Closed-loop fast primary frequency-response of type-3 wind power plants in low inertia grids

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Abstract
This paper proposes a frequency-control scheme for Doubly Fed Induction Generator (DFIG)-based (Type-3) wind turbines to improve the primary-frequency-control when the grid power balance is disturbed. The increasing penetration level of renewable energy sources, like wind power plants, reduces the total available inertia of modern grids, which deteriorate the frequency response in case of sudden power-mismatches. The proposed closed-loop participation of wind power plant interacts with the thermal units to reduce the frequency nadir and frequency settling-time, during the inertial and primary stages. The designed disturbance observer decreases the uncertainties in the estimation of grid parameters, which results in robust PI performance in adjusting the ancillary power provided by wind turbines. Certain measures considered within the control loop to limit the rate-of-change-of-frequency within the permissive range to avoid the protective relays tripping. Comparative simulations studies on modified IEEE 9-bus and 68-bus test systems verify the effectiveness and advantages of the proposed method.

1 | INTRODUCTION

1.1 | Motivation of study

Over the last decades, variable wind-speed Wind Turbine Generators (WTGs) such as Doubly-Fed Induction Generator (DFIG) and Permanent-Magnet Synchronous Generator (PMSG) widely employed in the power systems due to their ability to extract the maximum wind power at different wind-speeds [1]. Since the injected power from variable-speed wind turbines is processed thorough power electronics converters which make their rotor speed independent from the grid frequency, they are not able to support grid frequency regulation. In addition, installing wind farms instead of conventional Synchronous-Generator (SG) reduces power system inertia, which may jeopardize power system frequency stability [2, 3].

Since over-deviation of frequency may lead to instability of the power systems, Frequency Nadir (FN), the maximum frequency-deviation, is considered as an important index to prevent the frequency collapse [4, 5]. Therefore, the participation of DFIG-based wind farms in the frequency control has attracted great attention to improving the FN, the Rate-of-Change-of-Frequency (RoCoF or df/dt) and the frequency settling time [6]. Some presented methods maintain a pre-defined reserved-power and operate below the maximum-power-point (MPP) at each wind-speed, known as de-loaded operation, to support the frequency during active power shortage [7]. Although de-loading methods provide WTGs participation in frequency support, they suffer from the loss of annual energy generation, due to less power generation during normal grid frequency.

1.2 | Literature review

Various synthetic inertial control methods have been presented in [8–26] to exploit the kinetic energy stored in the masses of blades and gearbox stages of wind-turbines, to improve the inertial response while they operate in Maximum Power Point Tracking (MPPT) mode. These methods mimic the inertial and droop response of the conventional SGs, by adding an auxiliary loop to the power controller of the WTGs. The synthetic inertial control methods are classified as the frequency
deviation-based methods [8–18] and step over-production methods [19–26]. The frequency deviation-based methods employ a feedback loop with a constant or adaptive gain [11, 12] to compensate for the power mismatch. Application of fuzzy controller for adaptive tuning of inertial and droop gains of the auxiliary power loop provides a smoother contribution in frequency regulation in different wind speeds [13]. The constant inertia gain is improved by a lead-lag forward compensator to reduce the frequency nadir at the expense of slower response time [14].

Most of these methods consider a reduced-order model of the DFIG-based wind farm which has reasonable accuracy to investigated virtual inertia aspects [15]. Implementing linear virtual inertia approaches for individual turbines of a wind farm may face stability issues. Thus, a non-linear state feedback controller is designed for a matrix arrangement of the turbine to ensure the stability of the power system during primary frequency control [16]. The Newton method is applied to determine the amount of released kinetic energy for decentralized virtual inertia participation [17].

To achieve a faster inertial response, step over-production methods are presented which exchange WTGs’ output power with the grid based on a predefined reference function, upon detecting a disturbance. Methods in [19–21], inject a power-step with a preset time-duration which results in rotor deceleration. Although these methods improve the frequency support at a higher level than the frequency deviation-based methods, they may cause rotor over-deceleration, particularly in low wind-speeds. To prevent this over-deceleration, the injected power is decreased on a trajectory line in [21, 22] or on an upshifted-MPPT curve [23]. To decrease the FN, the method in [22] instantly releases the maximum amount of kinetic energy, considering the shaft torque limit. A comprehensive framework presented in [24] to determine the injected power set-point considering wind speed, pitch angle and available mechanical power to optimally contribute to primary frequency control. Since the injected power in methods [19–21] are independent of the disturbance size, they have appropriate responses only for specific disturbance sizes. Additionally, significant extra power injection by WTGs slows down SGs’ governor response, in compensating power mismatches. Faster secondary frequency response is achieved by limiting the released power of the DFIG turbine during the primary stage and compromising the frequency nadir, based on under-estimation of steady-state frequency value, which provokes the synchronous generators during the primary stage [25].

After improving the frequency response during the deceleration stage, it is necessary to restore the rotor speed to its pre-fault value. For this objective, some methods impose a sudden decrease to the electrical wind power, which causes considerable Second Frequency Drop (SFD) [22, 23]. A combination of step-wise and inertial methods is applied as a fuzzy-based two-stage frequency support scheme to improve the rotor speed restoration time [26].

1.3 Contributions

This paper proposes a new closed-loop control approach which improves the participation of DFIG-based wind-farms in frequency regulation of power grid. The PI controller is designed based on linearized model of power system, which adjusts the added wind power to smoothly approach the steady-state grid frequency, in case of a power mismatch event. Since wind farms are providing the added power to the grid, the performance of a conventional PI controller can be degraded due to parameter dependency of synchronous generators. Thus, a new disturbance observer-based controller is designed to obtain the auxiliary power reference for the DFIG. The proposed control method significantly improves the frequency-nadir and the frequency settling-time, due to the disturbance-observer-based closed-loop design which injects the ancillary power to the grid proportional to the magnitude of the power-mismatch.

The proposed approach facilitates adjustable frequency response of the grid by tuning the PI controller to decrease frequency undershoot (i.e. frequency nadir point) and settling time, without needing exact grid parameters. This approach results in a new added power profile accelerates the rotor speed immediately upon the power mismatch which eventually decreases the rotor speed restoration time while smoothing and decreasing the Second Frequency Drop (SFD). Moreover, it provokes the governors of SGs to inject more power which results in a faster frequency settling time.

The reference value of the closed-loop controller ensures the RoCoF \((\text{df} / \text{dt})\) within its permissible value and preventing protective relays from tripping. Since the DFIG-based wind farm is operating under the MPPT regime, its participation time is limited by a wash-out filter to avoid rotor under-speed.

2 DFIG-BASED WIND TURBINE CHARACTERISTICS

The configuration of a DFIG-based wind-turbine is shown in Figure 1, which includes fundamental components: wind turbine, three-stage gearbox, DFIG, and back-to-back converters, namely Rotor Side Converter (RSC) and the Grid Side Converter (GSC) [27].

The RSC adjusts the frequency and amplitude of the injected rotor currents to extract maximum mechanical-power from wind-energy over a wide range of rotor speed. At the optimum rotor speed, the mechanical extracted power can be obtained as follows [28]:

\[
P_m = \frac{1}{2} \rho \pi R^2 v_w C_p (\lambda, \beta) \tag{1}
\]

The parameters \(C_p\) and \(\lambda\) can be modelled as [28]:

\[
C_p (\lambda, \beta) = 0.51 \left( \frac{116}{\lambda} - 0.45\beta - 5 \right) e^{21 \lambda} + 0.0068\lambda \tag{2}
\]
FIGURE 1  Configuration of a DFIG-based wind turbine

TABLE 1  Parameters of DFIG-based wind turbine

| Parameter                  | Symbol | Value |
|----------------------------|--------|-------|
| Base power                 | $P_{base}$ | 1.5 MW |
| Base wind speed            | $v_w$ | 12 m/s |
| Inertia constant of wind   | $H_w$ | 6     |
| Base rotor speed           | $\Omega_{r,base}$ | 1.2 p.u. |
| Efficiency coefficient     | $C_p$ | 0.48  |
| Optimization constant      | $K_{opt}$ | 0.577 |
| Minimum/Maximum rotor speed| $\Omega_{min}, \Omega_{max}$ | 0.7 p.u. |
| Maximum rotor speed        | $\Omega_{max}$ | 1.2 p.u. |
| Pitch angle controller gains| $K_{ip}, K_{pp}$ | 25, 320 |
| Pitch angle rate limit     | $d\beta/dt$ | $\pm 2^\circ$/s |

Moreover, maximum power can be extracted at optimum tip speed $\lambda_{opt}$ which is:

$$\lambda_{opt} = \frac{R \omega_r}{v_p}$$  (4)

As represented in [29], the MPPT characteristic is applied for the speed-controller of DFIG to capture the maximum power, which can be obtained by substituting Equation (3) in Equation (1):

$$P_m = \begin{cases} 0 & \omega_r < \omega_{min} \\ K_{opt} \omega_r^\lambda & \omega_{min} \leq \omega_r \leq \omega_{max} \\ P_{max} & \omega_r > \omega_{max} \end{cases}$$  (5)

The value of constant $K_{opt}$ is mentioned in Table 1. Figure 2 shows the MPPT characteristic and the mechanical output power of the turbine, for different wind speeds. In this paper, power- and torque-limits, which are indicated with red dashed lines in Figure 2, are considered 1.2 and 1 p.u. respectively [30]. The electromechanical model of wind turbine and associated controller used for frequency control studies are depicted in Figure 3. The focus of this paper is on adjusting the active power reference on the Renewable Energy Plant Controller (REPC) to react to frequency variation and contribute to power mismatch regulation. The turbine parameters and speed and pitch angle controller specifications are detailed in Table 1.

3  EXISTING METHODS FOR PARTICIPATION OF WIND-FARMS IN FREQUENCY CONTROL

This section concisely describes the operational characteristics of two of the widely applied methods for the participation of wind farm in frequency control [8, 22].

3.1 Virtual inertia

The method in [8] participates the wind turbines in the frequency control, by adding an extra power $P_{add}$ to the conventional power controller. This extra power is provided by the stored kinetic-energy of the rotor-inertia of wind turbines. The presented supplementary loop consists of two terms; the first term emulates the inertial, the second term provides droop characteristic of synchronous generators. As illustrated in Equation (6), the added power $\Delta P_{add}$ is proportional to the rate of change of frequency $df/dt$ and the frequency deviation.

$$\Delta P_{add} = K_{ip} \frac{df}{dt} + K_f \Delta f$$  (6)

As shown in Figure 4, after fault detection, the controller is switched to virtual inertia scheme $P^*$. Therefore, the kinetic energy is injected into the power system, which improves the frequency nadir and ROCOF values. Consequently, the rotor speed is decelerated until it is converged to the equilibrium point on $P-\omega_r$ curve and stays there. Since the net released-kinetic-energy of DFIG wind turbine is zero, the rotor speed must be returned back to the pre-fault speed at the end of the participation period.

3.2 Torque-limit based frequency control

As shown in Figure 5, the method in [22] introduces a trajectory for the added power-waveform $P_{add}(t)$ to support the frequency after a power-mismatch. At the fault instant, the electrical wind power $P_{ew}$ is suddenly increased from $P_{MPP}$, point A, to the maximum shaft torque-limit [29] amount $P_{TL}$, point B. Afterwards, $P_{ew}$ is reduced on a trajectory line until the intersection of this line with the turbine $P-\omega_r$ characteristic, point C, while rotor speed is decelerating ($d\omega_r/dt < 0$). This large added power $P_{add}(t)$ improves the FN and ROCOF. The trajectory line
\[ P_{\text{add}} = P_{\text{add}}(\omega_0) - P_{\text{MPP}}(\omega_{\text{min}}) \frac{\omega_r - \omega_{\text{min}}}{\omega_r - \omega_{\text{ref}}} P_{\text{MPP}}(\omega_{\text{ref}}) \] 

In order to restore the rotor speed to its pre-fault value, \( P_{\text{cw}} \) is reduced promptly and maintained DD' while rotor speed is accelerating \((d\omega_r > 0)\) until it meets the MPPT curve, point D'. Then, \( P_{\text{cw}} \) increases up with the MPPT curve and the rotor speed reaches the pre-fault, point A.

### 4 | THE PROPOSED METHOD

Disturbances in conventional power systems, such as sudden load increase or generation missing, disrupt the power balance between generation and consumption; therefore, the frequency smoothly deviates from its nominal value. DFIG-based wind farms are preferred choices for frequency control, due to their ability to change quickly their output power by the means of grid-connected inverters. However, the output power of conventional DFIG wind farms is decoupled from grid frequency and they always operate in MPPT. Therefore, these wind farms have no contribution to frequency control. The following sections describe different aspects of the proposed controller, and explain how this method facilitates the DFIG wind farm contribution in the frequency control. The block diagram of this method, shown in Figure 6, consists of two main components: the closed-loop PI-based frequency controller and a disturbance-observer based compensation loop.

#### 4.1 | New closed-loop frequency control design

To exploit the available kinetic energy, the power reference value is adjusted, by adding a compensation term \((\Delta P_{\text{add}})\) provided by a PI closed-loop frequency controller. The new approach estimates the post-fault steady-state frequency and use it as the reference for the frequency controller. As shown in Equation (8), the steady-state frequency reference is calculated based on the RoCoF which is proportional to the power mismatch magnitude. Consequently, the frequency response can be regulated by injecting or absorbing power from the DFIG-based
turbines which improved frequency nadir and fast settling time.

The steady-state frequency-deviation $\Delta f_{ss}$ is considered as the reference signal of PI controller. Moreover, it is assumed that wind turbines operate in MPPT. Thus, after the frequency event, wind generation does not have a droop characteristic and has no impact on the final frequency deviation. Thus, $\Delta f^*$ is obtained as [31]:

$$\Delta f^* = \Delta f_{ss} = \frac{\Delta P_L}{\sum_{i=1}^{n} \frac{M_i}{K_{gi}} + D} \approx \sum_{i=1}^{n} \frac{M_i}{K_{gi}} \frac{d}{d\Delta f} \left( t = t_{fault}^+ \right)$$

(8)

The corresponding system frequency model is illustrated in Figure 7, where $D$ is considered to be small compared to $\Sigma K_{gi}$ for a typical large grid. During normal operation of power systems, generators are entered-in or tripped off the grid which increases or decrease both $\Sigma M_i$ and $\Sigma K_{gi}$ parameters, respectively. Thus, the ratio of these two parameters ($\Sigma M_i/\Sigma K_{gi}$) is less variable value than each of them. Therefore the estimation of $\Delta f_{ss}$ is almost accurate.

After a power mismatch $\Delta P_L$, the PI controller makes the frequency-deviation $\Delta f$ converge to its reference signal $\Delta f_{ss}$. Since DFIGs mostly operated under MPPT, they cannot provide additional steady state power. Therefore, the closed-loop
controller must be decayed out by a wash-out filter. The time constant of the wash-out filter is considered larger than that of PI controller, to avoid interfering primary frequency control. The wash-out should not affect the injected wind power before the steady-state condition; however, after primary response, the PI output is decayed by wash-out to avoid further rotor speed reduction. Thus, faster rotor speed recovery can be achieved and DFIG will return to MPP faster.

Another important feature of the frequency response is the rate of change which should not be exceeded from the permissible range. Therefore, the reference signal of the PI controller has a rate limiter to prevent the ROCOF relay tripping, as shown in Figure 6.

4.2 | New disturbance observer based feedforward loop

The existence of disturbances in most closed-loop controlled systems deteriorates the performance of the controller. Therefore, disturbance rejection or compensation is the main solution in control systems design [32]. The disturbance estimation, which is feed-forwarded as a compensation term, mitigates the disturbance effect on the controller and provides stable performance. More details are described in [33, 34].

The internal disturbances are created by un-modelled dynamic of the controlled system. The frequency-domain block-diagram of Disturbance Observer-Based Control (DOB) is shown in Figure 8, where:

- \( H(s), H_e(s) \) and \( C(s) \) are the real physical plant, the nominal model of plant and the feedback controller.
- \( y_r \) and \( y \) are reference signal and the output of the plant.
- \( C \) and \( u \) are the output of feedback controller and the input of the plant.
- \( d, d_L \) and \( \hat{d}_L \) are the external disturbance, the lumped disturbance and the estimation of lumped disturbance.

The disturbance observer is applied to estimate the Lumped Linear Disturbance (LLD) consisting of external and internal disturbances [33]. The LLD estimation can be obtained as follows:

\[
\hat{d}_L = H_n^{-1} y - u \tag{9}
\]

In Equation (8), the observer applies the inverse of a nominal model of the physical plant, which contains a differentiator that amplifies the high frequency noises created by measurement sensors. Therefore, these noises must be attenuated by a low-pass filter \( Q(s) \), as shown in Figure 8. The inverse of the plant model, in the disturbance observer, cannot be applied for non-minimum phase plants. The proof of local and global stability of DOBC and its robustness to estimated-parameters can be found in [32, 33]. The proposed frequency control in this paper is designed on the basis of the DOBC which is customized for the power grid model and DFIG wind farm frequency contribution. The designed DOBFC improves the performance of the PI controller by compensating the external and lumped-internal disturbances.

In order to track the reference signal \( \Delta f^* \), after a power mismatch disturbance \( \Delta P_L \), the PI controller compensates a part of the power mismatch \( \Delta P_L \) with changing wind power generation. Moreover, a disturbance observer is proposed to assist the PI controller, by feed-forwarding an estimation of the power-mismatch. Although this estimation has some error due to parameter dependency, the closed-loop controller is robust against this error.

According to Equation (9), the output of disturbance observer is estimated as:

\[
\hat{d}_L = Q(\Delta f - \Delta P_L) \tag{10}
\]

where \( P_n^{-1} \) is the inverse of nominal plant, obtained as:

\[
P_n^{-1} = \left( \frac{H_n}{1 + H_n G_n} \right)^{-1} = G_n + \frac{1}{H_n} = (m^f + D) + \left( \frac{k^d}{e_{\partial} + 1} \right) \tag{11}
\]

where, superscript ‘\( \prime \)’ defines the estimated values for power system parameters.

To consider the electrical and mechanical constraints of WG [30], the rate limit of PI is set on maximum power which is below the shaft torque-limit.

As mentioned in Equation (8), WG cannot affect the final frequency deviation because it operates in MPPT. Therefore, the estimated-governor signal \( \Delta P_g \) must be decayed out after improving the settling time and the frequency nadir. To achieve this, another wash-out function is used after the reduced governor model \( G_n(s) \), shown in Figure 6. The time constant of this wash-out filter is much smaller than the one at the total output of the proposed controller because this feed-forward signal is important just after disturbances and inertial response.

Moreover, if the approximated damping chosen to be zero \( (\gamma = 0) \), estimated \( M d f/dt \) automatically decays to zero due to differentiator so, its signal does not need washout. These techniques significantly decrease the restoration time of rotor speed because they prevent injecting useless extra power.

After controlling the frequency transient, the proposed DOBFC is switched out and the following controller is proposed to restore the wind generators power and the rotor speed to the pre-fault point.
4.3 | Restoration of rotor-speed to its initial value

The aim of this stage is providing fast $\omega_r$ restoration to $\omega_{MP\text{PPT}}$ while it has smooth and small SFD. To end this, $P_{add}$ should be chosen to have relatively a small negative value, for instance by choosing $P_{aw} = P_{aw} - 0.01 \text{ p.u.}$ Therefore, this extra mechanical torque accelerates the wind generator’s rotor speed to restore to $\omega_{MP\text{PPT}}$. Since a sudden decrease in $P_{add}$ causes an SFD, a delay function is employed to have a smooth decreasing of $P_{add}$, which results in a smooth frequency drop. Once $\omega_r$ meets the MPPT curve, the internal speed-controller of WGs regulates $\omega_r$ to its pre-fault value ($\omega_{0}, P_{MP\text{PPT}}$).

5 | SIMULATION RESULTS

The performance of the proposed method is studied under various wind speeds and Wind Power Penetration Level (WPPL), considering the IEEE nine-bus power system which is widely used to study the performance of load-frequency control methods [35,36]. The modified versions of this test system are widely used for verification of different wind-participation methods in highly-penetrated power systems with reduced inertia [37–39]. The single line diagram of this test system, presented in Figure 9, including; two SGs with total inertial constant $M = 10 \text{ s}$, loads with damping factor $D = 1\text{p.u.}$ and a DFIG-based wind farm with the parameters shown in Table 1. Moreover, the droop-gains and time-constants of conventional steam turbines are set to 5% and 0.04 s, respectively.

As the second test system, a modified IEEE 68-bus power system is chosen to confirm the effectiveness of the proposed method, during a realistic generation unit outage scenario. The details of this test system can be found in [40].

Simulation studies are performed using Simulink with ode45 solver and 100 $\mu$s time step. The proposed controller utilises discrete PI and transfer functions, to replicate the real-world implementation on micro processors.

5.1 | Wind speeds impact

In this subsection, the proposed method is compared with: Torque Limit Based Frequency Control (TLBFC) [22], virtual inertia method [8] and no participation method. Two different wind speeds of 8 and 10 m/s are chosen. In both speeds, WPPL and power mismatch $\Delta P_L$ are selected to be 30% and 7%, respectively.

Case 1: Wind speed = 8 m/s

As shown in Figure 10(a), after the power-mismatch event, in the TLBFC method, the wind-generator injects extra electrical-power to the grid, until the generator torque reaches the shaft limit. This power increase raises frequency-nadir compared to the conventional method. The frequency-nadir of the proposed methods is significantly higher than the other three methods. This is because:

- The controller is closed-loop and uses PI, which can track the reference frequency after a step disturbance.
- The steady-state frequency deviation of the system is considered in the reference frequency, $\Delta f = -\Delta P_L/K_g$, as explained in Section 4.1.
- The disturbance observer estimates the power-mismatch and governors’ response, and highly activates the governor during the transient compared to other methods, Figure 10(c).

Therefore, as shown in Figure 10(b), added- wind-power $P_{add}$ is significantly less than that of TLBFC, and the frequency reaches the steady-state value faster than the other methods. Moreover, since the proposed method employs a rate limiter after the step command $\Delta f$, the ROCOF is kept below the standard threshold (1 Hz/s).

Figure 10(d) shows the rotor speed variation $\Delta \omega_r$, during the primary frequency control. In virtual-inertia and TLBFC methods after injecting extra power, $\omega_r$ start decelerating until it gets to its equilibrium point ($\Delta P_{add} = 0$) at $t = 52 \text{ s}$ and $t = 18 \text{ s}$ respectively. Then in TLBFC, $P_{add}$ is instantly reduced which causes an SFD, and $\omega_r$ is accelerated until it is restored to its initial value $P_{MP\text{PPT}}(\omega_{0})$.

The rotor speed trajectory of the proposed method has two stages. First, the rotor accelerates by absorbing power from the grid ($\Delta P_{add} < 0$), immediately after fault until reaching the first equilibrium point, $P_{aw} = P_{aw}$, at the right side of MPPT point. Then, the controller injects extra power into the grid, which decelerates the rotor speed until reaching the second equilibrium point at the left side of MPPT at $t = 15.5 \text{ s}$.

Finally, to restore $\omega_r$ to its pre-fault value, $P_{add}$ is smoothly reduced by the proposed delay function, which causes smaller SFD compared to TLBFC method. Thus, $\omega_r$ accelerates until it reaches the MPPT curve and moves upward on it, back to its pre-fault value $P_{MP\text{PPT}}(\omega_{0})$.

As shown in Figure 10(d), $\omega_r$ recovery time of the proposed DOBFC is significantly decreased, compared to other methods. Since the net exchanged energy of the DFIG wind turbine is
FIGURE 10  Comparative studies on the 9-bus grid subject to a 7% sudden load increase, 8 m/s wind speed

FIGURE 11  Comparative studies on the 9-bus grid subject to a 7% sudden load increase, 10 m/s wind speed
zero, fast $\omega_r$ recovery in DOBFC is due to the initial absorbing power stage and nullifying the injected power of disturbance observer by the washout function.

Figure 10(e) shows the trajectory of electrical wind power. This figure clearly demonstrates that DOBFC releases less kinetic-energy compared to TLBFC scheme. Moreover, the electrical wind power of DOBFC method reaches the equilibrium point at lower rotor speed value compared to TLBFC method.

**Case 2: Wind speed $= 10$ m/s**

Similar to the results presented in the previous case, the proposed method injects less electrical wind power compared to TLBFC method, Figure 11(b), and SG governor is more activated, Figure 11(c). Therefore, the frequency nadir in the proposed method is better than TLBFC and supports the stability of the power system, Figure 11(a). Moreover, the proposed method causes faster activation of SGs, which results in reducing frequency steady state time. As shown in Figure 11(a), the DOBFC has a smooth SFD which starts at 28 s due to the smoothly decrease in the electrical wind power to recover the rotor speed. As illustrated in Figure 11(c), the proposed DOBFC and TLBFC reach the equilibrium at $\Delta\omega_r = -0.06$ p.u. and $\Delta\omega_r = -0.14$ p.u. respectively. Since the released kinetic energy of the DOBFC method is lower than TLBFC method, the restoration time of the proposed method is significantly shorter than TLBFC, Figure 11(d).

Table 2 shows a comparison between the proposed DOBFC and other methods in terms of frequency-nadir (Hz), second frequency drop (Hz), added wind power (p.u), the minimum value of the rotor-speed $\omega_{min}$ (p.u) and restoration-time of the rotor-speed $t_r$ (s), for cases 1 and 2.

Although the proposed method adds less extra-power than other schemes, it improves the frequency-nadir compared to other methods, Table 2. This is due to the faster activation of SGs imposed by the proposed method. Moreover, the proposed method significantly reduces the frequency settling time.

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**TABLE 2** Comparative studies of frequency control methods

| Parameter       | Method              | Case1 | Case2 |
|-----------------|---------------------|-------|-------|
| FN (Hz)         | Proposed DOBFC      | 49.59 | 49.63 |
| (Higher is better) | TLBFC [22]          | 49.45 | 49.61 |
|                 | Virtual inertia [8] | 49.51 | 49.5  |
|                 | No participation    | 49.36 | 49.36 |
| SFD (Hz)        | Proposed DOBFC      | 49.74 | 49.73 |
|                 | TLBFC [22]          | 49.7  | 49.69 |
| Added wind power (p.u) | Proposed DOBFC  | 0.03  | 0.04  |
|                 | TLBFC [22]          | 0.09  | 0.07  |
|                 | Virtual inertia [8] | 0.03  | 0.03  |
|                 | No participation    | –     | –     |
| $\omega_{min}$ (s) | Proposed DOBFC  | 0.76  | 0.94  |
|                 | TLBFC [22]          | 0.72  | 0.86  |
| $t_r$ (s)       | Proposed DOBFC      | 55    | 75    |
|                 | TLBFC [22]          | 63    | 88    |

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**FIGURE 12** Different wind power penetration level studies on the 9-bus grid: 5% sudden load increase, 9 m/s wind speed
compared to the TLBFC method. Furthermore, the proposed method decreases the SFD magnitude, while achieving shorter rotor-speed restoration time compared to the TLBFC scheme.

### 5.2 Wind-power penetration-level impact

The penetration level of wind farms in providing energy in power systems varies upon different conditions. Thus, it is important to evaluate the proposed method for different penetration levels. Therefore, the simulations are done under different WPPL (10%, 20%, 30%, 40%) while the wind-speed and power-mismatch are set to 9 m/s and 5%, respectively. It must be noted that the participation of the synchronous generators in frequency control varies upon WPPL.

As shown in Figure 12(a), with increase in wind power penetration, the frequency control of proposed method is improved, which proves the effectiveness of proposed DOBFC method. Increase of wind power penetration causes decrease of the amount of governor gain $K_g$ which reduces the frequency steady state value and governor activation, Figures 12(a) and 12(c) respectively. Moreover, since the value of the power system inertia\(^1\) $M$ is not changed, the RoCoF value is almost same in all cases.

Figure 12(b) shows that increase of wind power penetration increases the added wind power. This decelerates the rotor speed, Figure 12(e), which reduces the restoration-time of the rotor-speed, Figure 12(d).

### 5.3 Frequency control in a modified IEEE 68-bus

In this case, comprehensive studies are done on a modified IEEE 68-bus (16 machines) system with wind power penetration. As shown in Figure 13, the conventional generators G5 and G11 are replaced with wind farms W1 and W2 (with equivalent capacity), and W3 replaces G14-G15 with 2.8GW nominal power [40].

As presented in [40], the impact of DFIG-based wind farms on the system inertia and stability can be investigated using an aggregated single-turbine model of each wind farm. The accuracy of this aggregated model for power system dynamic studies has been proven in [41, 42]. Moreover, wind farms are considered to operate at different wind speeds, to be a realistic scenario. Wind farms W1 and W3 are operated below the nominal wind speeds of 9 and 10 m/s, respectively. The wind speed of 13 m/s (above the nominal value) is selected for W2 to assess the proposed method performance while the pitch angle controller is active. Figure 14(b) shows that after SG9 outage at $t = 5$ s, the proposed controller of W1 and W3 absorb and inject power to the grid. Similar to Section 5.1, the rotor speed decelerates based upon their participation factors as shown in Figure 14(c). The participation of W2 in frequency control is different, because it is above the nominal wind speed operating point. In this region, W2 rotor speed is regulated with the pitch-angle ($\beta \approx 2^\circ$) to avoid over-speeding and maintain the speed to its maximum value. After the generation-missing event and absorbing power from the grid, W2 pitch-angle controller increases to $\beta \approx 4^\circ$ (Figure 14(d)), to prevent further rotor speed acceleration, Figure 14(c). Comparing added powers of wind farms (Figure 14(b)) reveals that W2 (with activated pitch angle control) mostly improves the frequency settling time by absorbing power. Therefore, its injected power to the grid is limited, compared to W1 and W3. Figure 14(a) shows the effectiveness of the proposed controller to improve frequency-nadir and settling time, by comparing with the no-participation scenario.
6 | CONCLUSIONS

A closed-loop control method is proposed for the participation of DFIG-based wind power plants in load-frequency control, during inertial and primary stages. Application of this method facilitates better frequency response on the modern grid with a high level of wind energy penetration and improves the stability of low-inertia grids. The contributions of this method are highlighted as:

- Reducing the frequency settling time and frequency-nadir by regulating the power output of the wind turbine in a closed-loop manner
- Using estimated reference frequency which reduces the steady-state grid-frequency overshoot,
- The designed disturbance-observer provides robustness to grid parameter uncertainties to determine the power-mismatch magnitude, which results in nadir improvement,
- The PI controlled is capable of maintaining the RoCoF within the permissible range,
- Smooth and negligible SFD is achieved, during rotor speed restoration, by the proposed delayed power function.

The novel participation of wind turbines in primary frequency response facilitated by the proposed method accelerates the interaction of thermal governors which ultimately results in fast frequency response and reduced settling-time.

Simulation studies on the modified 9-bus system show the advantages of this method compared to two widely applied existing methods, virtual inertia and torque limit based, for different wind speed scenarios. The comparison of results reveals that the proposed method releases less kinetic energy while resulting in better nadir and faster frequency settling time, compared to other methods, particularly in low wind speeds.

**Nomenclature**

- $\Delta f$: Frequency deviation
- $\Delta P_{add}$: Added wind power
- $\Delta P_{ew}$: Electrical wind power
- $\Delta P_l$: Power mismatch
- $\Delta P_{mw}$: Mechanical wind power
- $C_p$: Power coefficient
- $D$: Power system damping
- $d$: External disturbance
- $df/dt$: Rate of change of frequency
- DFIG: Doubly-Fed Induction Generator
- $d_L$: Lumped disturbance
- DOBC: Disturbance Observer Based Control
- DOBFC: Disturbance Observer Based Frequency Control
- FN: Frequency Nadir
- $G_e$: Equivalent aggregated governor
- GSC: Grid Side Converter
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