotor speed operation margin for DFIGs compared to RRSC (see Figure 7c), merely resulting in RoCoF increased lightly.

CASE 2. Wind speed of 9 m/s and WPP level of 18.75%: in this case, less KE is stored, and FNs of TFS schemes are deteriorated. Figure 8 shows that the proposed scheme provides more significant power to FPDC in lower wind speed and further demonstrates that although with more KE released, QFC-based power reference effectively helps shorten the cycle of frequency regulation while avoiding obvious SFF compared to RRSC, improving generation efficiency and the capability of countering back-to-back disturbances. In another prospective, QFC-based trajectory allows a smaller power deloading \( \Delta p \) for activating recovery at the same level of recovering speed, which benefits alleviating SFF.

5.2 | Effects of wind power penetration level

With wind power penetration level grows, wind power undertakes bigger proportion of load, and the operation point of SGs is decreased; thus, the generation efficiency of WTGs is more critical because SGs will undertake more extra load at the same level of operation of WTGs. This subsection validates the performance of the TFS schemes at the wind speeds of 12 and 9 m/s for the 37.5% wind power penetration level.

CASE 3. Wind speed of 12 m/s and wind power penetration level of 37.5%: Figure 9 shows the results of Case 3, which is identical to Case 1 except for the WPP level. First, it can be seen that with FPDC, \( P_e \) cannot converge to \( P_m \), resulting in WTG instability and the loss of WTGs further leads to power system frequency collapse. Second, the improvement regarding RRSC in Case 3 should have been more significant than that in Case 1 because the wind power penetration level is higher and more quantity of rapid adjustment power is available. While the frequency deviation of the RRSC is 0.5828 Hz, which is larger than that of Case 1 by 0.1178 Hz, judging from Figure 10a, it seems that
power overshooting contributes to this problem, which will be more prominent for RSBIC with WPP level increasing. Conversely, there is no power overshooting in the situation of the proposed scheme while the performance of it is deteriorated as well. Relevant discussion is conducted specifically at the end of this subsection.

**CASE 4.** Wind speed of 9 m/s and WPP level of 37.5%: Figure 10 shows the results of Case 4, which is identical to Case 2 except for the WPP level of 37.5%. In this case, system fails to maintain stability in the condition of MPPT control, which addresses the necessity of applying...
TFS to help improve resilience of system. As can be seen that similar to Case 3 and Case 1, the performance of RSBICs is deteriorated with WPP level increases while that of FPDC are not that sensitive for Case 4 compared to Case 2.

In addition, it can be followed from Figures 11 and 12 that with the increasing of WPP and decreasing of wind speed, the frequency regulation capability of system is deteriorated overall. Although performances of RSBICs seem relatively stable while as what is mentioned in Cases 3–4, the inherent principle of interaction between WTGs and SG is to be illustrated. According to the studied results, the conclusion on this issue can be analyzed as the following:

First, the essence of synchronous machine inertia is that under the constraints of electromagnetic connection with grid and instantaneous power balance, power of synchronous machine is forced to be extracted for net load when power imbalance occurs. As showed in Figures 2, 7, 8, 9, and 10d–f, because there is delay and speed limitation in the control system, the power derived from SG consists of KE of the rotor and droop control before the Gate of valve catches up. During this period, according to the dynamic function of system, frequency deviation occurs.

Thus, how and when the inertia response of WTG participates in the frequency event impacts the net load to synchronous machine, resulting in different response of valve adjustment and frequency regulation performances. When frequency falls, SG and WTG should jointly undertake the frequency regulation mission in time. Considering the operation characteristics, SG can be cheated by the temporary unobvious frequency deviation resulted from the prompt output of WTG. See Figure 9d–f; at the onset of disturbance, prompt output of RRSC and the proposed

**FIGURE 10** Results of Case 4

**FIGURE 11** Comparing results of frequency deviation (Hz)
scheme inhibit the action of Gate of valve. Subsequently, the output of WTG must decrease rapidly considering the limited KE stored and converging with \( P_m \) to avoid OD and SFF. At this time, rotor speed of WTG is lower than the optimal point, and \( P_m \) is greatly reduced. Consequently, synchronous machine is forced to bear a larger imbalance power, with the reduced captured wind power generation superimposed, and the vacancy between electrical power and mechanical power cannot be narrowed down perfectly, contributing less to system frequency regulation. At this point, what is different between RRSC and the proposed scheme is that the latter seeks to contribute a more gentlest transit of the WTG power reduction by tracking a power reference as “anti-S,” which not only reduces the risk of frequency overregulation inducing power turbulences (see Figures 7–10a) but also enhances the stable operation margin of WTG rotor speed (see Figures 7c and 9c).

In comparison, the slower output of FPDC makes room for Gate to open with full rate at the beginning. Considering after the transient of frequency regulation SG undertakes the whole extra load, it can be drawn that it will be optimized for regulation if the Gate moves around the steady state with a bit overshooting at the beginning, as the situation of FPDC showed in Figure 9. In fact, the coordinative operation between
SG and the prime mover had been studied. Similarly, the conclusion was that to improve the response speed of synchronous machine, it was optimized to open valve fast and then adjust it.

### 5.3 Arresting over releasing of KE and handling back-to-back disturbances

**CASE 5.** Wind speed of 12 m/s and wind power penetration level of 37.5%: as what is concluded in Section 2, because system frequency regulation has the characteristics of attenuation, hysteresis, and static deviation, the threshold of FEDOS is prone to be crossed when suffers a relative small disturbance though. The fundamental settings are identical to that of Case 3 except for the disturbance, which is replaced by a steady 40-MW incremental static load.

It follows from Figure 13a that for RRSC, since DFIGs' output is decoupled from system frequency and without arresting over releasing of KE, FN is not improved but deteriorated with a sharp fluctuation and significant overshoot in frequency. In contrast, when FEDOS is applied, the output of WTG is linearly limited basing on the overshooting $\Delta f$. Since $P_{ref}$ is referred to $\omega_r$ and $k_{FEDOS}$ is referred to $\Delta f$, the proposed scheme remains satisfied performance at SFF and ROCOF arresting. Regarding FPDC, with the contribution of feedback adjustment, the phenomenon of overshooting will not occur unless a huge inertia gain is applied. And note that this issue will be severer with the WPP level increasing and the importance of applying FEDOS for RSBICs is getting remarkable.

**CASE 6.** Wind speed of 12 m/s and wind power penetration level of 37.5%: the capability of the TFSs to support frequency is critically dependent on the stored KE, which can be impacted by the wind speed and WPP as mentioned in the previous subsections or active controls conducted resulting in varied rotor speed. Thus, this section describes the investigation results when TFSs counter back-to-back disturbances. Figure 14 illustrates that for RRSC, without comprehensive mechanism for retriggering inertia control and suppressing over
releasing KE, the system encounters a severer burden consisting of second frequency event and the lower deloading generation state during recovery, which brings about a worse frequency fall even compared to the situation with MPPT. Conversely, the performance of the proposed scheme with FEDOS is significantly improved, and FPDC performs well in countering back-to-back small disturbances. To this end, the characteristics of WTG adopting RRSC, FPDC, and the proposed scheme on operation performances, including frequency support, rotor speed deviation, and WTG rotor speed recovery, can be drawn as the Table 2 below.

6 | CONCLUSIONS

This paper proposes a novel strategy for frequency regulation based on RSBIC and investigates the performances of it under different conditions of wind speed and WPP. Analyzing the results of cases studied, conclusions can be drawn as follows:

- Coupling with system frequency, FPDC has the advantages of effectiveness in counter back-to-back small disturbances inherently and parameter robustness, with less inertia released while achieving satisfactory performance.
- The superiority of RSBIC lies at decoupling with system frequency, which decouples the inertial response speed from the response amplitude; i.e., the combination of infinite inertia response speed and appropriate response amplitude can be realized, ensuring stable operation of WTG and system.
- The proposed scheme and RRSC have the same contribution in suppressing FN and ROCOF and further improve SFF, gaining more sufficient operation margin for rotor speed operation, simultaneously. In addition, for the disturbances with unpredictable severity, the introduction of FEDOS revises the wind power when its frequency regulation is triggered by relatively small disturbance. It balances the goal of pursuing “infinite inertia response” compared to FBIC, obtaining sufficient frequency regulation contribution and suppressing frequency reversed oscillation.
- Considering cooperation with synchronous machine, faster response speed or larger amplitude may not contribute to the better frequency regulation performance for WTG. Take major delays in frequency response into account, it is suggested to guide steam turbine to open the Gate at full rate to the steady state (the state of Gate when SG bears the whole incremental load after primary frequency regulation) around with subsequent valve adjustment. Under this premise, the faster and higher response contributes better frequency regulation performance.
- FBIC and RSBIC can be improved by imitating the advanced characteristics from each other. In addition, switching the modes of control regarding different disturbances can be another solution to give full play to the strengths of FBIC and RSBIC.

NOMENCLATURE

AGC automatic generation control
A power reference magnitude at the starting point of the proposed scheme for frequency regulation

| Schemes            | Frequency support                                                                 | Rotor speed deviation | Rotor speed recovery                                      |
|--------------------|-----------------------------------------------------------------------------------|-----------------------|-----------------------------------------------------------|
| RRSC               | Sufficient and quick but may incur frequency over-regulation when triggered by relative small frequency violations in the system with high wind power penetration. Can be designed directly and accurately to guide WTG operation while relatively rigid compared to the FBICs under frequently fluctuating wind condition. | Relatively heavy      | Yes, but relative slow and has a significant second frequency impact under high wind power penetration |
| FPDC               | Flexible but the response may be slow, which is limited by the inherent characteristic of feedback control. Needs careful parameter setting to balance insufficient inertial response, rotor speed over-delinking, etc. | Mildest               | No, can be improved but it needs more complicated manipulations for scheme design and control parameters |
| Proposed scheme    | Sufficient and quick, avoiding incurring frequency over-regulation when triggered by relative small frequency violations in the system with high wind power penetration. Can be designed directly and accurately to guide WTG operation while relatively rigid compared to the FBICs under frequently fluctuating wind condition. | Relatively slight     | Yes, quicker than RRSC with the same rotor speed recovery activation delinking and significantly narrows down the second frequency impact |
\( C_p \) wind energy conversion rate of DFIG
DFIG doubly fed induction generator
\( D \) damping coefficient of system
FN frequency nadir during power disturbance
FBIC frequency-based inertia control
FPDC fixed PD Control
FEDOS frequency event detector and output suppressor
GSC generator side convertor
\( H \) coefficient of inertia of wind turbine
KE kinetic energy
\( k_{\text{FEDOS}} \) the coefficient of frequency event detector and output suppressor
\( k_{\text{map}} \) the mapping factor of the proposed scheme
\( K_{\text{pan}} \) the coefficient used to help adjust the starting point of \( P_{\text{ref, II}} \)
MPPT maximum power point tracking
OD over-deceleration of rotor speed of DFIG
\( P_{\text{MPPT}} \) power reference for MPPT control
\( P_{\text{Tlim}} \) power limitation of WTG considering torque protection
\( P_m \) mechanical input power
\( P_e \) electrical output power
\( P_{\text{ref}} \) active power reference
\( P_{\text{ref, I}} \) the power reference in Stage I of the proposed scheme
\( P_{\text{ref, II}} \) the power reference in Stage II of the proposed scheme
\( \Delta p \) reduced power for speed recovery
QFC quadratic function curve
ROCOF rate of change of frequency
RSBIC rotor speed-based inertia control
RRSC referenced rotor speed control
RSC rotor side convertor
SG synchronous generator
SFF second frequency fall
SFT sinusoidal function trajectory
TFS temporary frequency support
\( T_p \) torque protection limitation
VSWTG variable speed wind turbine generator
WPP wind power penetration
WTG wind turbine generator
\( \omega_{\text{min}} \) minimum rotor speed
\( \omega_{\text{min plus}} \) specific rotor speed ensuring no rotor speed violation when designing control scheme
\( \delta \) frequency regulation coefficient

DATA AVAILABILITY STATEMENT
Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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