

Article

A Pre-Synchronized GFL/GFM Switching Method Triggered by Local Operating Indicators for DFIG Wind Turbines Under Weak-Grid Conditions

Zhishuai Hu ^{1,2} , Yongyi Lang ¹, Chenzhi Fang ¹ and Yongfeng Ren ^{1,2,*}

¹ College of Energy and Power Engineering, Inner Mongolia University of Technology, Hohhot 010051, China; ephzs@imut.edu.cn (Z.H.); 20241800283@imut.edu.cn (Y.L.); 20211000037@imut.edu.cn (C.F.)

² Key Laboratory of Wind Energy and Solar Energy Utilization Technology (Ministry of Education), Inner Mongolia University of Technology, Hohhot 010051, China

* Correspondence: renyongfeng@imut.edu.cn

Abstract

Under weak-grid conditions, grid-following (GFL) control of doubly fed induction generators (DFIGs) suffers from reduced stability margins, deteriorated dynamic performance, and intensified oscillations near the stability boundary. To address these issues, a pre-synchronized switching strategy between GFL and grid-forming (GFM) modes, triggered by locally measured operating variables, is proposed. Based on the GFL control model, the evolution of system dynamics with decreasing short-circuit ratio is analyzed, thereby elucidating how reduced grid strength progressively weakens robustness and disturbance rejection and eventually leads to instability. To characterize this deterioration, a set of normalized indices is constructed to quantify the oscillation levels of active power, phase-locked loop frequency, and point of common coupling voltage, enabling reliable identification of control-performance deterioration. A pre-synchronization scheme based on a virtual power closed loop is then developed, allowing the target mode to converge to the current operating point prior to takeover and enabling smooth bidirectional switching between GFL and GFM modes. Hardware-in-the-loop results demonstrate that the proposed strategy accurately detects GFL performance deterioration and effectively suppresses boundary oscillations while mitigating switching transients, thereby enhancing the adaptability of DFIGs to variations in grid strength.

Keywords: doubly-fed induction generator (DFIG); weak grid; GFL/GFM mode switching; pre-synchronization; local operating parameters



Academic Editor: Juri Belikov

Received: 26 April 2026

Revised: 13 June 2026

Accepted: 18 June 2026

Published: 20 June 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and

conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

With the increasing penetration of converter-interfaced wind generation, long-distance power transmission, declining short-circuit capacity at grid connection points, and reduced system inertia have become increasingly common. Weak-grid operation has become an important operating condition for wind turbines, particularly in distributed wind applications [1,2]. Under such conditions, the challenge of grid-connected control is not simply a reduced stability margin. More fundamentally, weakening grid strength intensifies the dynamic coupling between the turbine and the external grid, leading to progressive performance deterioration. For the widely used grid-following (GFL) control, this deterioration typically manifests as reduced damping and intensified oscillations, and may eventually

lead to instability [3,4]. Quantifying and suppressing GFL performance deterioration under weak-grid conditions is therefore essential for stable operation.

The origin of this deterioration has been studied mainly through analysis of the coupling between doubly-fed induction generator (DFIG) converter control and the external weak grid. For GFL-controlled DFIGs, the phase-locked loop (PLL) and the associated reference-frame construction have been shown to exert a strong influence on damping characteristics and stability margins under weak-grid conditions [5]. As grid strength decreases, the PCC voltage becomes more sensitive to current disturbances. This strengthens the coupling between synchronization dynamics and grid impedance, thereby increasing negative-resistance behavior and oscillatory risks over a wider frequency range [6]. Based on this understanding, some studies have sought to improve weak-grid adaptability without departing from the conventional GFL framework. In particular, the influence of short-circuit ratio (SCR) on the DFIG stability boundary and on the feasible range of controller parameters has been clarified in [4], while [2] investigates the relationship between PLL tuning and oscillatory behavior. Although such approaches can alleviate synchronization-induced stability problems, they still rely on PLL-based synchronization. Other efforts have moved beyond this path by restructuring synchronization mechanisms or redesigning control modes, including voltage-controlled DFIG operation [7], hybrid synchronization in which the rotor-side converter (RSC) and grid-side converter (GSC) adopt different synchronization modes [8], and hybrid GFL/GFM control [9]. By introducing voltage-source control, power synchronization, or grid-forming (GFM) features, these methods reduce dependence on external voltage phase tracking and provide alternative means to improve weak-grid adaptability. In addition, Ref. [10] shows that GFM-controlled DFIGs can enhance electrical stability under weak-grid conditions. Overall, existing work has improved DFIG control from the perspectives of PLL optimization, synchronization restructuring, and hybrid control, whereas switching decisions and switching execution across varying grid strengths remain much less studied.

As the adaptability of a single GFL mode becomes increasingly constrained by grid-strength variations, recent studies have turned to the formulation of GFL/GFM switching criteria. A first group of studies formulates switching criteria through SCR-related strength indices. Ref. [11] proposes the generalized operational short-circuit ratio (gOSCR) and its critical value to characterize the stability boundary of multi-converter systems under practical operating conditions, whereas Ref. [12] evaluates the stability and stability margin of heterogeneous GFL converter systems using generalized SCR (gSCR). In a similar vein, Ref. [13] employs a virtual dynamic SCR to construct switching-related control criteria, and Ref. [14] quantifies the stability and stability margin of hybrid GFL/GFM systems using voltage and current strength indices. A second group formulates switching criteria directly from impedance modeling or online estimation. In [15], a GFL/GFM switching boundary is established from impedance analysis, while Ref. [16] identifies grid-strength variations through online grid-impedance estimation and uses them to construct a switching criterion. These studies provide quantitative bases for switching-criteria design, but their criteria still depend largely on explicit grid-strength or impedance information. In practice, such quantities are often difficult to obtain accurately, and some identification procedures require additional disturbance injection or external excitation. By contrast, switching decisions based on locally observable signs of performance deterioration can reduce reliance on accurate grid-strength estimation. From this standpoint, the formulation of switching criteria based on local operating parameters remains insufficiently explored.

The dynamic performance of GFL/GFM mode switching directly determines the disturbance level induced by control-mode transition under weak-grid conditions. Low-disturbance switching therefore requires the target control mode to be accurately initialized

at the correct steady-state operating point. Existing methods can be divided into two categories. In [17], both modes remain active and the transition is achieved through weighting, so that the switching process remains smooth near a common operating point. For schemes without simultaneous operation, by contrast, the target control mode must be initialized before control transfer. In [18], smooth switching is achieved by adjusting only the outer loops while keeping the inner-current-loop references consistent during the transition. In [19], a switchable GFL/GFM control structure is constructed within a unified framework, in which both modes share the same measurements and inner current loop. In [20], fast phase locking is used to improve phase alignment across the transition, given the different angle-generation mechanisms of GFL and voltage-source GFM. In [21], mode transfer and state recovery are investigated under fault ride-through and current-limiting scenarios. In short, existing methods mainly suppress switching disturbances through weighted transition, operating-point consistency, unified control structures, or phase alignment. For DFIGs under weak-grid conditions, the central issue in non-simultaneous switching lies in the initialization of the target mode. However, the initial operating point of the target mode is determined from the current DFIG operating state. Under weak-grid conditions, the GFL operating state may already have deteriorated, so the resulting initialization error can directly increase the switching disturbance.

Against this background, this paper addresses bidirectional GFL/GFM switching of DFIG wind turbines under weak-grid conditions by focusing on two closely related issues. The first is how to characterize the dynamic signatures of GFL performance deterioration using local operating signals and convert them into a switching criterion. The second is how to establish an accurate steady-state operating point for the target control mode during transition and realize the corresponding bidirectional handover mechanism. To address these issues, an integrated solution is developed, composed of a local-parameter-based switching criterion, a virtual-power-loop-based pre-synchronization mechanism, and a bidirectional state-transition strategy. The main contributions are summarized as follows.

- (1) The coupling between GFL control and PCC voltage in weak-grid-connected DFIGs is analyzed, and the mechanism of GFL performance deterioration under weak-grid conditions is clarified. The coordinated oscillatory behavior of power, frequency, and voltage responses near the stability boundary is identified, providing the physical basis for switching-criterion design.
- (2) A local-parameter-based GFL/GFM switching criterion is proposed. Without requiring online estimation of grid impedance or SCR, the method identifies the deterioration of GFL control from the oscillatory signatures of local signals, including stator active power, PLL frequency, and PCC voltage, thereby enabling an objective forward-switching decision under weak-grid conditions.
- (3) A virtual-power-loop-based pre-synchronized switching method and a bidirectional GFL/GFM switching framework are proposed for DFIG wind turbines. By driving the target mode toward the current steady-state operating point before control transfer, the proposed method enables smooth and stable bidirectional pre-synchronized switching with improved adaptability under weak-grid conditions.

The remainder of this paper is organized as follows. Section 2 presents the modeling framework and switching requirements under weak-grid conditions. Section 3 analyzes the weak-grid-induced coupling mechanism and stability characteristics of GFL control. Section 4 develops the bidirectional GFL/GFM switching criterion and the pre-synchronization switching method. Section 5 provides HIL-based validation. Section 6 concludes the paper.

2. Modeling Framework and Weak-Grid Switching Requirements

2.1. GFL and GFM Control Models

GFL and GFM are two typical control modes for DFIG grid-connected operation. Under GFL control, synchronization is established from the grid voltage angle, and power injection is regulated through current control. Under GFM control, the converter actively establishes its terminal voltage through synchronous-machine emulation and exchanges power with the grid on that basis. The typical GFL and GFM control structures for a DFIG are shown in Figure 1.

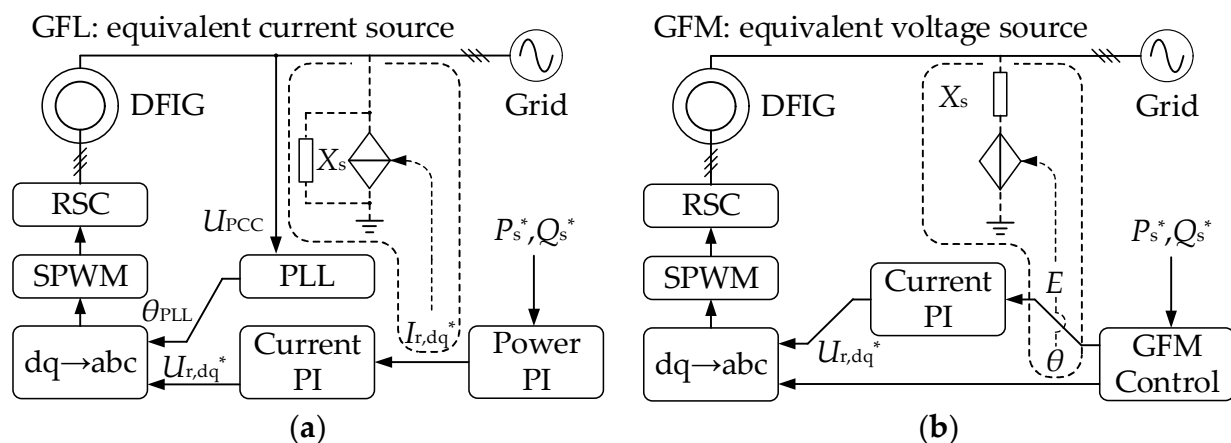


Figure 1. Typical stator-side control structures of the DFIG: (a) GFL; (b) GFM.

The typical GFL structure is shown in Figure 1a. The control of the DFIG rotor-side converter generally consists of a PLL, an outer power-control loop, and an inner current-control loop. The PLL extracts the synchronization angle from the PCC voltage and provides the reference for coordinate transformation. The outer power-control loop generates current references from the active- and reactive-power commands, while the inner current-control loop ensures fast tracking of these references. As a result, the dynamic behavior of GFL control depends directly on the PCC voltage, particularly on its phase angle.

The typical GFM structure is shown in Figure 1b. In this mode, the rotor-side controller no longer relies on the grid voltage angle as the synchronization reference. Instead, it internally establishes the magnitude, frequency, and phase of the converter terminal voltage. Its control structure typically includes a voltage-forming loop together with an inner current-control loop. Unlike GFL, which behaves as a controlled current source at the terminal, GFM behaves as a controlled voltage source. Its power exchange with the grid is therefore governed by the internally established terminal voltage rather than by grid-angle tracking.

In summary, both GFL and GFM enable power exchange between the DFIG and the grid through closed-loop control, but they differ in how synchronization is achieved. GFL relies on the grid voltage angle and regulates power through current control, whereas GFM establishes the converter terminal voltage through internal voltage-forming control and exchanges power on that basis. Consequently, the two modes exhibit different power dynamic responses to PCC-voltage disturbances under weak-grid conditions.

2.2. Weak-Grid Characterization

As the equivalent grid impedance increases, the sensitivity of the PCC voltage to injected power becomes more pronounced. For wind turbine control, this means that the PCC voltage can no longer be approximated as a stiff external quantity. Instead, both its

phase angle and magnitude vary with the turbine output power, thereby coupling the turbine power with the PCC voltage. As a result, PCC voltage disturbances no longer act merely as external inputs, but can feed back into the turbine active-power output, thereby forming an additional coupling loop that underlies the dynamics under weak-grid conditions.

In engineering practice, grid strength is commonly characterized by the SCR, which characterizes the support strength of the external grid seen from the PCC and can be used to reflect the strength of weak-grid coupling. Under weak-grid conditions, however, the actual coupling strength between the turbine and the PCC voltage depends not only on the short-circuit capacity of the grid but also on the instantaneous grid-connected active power. Therefore, the conventional SCR defined with rated power cannot accurately represent the actual coupling strength under different operating conditions, and this mismatch becomes more pronounced as the grid weakens. To account for this operating-point dependence, the equivalent short-circuit ratio (ESCR) is introduced as

$$ESCR = \frac{S_c}{P_g}, \quad (1)$$

where S_c is the short-circuit capacity at the PCC and P_g is the grid-connected active power. This quantity reflects the actual grid strength at different operating points.

To capture the dominant coupling between the turbine power and the PCC voltage under weak-grid conditions, the grid is represented by a simplified model consisting of an ideal voltage source in series with an equivalent impedance. Let the ideal grid voltage be $U_{\text{grid}} \angle 0$ and the PCC voltage be $U_{\text{PCC}} \angle \theta_{\text{PCC}}$. The two are connected through the equivalent impedance $Z_g = R_g + jX_g$. Since the transmission lines and the upstream grid are typically characterized by high reactance and low resistance at the fundamental frequency, the following analysis adopts the inductive-grid approximation $X_g \gg R_g$. Under this condition, the active power delivered to the grid can be expressed as

$$P_g = -\frac{U_{\text{grid}} \cdot U_{\text{PCC}}}{X_g} \sin(\theta_{\text{PCC}}). \quad (2)$$

Linearization around the steady-state operating point $(P_{g,0}, U_{\text{PCC},0}, \theta_{\text{PCC},0})$ yields

$$G_{\theta_{\text{PCC}}, P_g}(s) = \frac{\Delta \theta_{\text{PCC}}(s)}{\Delta P_g(s)} = -\frac{X_g}{U_{\text{grid}} U_{\text{PCC},0} \cos(\theta_{\text{PCC},0})}. \quad (3)$$

Thus, in the vicinity of the operating point, the active-power perturbation and the PCC angle perturbation satisfy an approximately static proportional relationship. As X_g increases, the grid weakens, and the gain from active-power disturbance to PCC angle disturbance increases accordingly. This relationship provides the basis for the subsequent small-signal coupling analysis. For grids with non-negligible resistance, the grid resistance should be retained in the derivation of (2)–(3).

2.3. Mode-Switching Requirement of DFIG Under Weak-Grid Conditions

As grid strength weakens, the DFIG operating problem no longer manifests merely as a static performance issue under a single control mode, but instead becomes a problem of matching the operating mode to the external grid condition. When grid support is sufficiently strong, the PCC voltage remains approximately stiff, and normal grid-connected operation can be maintained under GFL control. As the grid strength decreases, however, the additional coupling loop between the turbine power and the PCC voltage is progressively strengthened, driving the GFL operating state toward its stability boundary

and potentially leading to reduced damping and aggravated oscillations. Under such conditions, the operating mode needs to shift from GFL to GFM in order to maintain stable grid-connected operation. Correspondingly, when the external grid condition recovers, the GFL mismatch caused by grid weakening no longer persists, and the system should retain the capability to return to GFL operation.

Accordingly, under weak-grid conditions, DFIG operation requires both forward mode takeover and reverse mode restoration. Specifically, when the GFL operating state progressively approaches its stability boundary as the grid weakens, smooth takeover by GFM is required; when the external grid condition recovers, stable transfer back to GFL should be achieved.

3. Weak-Grid-Induced Coupling Mechanism in GFL

The mode-switching requirement under weak-grid conditions arises from the strengthening of the additional coupling between GFL control and the PCC voltage. Constructing an effective switching criterion requires clarifying the evolution of this coupling as grid strength decreases and identifying the oscillatory characteristics that develop near the stability boundary. Accordingly, a unified analysis of the dominant coupling mechanism and stability evolution under weak-grid conditions is required.

3.1. Coupling Mechanism Between GFL Dynamics and PCC Voltage

For GFL control, the PLL provides the synchronous reference angle for both the power and current control loops and therefore constitutes the key link in the additional coupling between the PCC voltage and the GFL dynamics. A transient mismatch between the actual PCC voltage angle and the PLL output angle causes a projection error of the current vector in the actual grid-voltage-oriented reference frame, which is further fed back into the active-power output. This mechanism is the fundamental origin of the additional coupling. As the grid strength decreases, the effect of this coupling is progressively amplified, eventually leading to stability issues in GFL operation under weak-grid conditions.

The transient mismatch angle σ_e is defined as the deviation of the PLL output angle from the actual PCC voltage angle. Around the operating point, its small-signal expression is given by:

$$\Delta\sigma_e = \Delta\theta_{PLL} - \Delta\theta_{PCC}. \quad (4)$$

where $\Delta\theta_{PLL}$ denotes the perturbation of the PLL output angle.

Within the PLL, the corresponding q-axis detection error of the PCC voltage can be expressed as

$$u_{eq} = -U_{PCC}\sin(\sigma_e). \quad (5)$$

By setting $\sigma_e = 0$ at the operating point and linearizing (5), one obtains

$$\Delta u_{eq} = -U_{PCC,0}\Delta\sigma_e. \quad (6)$$

The PLL regulates the error input Δu_{eq} through a PI controller and generates the estimated PCC voltage angle through an integrator:

$$\Delta\theta_{PLL}(s) = \Delta u_{eq}(s) \cdot \frac{K_{p,PLL} + K_{i,PLL}/s}{s}, \quad (7)$$

where $K_{p,PLL}$ and $K_{i,PLL}$ are the proportional and integral gains of the PLL PI controller.

From (4), (6), and (7), the PLL angle-tracking transfer function is given by

$$G_{\theta_{PLL},\theta_{PCC}}(s) = \frac{\Delta\theta_{PLL}(s)}{\Delta\theta_{PCC}(s)} = \frac{U_{PCC,0}(K_{p,PLL}s + K_{i,PLL})}{s^2 + U_{PCC,0}K_{p,PLL}s + U_{PCC,0}K_{i,PLL}}, \quad (8)$$

Accordingly, the transfer function from the PCC voltage angle perturbation to the transient mismatch angle is given by

$$G_{\sigma_e, \theta_{PCC}}(s) = \frac{\Delta\sigma_e(s)}{\Delta\theta_{PCC}(s)} = G_{\theta_{PLL}, \theta_{PCC}}(s) - 1 = -\frac{s^2}{s^2 + U_{PCC,0}K_{p,PLL}s + U_{PCC,0}K_{i,PLL}}. \quad (9)$$

Since $\Delta\sigma_e$ is defined as the difference between the PLL output angle and the actual PCC voltage angle, all control loops established with θ_{PLL} as the synchronous angle include this mismatch angle. In addition to participating in the PLL angle-tracking loop, this transient mismatch angle causes a projection deviation of the current vector in the actual grid-voltage-oriented reference frame, thereby entering the turbine power-control process.

Under grid-voltage orientation, based on the steady-state power relationship, the turbine active-power perturbation around the operating point can be linearized as a function of the perturbation of the rotor d -axis current:

$$\Delta P_g = -\frac{U_{PCC,0}L_m}{L_s}\Delta i_{rd}^{(g)}, \quad (10)$$

where L_m and L_s denote the magnetizing inductance and stator inductance, and $i_{rd}^{(g)}$ is the rotor d -axis current in the actual grid-voltage-oriented reference frame.

On the control side, the active-power PI controller generates the rotor d -axis current reference as

$$\Delta i_{rd}^{*(c)} = -\left(K_{p,P} + \frac{K_{i,P}}{s}\right)(\Delta P_g^* - \Delta P_g), \quad (11)$$

where $K_{p,P}$ and $K_{i,P}$ are the proportional and integral gains of the active-power PI controller. In the perturbation analysis, the active-power reference perturbation ΔP_g^* is assumed to be zero, i.e., $\Delta P_g^* = 0$.

With the closed-loop tracking dynamics of the inner current loop taken into account, the rotor d -axis current in the PLL reference frame can be written as

$$\Delta i_{rd}^{(c)} = \frac{K_{p,P} + K_{i,P}/s}{T_i s + 1} \Delta P_g, \quad (12)$$

where T_i is the equivalent time constant of the inner current loop.

Accordingly, the rotor current satisfies the following coordinate transformation relation between the PLL reference frame and the actual grid-voltage-oriented reference frame:

$$\begin{bmatrix} i_{rd}^{(g)} \\ i_{rq}^{(g)} \end{bmatrix} = \begin{bmatrix} \cos(\sigma_e) & -\sin(\sigma_e) \\ \sin(\sigma_e) & \cos(\sigma_e) \end{bmatrix} \begin{bmatrix} i_{rd}^{(c)} \\ i_{rq}^{(c)} \end{bmatrix}. \quad (13)$$

Linearization around the steady-state operating point yields

$$\Delta i_{rd}^{(g)} = \Delta i_{rd}^{(c)} - i_{rq,0}^{(c)} \Delta\sigma_e, \quad (14)$$

where $i_{rq,0}^{(c)}$ is the steady-state q -axis current in the PLL reference frame at the operating point.

Substituting (12) into (14) and combining the result with (10) yields

$$\Delta P_g = -\frac{U_{PCC,0}L_m}{L_s} \left[\frac{K_{p,P} + K_{i,P}/s}{T_i s + 1} \Delta P_g - i_{rq,0}^{(c)} \Delta\sigma_e \right]. \quad (15)$$

Further rearrangement yields the feedback transfer function from the transient mismatch angle to the active-power output:

$$G_{P_g, \sigma_e}(s) = \frac{\Delta P_g(s)}{\Delta \sigma_e(s)} = \frac{(U_{PCC,0} L_m / L_s) i_{rq,0}^{(c)}}{1 + \left(\frac{U_{PCC,0} L_m}{L_s} \right) \left(\frac{K_{p,P} + K_{i,P}/s}{T_i s + 1} \right)}. \quad (16)$$

Equation (16) indicates that the transient mismatch angle enters the active-power control channel through the projection deviation of the current vector, thereby introducing dynamic feedback into the active-power output.

Equations (3), (9), and (16) represent the power-to-PCC-angle transfer function, the PCC-angle-to-mismatch-angle transfer function, and the mismatch-angle-to-active-power feedback transfer function. Cascading these three transfer functions yields the open-loop path of the dominant additional coupling loop under weak-grid conditions. The corresponding equivalent open-loop transfer function $L_{cpl}(s)$ can be written as:

$$L_{cpl}(s) = G_{\theta_{PCC}, P_g}(s) G_{\sigma_e, \theta_{PCC}}(s) G_{P_g, \sigma_e}(s). \quad (17)$$

Substituting (3), (9), and (16) into (17) yields

$$L_{cpl}(s) = \frac{X_g L_m i_{rq,0}^{(c)}}{L_s U_{grid} \cos(\theta_{PCC,0})} \cdot \frac{s^2}{(s^2 + U_{PCC,0} K_{p,PLL} s + U_{PCC,0} K_{i,PLL}) \left[1 + \left(\frac{U_{PCC,0} L_m}{L_s} \right) \left(\frac{K_{p,P} + K_{i,P}/s}{T_i s + 1} \right) \right]}. \quad (18)$$

Equation (18) shows that the external grid parameters enter this coupling loop through the coefficient $X_g/[U_{grid} \cos(\theta_{PCC,0})]$, and an increase in X_g strengthens the additional coupling. The active-power small-signal model of the system in GFL mode, with the additional coupling taken into account, is shown in Figure 2.

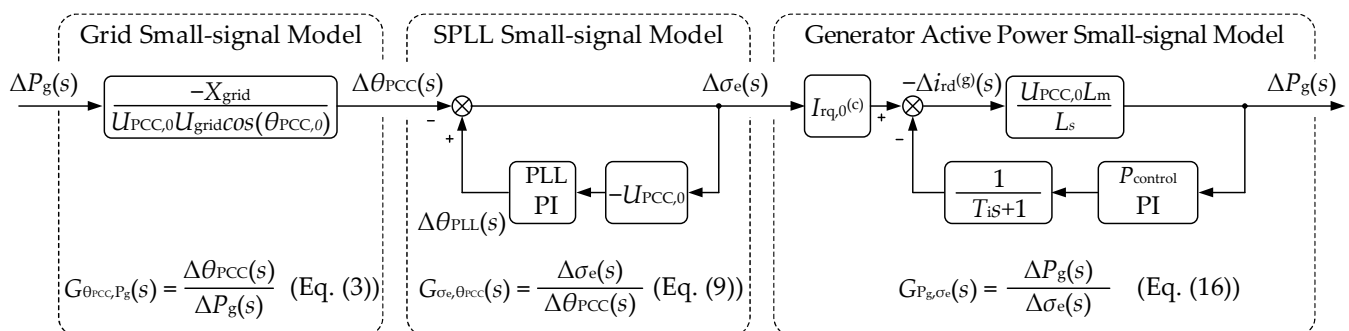


Figure 2. Active-power small-signal model of the system in GFL mode with the additional coupling.

3.2. Stability Characteristics of GFL Under Weak-Grid Conditions

Based on (18), the closed-loop characteristic equation associated with the additional coupling under weak-grid conditions can be written as

$$1 + L_{cpl}(s) = 0. \quad (19)$$

Accordingly, the influence of grid strength on the closed-loop dynamics can be examined from two complementary perspectives: closed-loop pole trajectories and sensitivity-based robustness analysis.

Figure 3 shows the trajectories of the closed-loop characteristic roots as SCR decreases. As the grid weakens, one complex-conjugate pole pair gradually approaches the real axis and eventually evolves into two real poles. Meanwhile, the dominant rightmost real pole

continues to move toward the imaginary axis and, under sufficiently weak-grid conditions, crosses into the right-half plane, which leads to instability. This result indicates that weak-grid conditions affect not only the locations of the dominant closed-loop poles, but also the form of the dominant mode. From the root-locus trajectories, a reduction in grid strength continuously amplifies the additional coupling mechanism identified in Section 3.1 and pushes the closed-loop system toward the stability boundary.

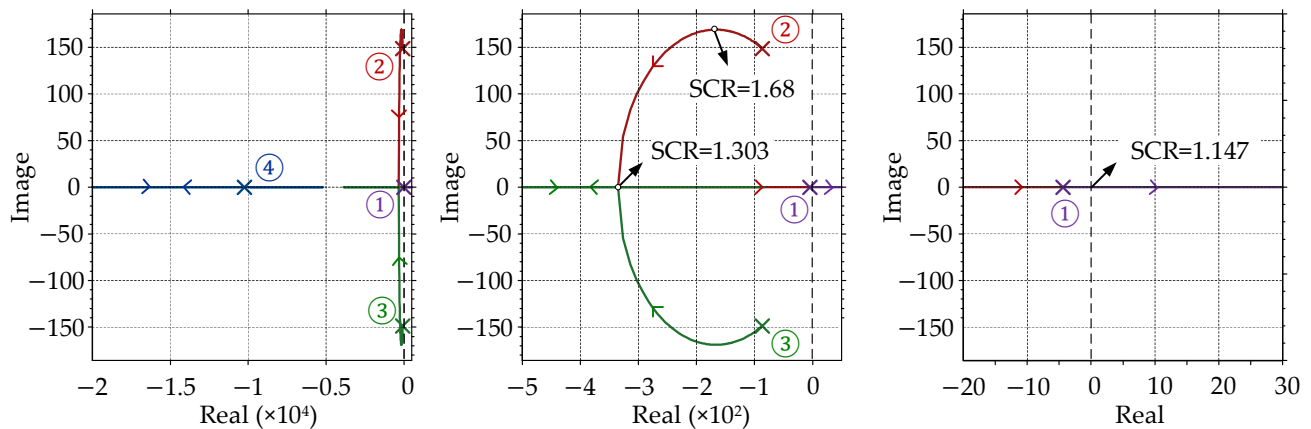


Figure 3. Closed-loop pole trajectories as SCR decreases from 10 to 0.9.

However, under weak-grid conditions, closed-loop performance deterioration appears before any pole enters the right-half plane. To characterize this behavior, the sensitivity function is introduced as

$$S(s) = \frac{1}{1 + L_{\text{cpl}}(s)}, \quad (20)$$

and its peak value is defined as

$$M_s = \max |S(j\omega)|. \quad (21)$$

Here, $S(s)$ characterizes the sensitivity of the closed-loop system to external disturbances and model uncertainty, and M_s represents the maximum amplification level over frequency. In general, a larger M_s indicates weaker disturbance rejection capability and poorer closed-loop robustness. In the numerical evaluation, M_s is obtained over the control-frequency range from 0 to 3000 rad/s. The upper limit is above the current-loop bandwidth, so the main dynamic range of the averaged control model is included.

Figure 4a presents the magnitude responses of $|S(j\omega)|$ under several representative SCR conditions. As SCR decreases, the sensitivity peak rises continuously, indicating that the system becomes increasingly sensitive to disturbances and parameter deviations over specific frequency ranges. Figure 4b further summarizes this tendency through the variation of the sensitivity peak M_s . It can be observed that M_s increases nonlinearly as SCR decreases, with a markedly faster rise near the critical weak-grid region. This behavior indicates a continuous reduction in closed-loop robustness, a weaker tolerance to disturbances, and an accelerated deterioration in dynamic performance.

Taken together, the above results show that the evolution of closed-loop stability is accompanied by a simultaneous weakening of performance. Under weak-grid conditions, the GFL system exhibits two stability-related characteristics. First, decreasing SCR drives the dominant closed-loop poles toward the stability boundary and eventually causes instability. Second, even before the poles cross into the right-half plane, the sensitivity peak has already increased substantially, indicating that closed-loop performance deteriorates prior to instability. Therefore, the influence of weak-grid conditions on GFL is reflected not

only in the eventual loss of stability, but also in the progressive weakening of robustness and disturbance rejection capability.

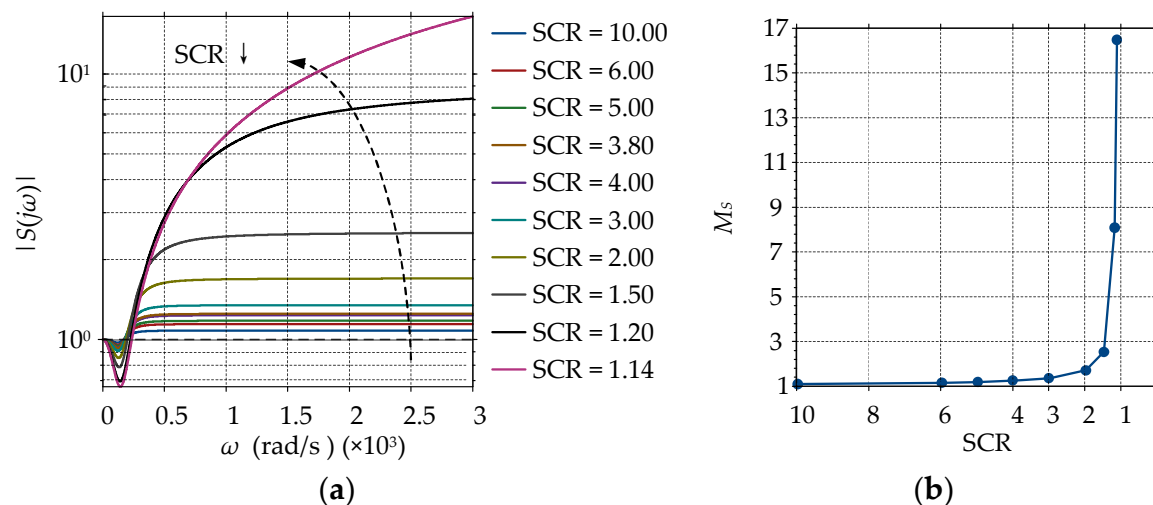


Figure 4. Sensitivity-based performance characterization over the SCR range: (a) magnitude of the sensitivity function $|S(j\omega)|$ for representative SCR values; (b) variation of the sensitivity peak M_s with SCR.

4. Bidirectional GFL/GFM Switching Methodology

Under weak-grid conditions, the GFL mode may exhibit deteriorated dynamic performance and even lose stability, making active mode switching necessary. Timely identification of performance deterioration and smooth mode transition once the switching criterion is met are therefore essential for maintaining stable operation.

4.1. Switching Criterion Based on Local Operating Parameters

As grid strength decreases, deterioration of GFL performance does not typically first appear as an abrupt change in steady-state variables, but is first reflected in the sustained amplification of local oscillatory responses. The oscillatory components in the power response, synchronization dynamics, and PCC voltage-coupling response gradually increase and exhibit clear coordinated amplification. Accordingly, forward switching to GFM should be triggered not by a transient anomaly in any single variable, but by the coordinated growth of local oscillatory responses as the system approaches the weak-grid boundary.

Based on this observation, the forward-switching criterion does not rely on online grid-strength estimation, but instead uses local operating responses to assess the proximity of the current GFL mode to the mismatch boundary under weak-grid conditions. Near this boundary, the system may not yet be unstable, but the oscillatory modes associated with the power response, PLL synchronization response, and PCC voltage-coupling response are already significantly intensified, indicating a progressive loss of closed-loop robustness and disturbance rejection capability. Under such conditions, continued GFL operation may further deteriorate system performance. The switching criterion should therefore be established directly from local signatures of the mismatch state.

To quantify the mismatch characteristics described above, stator active power P_s , PLL output frequency f_{PLL} , and PCC voltage magnitude U_{PCC} are selected as the monitoring signals, representing the power response, PLL synchronization response, and PCC voltage-

coupling response, respectively. For each signal, $x \in \{P_s, f_{PLL}, U_{PCC}\}$, its slowly varying steady-state component is first extracted over a time window of length T_{dc} as

$$x_{dc}(k) = \frac{1}{N_{dc}} \sum_{i=0}^{N_{dc}-1} x(k-i), \quad N_{dc} = \frac{T_{dc}}{T_s}. \quad (22)$$

Here, k denotes the discrete-time index, T_s is the sampling period and i is the summation index. The window length T_{dc} is set to 0.2 s, shorter than the dominant power-regulation time scale of the DFIG unit. This setting retains the low-frequency operating trend while suppressing oscillatory components and measurement noise through moving-average filtering.

On this basis, the oscillatory component is defined as

$$x_{osc}(k) = x(k) - x_{dc}(k). \quad (23)$$

This operation extracts the oscillatory component from the original response for subsequent weak-grid mismatch identification. The root-mean-square (RMS) value of this oscillatory component is then computed over a short window of length T_{rms} to characterize the local oscillation energy level:

$$x_{rms}(k) = \sqrt{\frac{1}{N_{rms}} \sum_{i=0}^{N_{rms}-1} x_{osc}^2(k-i)}, \quad N_{rms} = \frac{T_{rms}}{T_s}. \quad (24)$$

Here, x_{rms} is used to characterize the energy level of local oscillations rather than spectral components at a fixed frequency. The RMS window T_{rms} is set to 0.1 s, within the time scale of T_{dc} , so that the RMS calculation characterizes the local oscillation level after the slowly varying component is removed. Since the oscillation frequency near the weak-grid boundary varies with the operating condition, RMS-based characterization provides a more robust measure of mismatch-mode amplification than fixed-frequency detection.

To eliminate the influence of differences in the oscillation baseline under different operating conditions, a background component is further extracted over a slower time scale with T_b as

$$x_{rms,dc}(k) = \frac{1}{N_b} \sum_{i=0}^{N_b-1} x_{rms}(k-i), \quad N_b = \frac{T_b}{T_s}. \quad (25)$$

Here, T_b is set to 3 s, much larger than T_{rms} , so that the background oscillation level is updated slowly and remains a stable reference for evaluating sustained oscillation enhancement.

The normalized oscillation-enhancement index is then defined as

$$I_x(k) = \frac{x_{rms}(k)}{x_{rms,dc}(k)}. \quad (26)$$

Accordingly, three normalized indices, I_P , I_f , and I_U , are obtained to quantify the enhancement of active-power oscillations, PLL synchronization oscillations, and PCC voltage-coupling oscillations relative to their respective background levels. In this form, the weak-grid mismatch state is transformed into a set of comparable local oscillation-energy indices.

Since the mismatch near the weak-grid boundary is manifested as an overall oscillation enhancement jointly involving the power response, PLL synchronization response, and PCC voltage-coupling response, the forward-switching criterion is defined based on the joint triggering of all three indices. This joint-triggering scheme effectively avoids false

switching decisions caused by transient fluctuations of a single index under individual active-power regulation, reactive-power regulation, or local voltage disturbances. Only the simultaneous and sustained enhancement of all three responses is taken to indicate that the current GFL mode has entered the mismatch state near the weak-grid boundary.

Accordingly, the forward-switching condition is defined as

$$I_p > 2, I_f > 2, I_U > 2, \quad (27)$$

with a holding time of $T_{\text{hold}} = 0.5$ s. The threshold value of 2 is selected to balance detection sensitivity and false-triggering suppression. Since the monitored variables are slowly varying operating quantities, the indices are calculated from the RMS values of the extracted oscillatory components after the slowly varying components are removed. Thus, an index value above 2 indicates that the local oscillation level has increased to more than twice the background level, which provides a sensitive indication of weak-grid-induced deterioration. The 0.5 s holding time is longer than T_{rms} and much shorter than T_b , which improves triggering accuracy through sustained confirmation while avoiding the loss of detection sensitivity caused by an elevated background oscillation level.

When all of the above conditions are satisfied, the current GFL mode is considered to have entered the mismatch state near the weak-grid boundary, thereby triggering the forward transition from GFL to GFM. In this way, the joint criterion not only suppresses false triggering caused by single-channel transient disturbances, but also provides a more reliable indication of the overall mismatch state near the weak-grid boundary. The proposed criterion uses only local operating signals and does not require online impedance identification, active disturbance injection, or inter-unit communication, which makes it simple, reliable, and suitable for local implementation.

4.2. Pre-Synchronized Switching via a Virtual Power Closed Loop

The control structure for bidirectional pre-synchronized GFL/GFM switching based on a virtual-power closed loop is shown in Figure 5. The system incorporates both GFL and GFM controllers, while only the currently active mode is connected to the rotor-side converter of the DFIG during normal operation. Once a switching command is issued, the standby mode is activated, and its outer-loop state is established through a virtual-power closed loop. Control authority is transferred only after the pre-synchronization condition is satisfied.

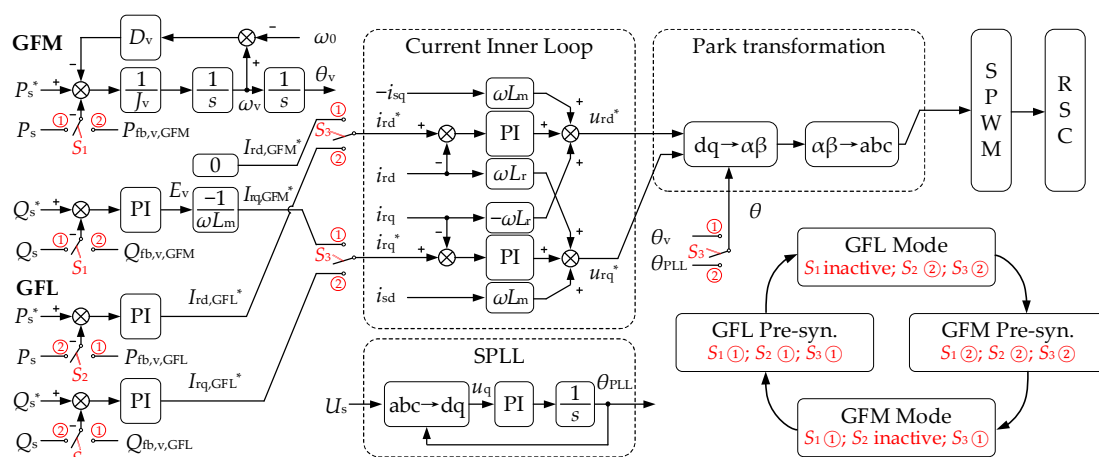


Figure 5. Control structure of bidirectional pre-synchronized GFL/GFM switching based on a virtual-power closed loop.

The proposed pre-synchronization structure is developed for the outer power loop of the standby mode. During pre-synchronization, the feedback power used by the standby mode is defined as follows:

$$\begin{cases} P_{fb,v} = -P_v + PI(P_s - P_v) \\ Q_{fb,v} = -Q_v + PI(Q_s - Q_v) \end{cases} \quad (28)$$

Here, P_s and Q_s denote the instantaneous stator active and reactive powers of the DFIG, respectively. P_v and Q_v denote the virtual active and reactive powers of the standby mode during pre-synchronization. These virtual power quantities are calculated from the rotor-current references generated by the standby mode as follows:

$$\begin{cases} P_v = \frac{i_{rd}^* U_{PCC} L_m}{L_s} \\ Q_v = \frac{U_{PCC}^2}{\omega_g L_m} + \frac{i_{rq}^* U_{PCC} L_m}{L_s} \end{cases} \quad (29)$$

In this feedback structure, the virtual power is used as the standby-mode feedback to establish its outer loop. The difference between the actual stator power and the virtual power is then processed by a PI controller, so that the standby operating point tracks the current DFIG operating point. When the following synchronization conditions are satisfied:

$$\begin{cases} |P_s - P_v| < e_p \\ |Q_s - Q_v| < e_q \end{cases} \quad (30)$$

where e_p and e_q denote the prescribed synchronization error thresholds for the active-power and reactive-power channels, respectively, the standby mode is deemed to be aligned with the current operating point of the DFIG, and switching can then be executed.

Under this structure, once a switching command is issued, the currently active mode continues to regulate the DFIG, while the standby mode undergoes outer-loop pre-synchronization through the virtual-power closed loop. Control authority is transferred once the operating state of the standby mode has become aligned with the current DFIG operating state under the active mode. At the switching instant, the virtual-power feedback is replaced by the actual machine power feedback, and the inner-current-loop PI controller is reset to remove the residual integral state accumulated while the target mode is inactive.

As a result, when the target mode takes over, its operating state is already aligned with the current DFIG operating state under the active mode, thereby reducing transient disturbances during the switching process. The same pre-synchronization structure applies to both switching directions: for forward switching to GFM, GFM serves as the target mode and completes pre-synchronization; for reverse switching back to GFL, GFL serves as the target mode and completes pre-synchronization using the same structure.

4.3. State-Transition Strategy

The state-transition relationships of the GFL/GFM switching system are shown in Figure 6. The transition structure comprises two main operating states and two intermediate states, namely the GFL state, the GFM state, the GFM pre-synchronization state, and the GFL pre-synchronization state.

When the system operates in the GFL state and the forward-switching criterion is satisfied, it enters the GFM pre-synchronization state. In this intermediate state, GFL continues to regulate the machine, while GFM performs pre-synchronization. Once the synchronization criterion is satisfied, the system transitions to the GFM state, thereby completing the forward mode switch.

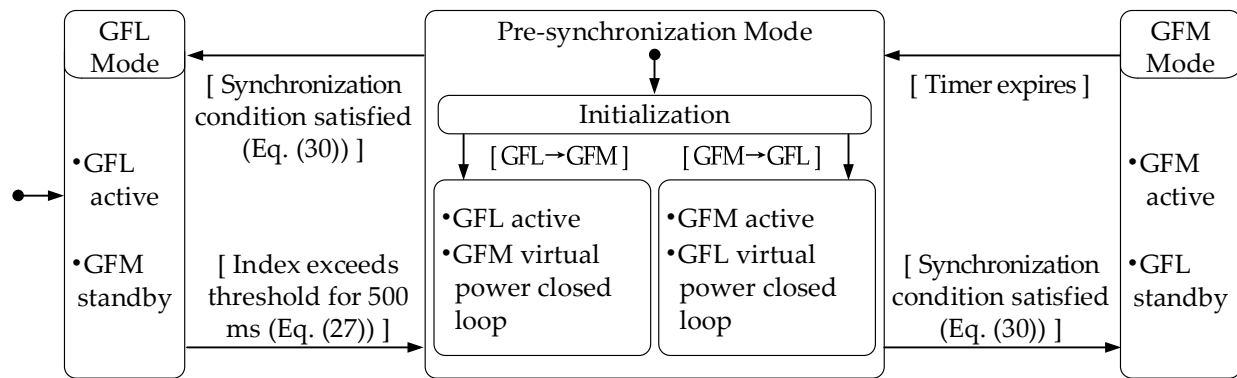


Figure 6. State-transition relationships of the GFL/GFM switching system.

After switching to GFM, the local oscillatory features used to indicate weak-grid deterioration are suppressed. Thus, the local-operating-indicator-based criterion cannot serve as the basis for reverse switching, and a prescribed timed return command is adopted. When the system operates in the GFM state, the return to GFL is triggered with a prescribed time delay. Once the return command is issued, the system enters the GFL pre-synchronization state. In this state, GFM continues to regulate the machine, while GFL performs pre-synchronization. Once the synchronization criterion is satisfied, the system transitions to the GFL state, thereby completing the reverse mode switch.

5. HIL-Based Validation

This chapter presents the HIL results of bidirectional GFL/GFM switching for the DFIG unit. In the tests, the GSC uses conventional vector control to regulate the DC-link voltage and remains unchanged during stator-side control-mode switching. It verifies the smoothness and operating adaptability of the pre-synchronized switching process under different operating conditions, and further demonstrates the effectiveness of the proposed bidirectional switching strategy under reduced-SCR conditions. The main case-study parameters are listed in Table 1.

Table 1. Parameters of the HIL simulation system.

Parameter	Value	Parameter	Value
rated voltage	1140 V	switching frequency	10 kHz
rated frequency	50 Hz	pre-synchronization e_P/e_Q	60 kW/
rated power	5.17 MW	error threshold	60 kVar
rated DC-link voltage	1800 V	VSG inertia coefficient J	800
stator-to-rotor voltage ratio	1140/425	VSG damping coefficient D	3360
number of pole pairs	2	current-loop bandwidth	370 Hz
rated slip	−0.158	PLL bandwidth	8.4 Hz
rated wind speed	10.8 m/s	test SCR range	2.3–4.1
		HIL simulation time step	0.5 us

5.1. GFM Pre-Synchronized Switching Under Rated Conditions

The HIL test results of switching from GFL to GFM under rated operating conditions are shown in Figure 7.

As shown in Figure 7a, the pre-synchronization trigger arrives at t_1 . Before t_1 , GFM remains in the standby state. After t_1 , GFM enters the pre-synchronization state, where the feedback power $P_{fb,GFM}$ in Figure 7b is provided by the virtual power defined in (28). Meanwhile, the GFM power angle σ and excitation voltage E in Figure 7c,d gradually

approach the steady-state values corresponding to the current operating condition of the DFIG unit.

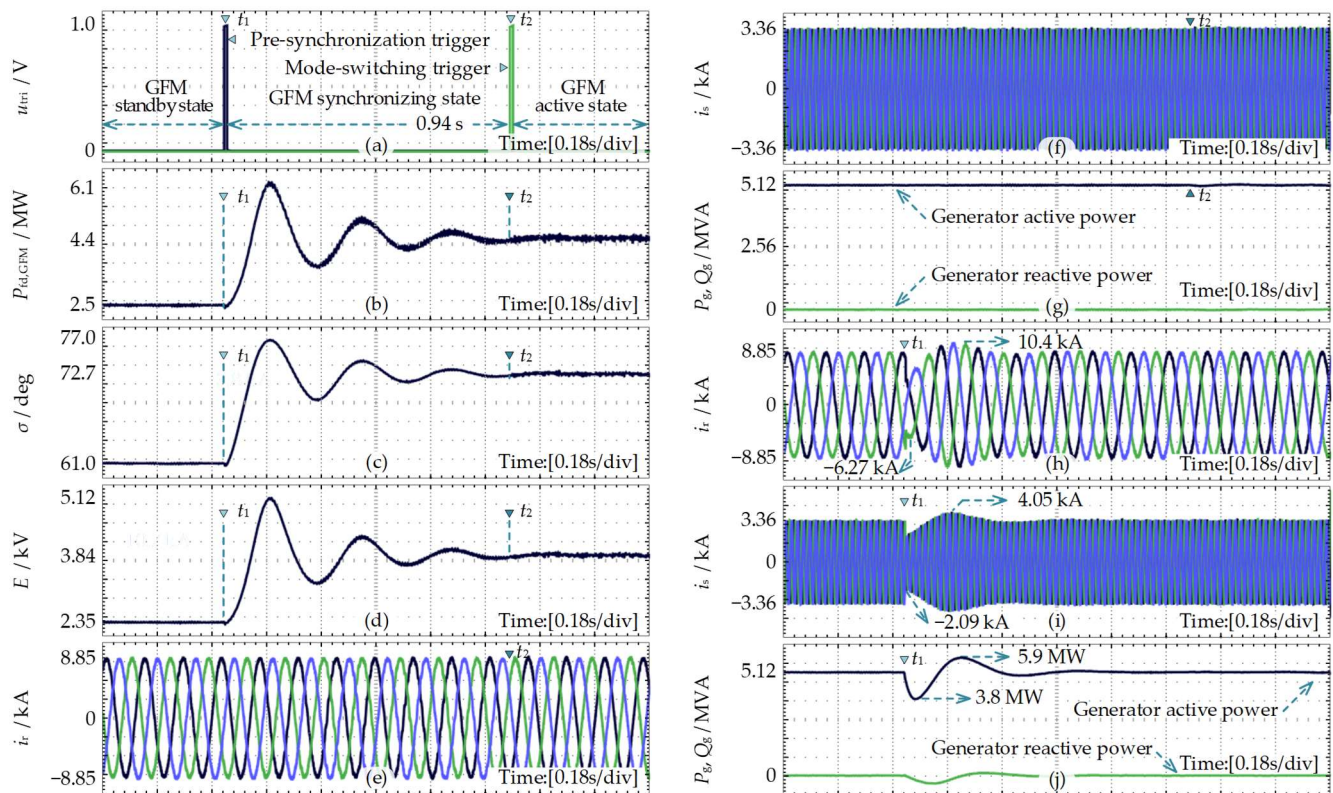


Figure 7. Switching results from GFL to GFM under rated operating conditions: (a) trigger signal u_{tri} ; (b) feedback power $P_{fb,GFM}$ in GFM mode; (c) power angle σ in GFM mode; (d) excitation voltage E in GFM mode; (e) rotor current i_r ; (f) stator current i_s ; (g) generator active and reactive powers P_g and Q_g ; direct switching without pre-synchronization: (h) rotor current i_r , (i) stator current i_s ; and (j) generator active and reactive powers P_g and Q_g .

When the deviation between the virtual power feedback and the actual unit power satisfies the threshold specified in (30), the mode-switching signal is issued at t_2 , as shown in Figure 7a. At this instant, the GFM feedback power is switched from the virtual power to the measured unit power. GFM then takes over system control, while GFL returns to standby, thereby completing the mode transition. The pre-synchronization duration is 0.94 s.

As shown in Figure 7e–g, the rotor current i_r , stator current i_s , and the unit active and reactive powers P_g and Q_g all undergo smooth transitions, with no observable disturbance.

The direct-switching results without pre-synchronization are shown in Figure 7h–j. Direct switching is performed at t_1 without activating the pre-synchronization process. After direct switching, the maximum disturbances in rotor-current and stator-current amplitudes reach 2.58 kA and 1.27 kA, corresponding to 29.2% and 37.8% of their respective pre-switching steady-state values. The maximum active-power disturbance is 1.32 MW, corresponding to 25.8% of the pre-switching steady-state active power. The transient process lasts approximately 0.72 s. These results indicate that, without pre-synchronization, the target GFM mode is not aligned with the current operating point before takeover, resulting in significant current and power transients.

5.2. GFL Pre-Synchronized Switching Under Rated Conditions

The HIL test results of switching from GFM to GFL under rated operating conditions are shown in Figure 8.

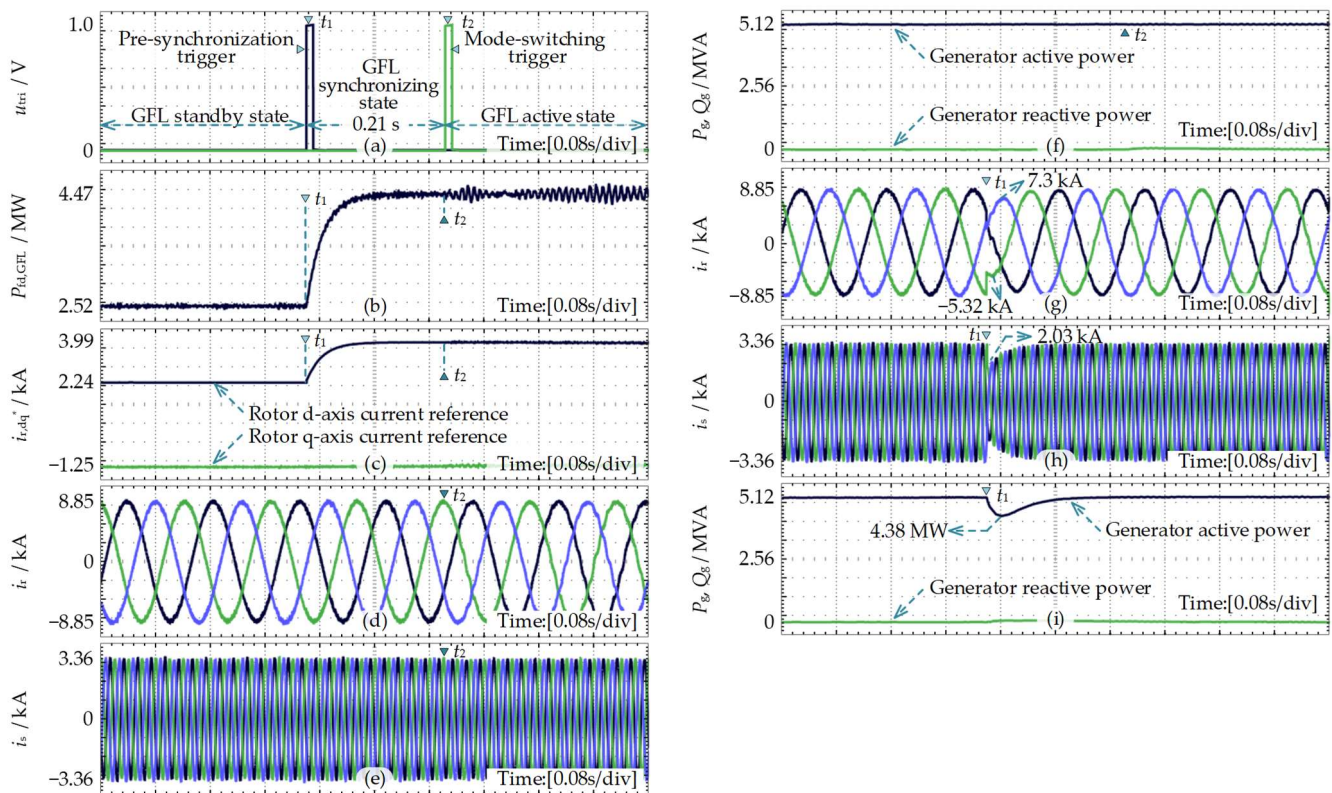


Figure 8. Switching results from GFM to GFL under rated operating conditions: (a) trigger signal u_{tri} ; (b) feedback power $P_{fb,GFL}$ in GFL mode; (c) rotor dq-axis current references $i_{r,dq}^*$ in GFL mode; (d) rotor current i_r ; (e) stator current i_s ; (f) generator active and reactive powers P_g and Q_g ; direct switching without pre-synchronization: (g) rotor current i_r , (h) stator current i_s , and (i) generator active and reactive powers P_g and Q_g .

As shown in Figure 8a, the pre-synchronization trigger arrives at t_1 . Before t_1 , GFL remains in the standby state. After t_1 , GFL enters the pre-synchronization state, where the stator feedback power $P_{fb,GFL}$ in Figure 8b is provided by the virtual power defined in (28). Meanwhile, the GFL rotor dq-axis current references i_{rd}^* and i_{rq}^* in Figure 8c gradually approach the steady-state values corresponding to the current operating condition of the DFIG unit.

When the deviation between the virtual power feedback and the actual stator power satisfies the threshold specified in (30), the mode-switching signal is issued at t_2 , as shown in Figure 8a. At this instant, the GFL feedback power is switched from the virtual power to the measured stator power. GFL then takes over system control, while GFM returns to standby, thereby completing the mode transition. The pre-synchronization duration is 0.21 s. Owing to the lower power inertia of GFL than GFM, the corresponding pre-synchronization time is shorter.

As shown in Figure 8d–f, the rotor current i_r , stator current i_s , and the unit active and reactive powers P_g and Q_g all undergo smooth transitions, with no observable disturbance.

The direct-switching results without pre-synchronization are shown in Figure 8g–i. Direct switching is performed at t_1 without activating the pre-synchronization process. After direct switching, the maximum disturbances in rotor-current and stator-current amplitudes reach 3.53 kA and 1.33 kA, corresponding to 39.9% and 39.6% of their respective

pre-switching steady-state values. The maximum active-power disturbance is 0.74 MW, corresponding to 14.5% of the pre-switching steady-state active power. The transient process lasts approximately 0.16 s. These results indicate that, without pre-synchronization, the target GFL mode is not aligned with the current operating point before takeover, resulting in significant current and power transients.

5.3. Bidirectional Pre-Synchronized Switching Under Variable Wind Speeds

Figure 9 presents the HIL test results of bidirectional GFL/GFM mode switching under variable wind speed conditions, with the system initially operating in GFM mode.

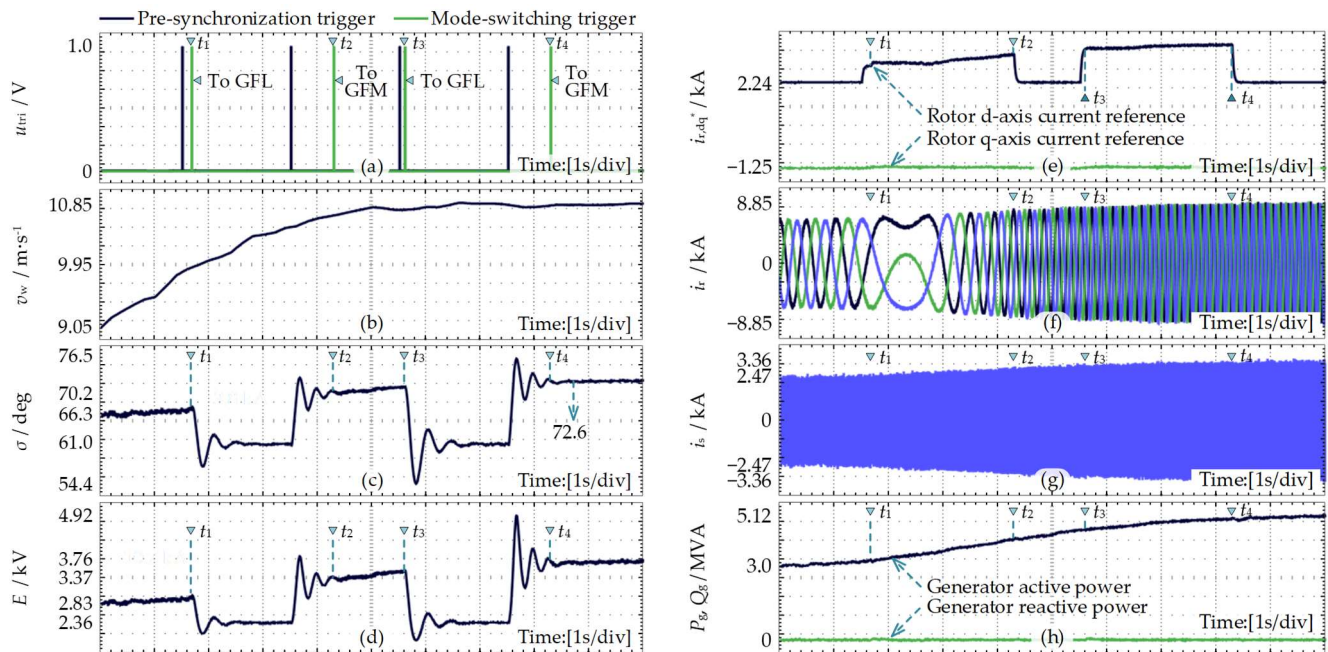


Figure 9. Results of bidirectional mode switching under variable wind speed conditions: (a) trigger signal u_{tri} ; (b) wind speed v_w ; (c) power angle σ in GFM mode; (d) excitation voltage E in GFM mode; (e) rotor dq -axis current references $i_{r,dq}^*$ in GFL mode; (f) rotor current i_r ; (g) stator current i_s ; (h) generator active and reactive powers P_g and Q_g .

As indicated by the trigger signal in Figure 9a, the operating mode is switched to GFL at t_1 and t_3 , and back to GFM at t_2 and t_4 . All switching actions are carried out while the wind speed in Figure 9b continues to vary.

During t_1 – t_2 and t_3 – t_4 , the system operates in GFL mode. In these intervals, the GFL rotor dq -axis current references $i_{r,dq}^*$ in Figure 9e serve as the active control variables, whereas the GFM power angle σ and excitation voltage E in Figure 9c,d remain in the standby or pre-synchronization state.

Before t_1 , during t_2 – t_3 , and after t_4 , the system operates in GFM mode. In these intervals, the GFM power angle σ and excitation voltage E serve as the active control variables, whereas the GFL rotor dq -axis current references $i_{r,dq}^*$ remain in the standby or pre-synchronization state.

As the wind speed increases, the active power in Figure 9h rises from 3 MW to 5.12 MW, while the reactive power remains at zero. Accordingly, the rotor and stator currents in Figure 9f,g increase in magnitude. Meanwhile, the phase sequence of the rotor current reverses, indicating a transition of the DFIG from subsynchronous to super-synchronous operation. Overall, throughout DFIG operating-point migration, the active and reactive powers, together with the stator and rotor currents, remain smooth during repeated bidirectional mode switching, with no observable disturbance. These results

demonstrate the adaptability of the proposed pre-synchronized switching method under varying operating conditions.

5.4. Mode Switching Under Reduced System Short-Circuit Ratio

The system is initially operated in GFL mode under rated operating conditions. The HIL results of mode switching under a reduced system SCR are shown in Figure 10.

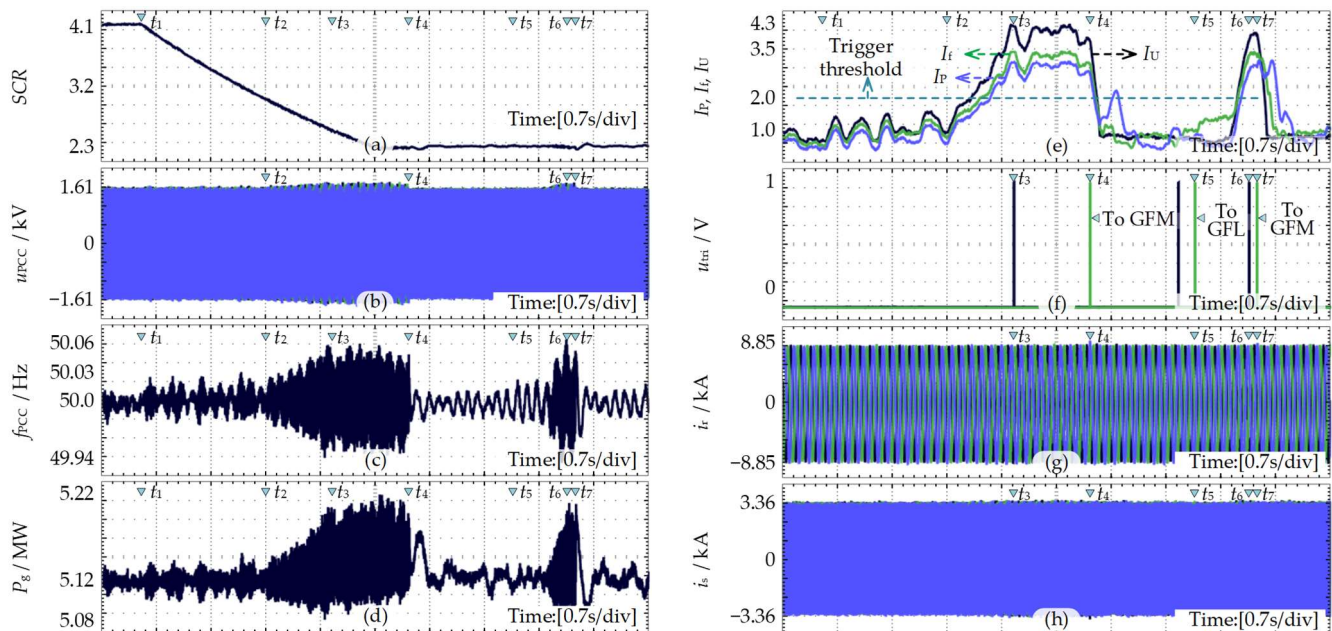


Figure 10. Results of mode switching under reduced SCR conditions: (a) system SCR; (b) voltage at the PCC u_{PCC} ; (c) frequency at the PCC f_{PCC} ; (d) generator active power P_g ; (e) operational performance indices I_P , I_f , and I_U ; (f) trigger signal u_{tri} ; (g) rotor current i_r ; (h) stator current i_s .

As shown in Figure 10a, the system SCR is reduced at t_1 . As the SCR decreases, the control performance progressively deteriorates. By t_2 , the oscillations in the PCC voltage u_{PCC} , the PCC frequency f_g , and the generator active power P_g in Figure 10b–d become significantly more pronounced. This deterioration is quantified by the power index I_P , frequency index I_f , and voltage index I_U in Figure 10e. After t_2 , all three indices rise simultaneously from values close to 1 and reach a maximum of 4.3. Once the prescribed threshold is exceeded, the GFM pre-synchronization signal in Figure 10f is triggered at t_3 . After pre-synchronization is completed, the mode-switching signal is issued at t_4 , and the system enters GFM operation. Following the transition, the oscillations in voltage, frequency, and power are all markedly attenuated, and the performance indices return to their pre-deterioration levels.

To verify the bidirectional switching capability, the system is switched back to GFL at t_5 according to the preset sequence. Since the SCR remains unchanged, the control performance deteriorates again after the reverse transition. Once the forward-switching criterion is satisfied again, GFM pre-synchronization is reinitiated at t_6 , and the system is switched back to GFM at t_7 . It should be noted that, during the reverse transition from GFM to GFL, the GFM channel is frozen with a delay so that the system can rapidly return to GFM if performance deterioration occurs after the switch-back. As shown in Figure 10f, the pre-synchronization interval for the second transition to GFM is clearly shorter than that for the first, and the corresponding duration of deteriorated GFL operation is also reduced.

Detailed waveforms of the PCC voltage and the stator and rotor currents around t_4 are shown in Figure 11. As shown in Figure 11a–c, before t_4 , deteriorated GFL performance causes evident distortion in u_{PCC} , i_r , and i_s . After the system is switched to GFM, these distortions are rapidly suppressed.

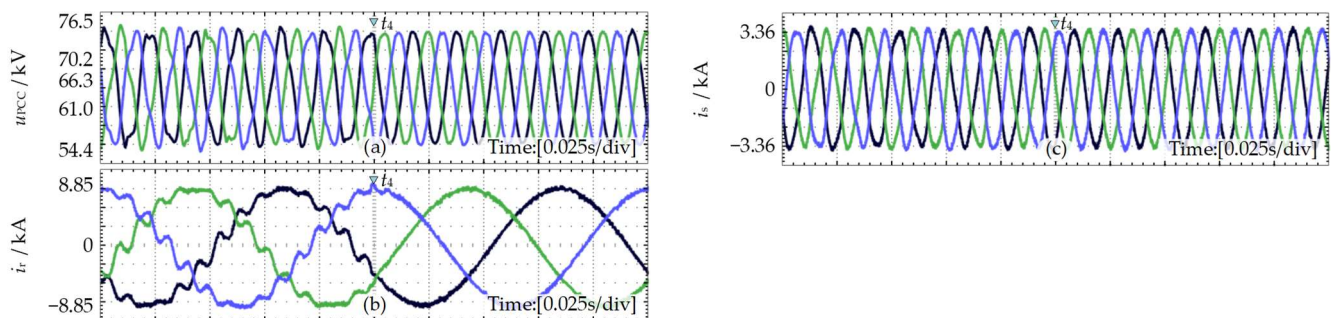


Figure 11. Detailed waveforms around t_4 under reduced SCR conditions: (a) voltage at the PCC u_{PCC} ; (b) rotor current i_r ; (c) stator current i_s .

These results show that, when a reduced SCR leads to deteriorated GFL performance, the proposed switching strategy can trigger GFM takeover in a timely manner based on the operational performance indices. After the reverse transition back to GFL, the system can still return rapidly to GFM if performance deterioration reappears, thereby confirming the effectiveness of the proposed bidirectional switching strategy under weak-grid conditions and its capability for repeated response to renewed deterioration.

5.5. Mode Switching Under Increasing Wind Speed

The HIL results of mode switching under increasing wind speed are shown in Figure 12, with the system initially operating in GFL mode.

As shown in Figure 12a, the wind speed v_w increases progressively from 9.4 m/s, leading to a corresponding rise in the generator active power. With the resulting operating-point migration, the ESCR gradually decreases, as shown in Figure 12b. During this process, the control performance progressively deteriorates. By t_1 , the oscillations in the PCC voltage u_{PCC} , the PCC frequency f_{PCC} , and the generator active power P_g in Figure 12c–e have all become significantly more pronounced.

The power index I_P , frequency index I_f , and voltage index I_U in Figure 12f provide a quantitative measure of this deterioration. It is worth noting that, before t_1 , I_P exhibits fluctuations due to normal power regulation, whereas I_f and I_U remain essentially stable. Only after t_1 do all three indices increase simultaneously. This indicates that the proposed index set can distinguish fluctuations caused by normal regulation from the coordinated rise of multiple indices caused by control-performance deterioration, thereby enabling reliable identification of the deteriorated operating state. Once the threshold is exceeded, the GFM pre-synchronization signal in Figure 12g is triggered at t_2 , and the mode-switching signal is issued at t_3 , after which the system enters GFM operation.

As seen from Figure 12c–f, after the transition to GFM mode, the oscillations in voltage, frequency, and power are all markedly reduced, and the performance indices return to their pre-deterioration levels. Meanwhile, the rotor current i_r and stator current i_s in Figure 12h,i adjust with the power variation and remain smooth throughout the switching process, with no observable disturbance.

These results show that increasing wind speed can reduce the effective SCR and deteriorate GFL performance, while the proposed switching strategy can still trigger timely GFM takeover based on the operational performance indices.

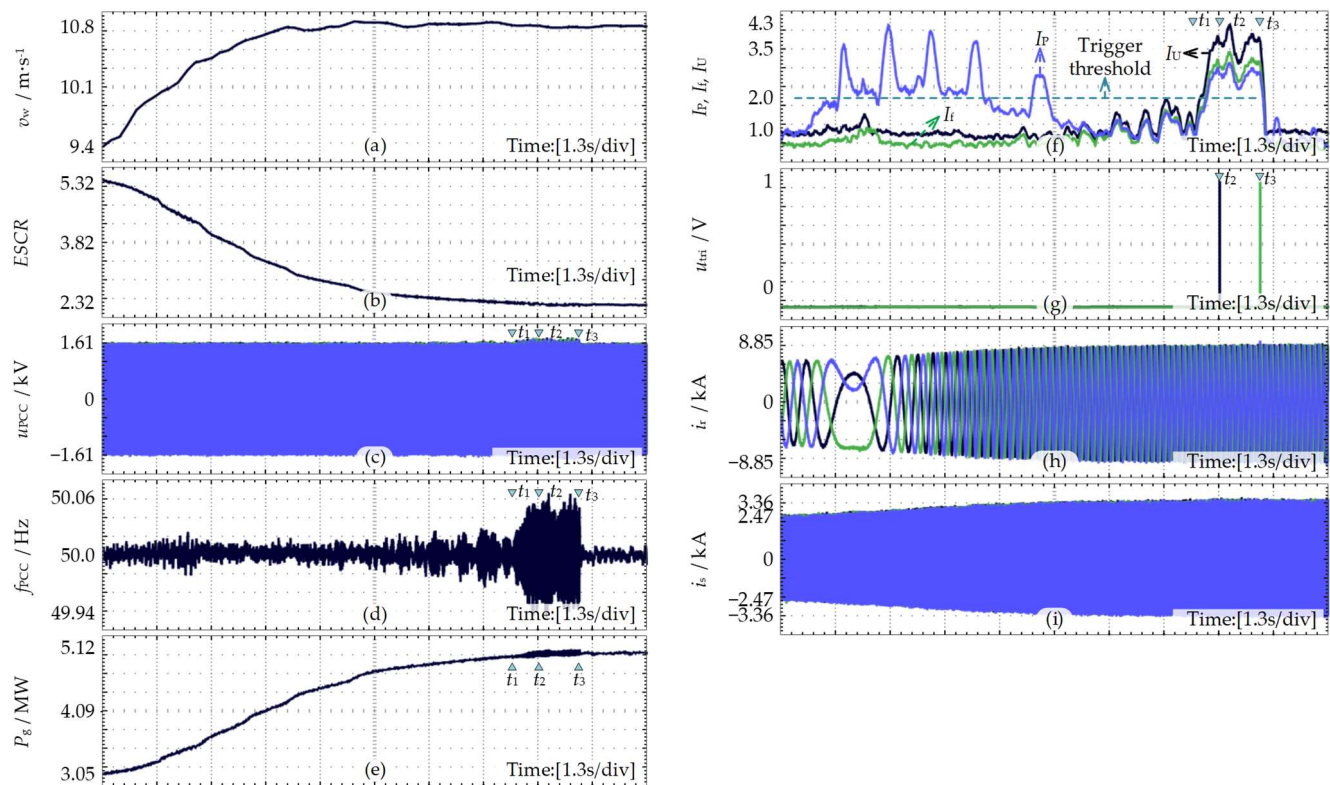


Figure 12. Results of mode switching under increasing wind speed conditions: (a) wind speed v_w ; (b) equivalent SCR; (c) voltage at the PCC u_{PCC} ; (d) frequency at the PCC f_{PCC} ; (e) generator active power P_g ; (f) operational performance indices I_P , I_f , and I_U ; (g) trigger signal u_{tri} ; (h) rotor current i_r ; (i) stator current i_s .

6. Conclusions

This paper investigates bidirectional GFL/GFM mode switching for DFIG wind turbines under weak-grid conditions with a predominantly inductive grid impedance. The results show that weak-grid deterioration of GFL-controlled DFIGs does not begin with abrupt instability. Instead, control performance progressively degrades as the system approaches the stability boundary, with increasingly coordinated oscillations in power, frequency, and voltage that eventually develop into instability. On this basis, a unified framework is established around performance-deterioration identification, pre-synchronized takeover by the target mode, and smooth bidirectional state transition. Within this framework, a switching criterion based on local operating variables, a pre-synchronization mechanism based on a virtual power closed loop, and the corresponding bidirectional state-transition strategy are developed.

The HIL results confirm that the proposed method enables smooth bidirectional switching between GFL and GFM under both rated and variable-wind operating conditions. Under both direct SCR reduction and ESCR reduction caused by operating-point variations, the proposed indices can distinguish local fluctuations associated with normal operation from coordinated oscillatory responses caused by control-performance deterioration, thereby enabling timely GFM takeover. After the reverse transition back to GFL, the system can still return rapidly to GFM if deterioration reappears. Taken together, these results demonstrate that the proposed method can effectively suppress oscillations near the weak-grid stability boundary, mitigate switching transients, and improve the adaptability of DFIG wind turbines to variations in grid strength.

Future work will further investigate the engineering applicability of the proposed switching criterion and pre-synchronization strategy through full-scale experiments or field tests under wider ranges of grid strength, wind speed, and disturbances.

Author Contributions: Conceptualization, Z.H.; methodology, C.F.; software, Y.L.; validation, C.F.; formal analysis, Z.H.; investigation, Y.L.; resources, Y.R.; data curation, Y.L.; writing—original draft preparation, Z.H.; writing—review and editing, Z.H.; visualization, Z.H.; supervision, Y.R.; project administration, Z.H.; funding acquisition, Y.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China, grant number 52367022; the Natural Science Foundation of Inner Mongolia, grant number 2024QN05045; First-Class Disciplines Research Excellence Program of Inner Mongolia Autonomous Region, grant number YLXKZX-NGD-006; Key R&D and Achievement Transformation Project of Inner Mongolia Autonomous Region, grant number 2023YFHH0077.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

DFIG	Doubly-Fed Induction Generator
PCC	Point of Common Coupling
PLL	Phase-Locked Loop
SCR	Short-Circuit Ratio
ESCR	Equivalent Short-Circuit Ratio
GFL	Grid-Following
GFM	Grid-Forming

References

1. Din, Z.; Zhang, J.; Xu, Z.; Zhang, Y.; Milyani, A.H.; Cheema, K.M.; Nawaz, A.; Song, Y. Recent development and future trends of resonance in doubly fed induction generator system under weak grid. *IET Renew. Power Gener.* **2022**, *16*, 807–834. [\[CrossRef\]](#)
2. Nair, A.; Kamalasadan, S.; Geis-Schroer, J.; Patel, S.; Smith, M. An investigation of grid stability and a new design of adaptive phase-locked loop for wind-integrated weak power grid. *IEEE Trans. Ind. Appl.* **2022**, *58*, 5871–5884. [\[CrossRef\]](#)
3. Mirmohammad, M.; Azad, S.P. Control and stability of grid-forming inverters: A comprehensive review. *Energies* **2024**, *17*, 3186. [\[CrossRef\]](#)
4. Pedra, J.; Sainz, L.; Monjo, L. Impact of short-circuit ratio on control parameter settings of DFIG wind turbines. *Energies* **2024**, *17*, 1825. [\[CrossRef\]](#)
5. Hu, B.; Nian, H.; Li, M.; Liao, Y.; Yang, J.; Tong, H. Impedance characteristic analysis and stability improvement method for DFIG system within PLL bandwidth based on different reference frames. *IEEE Trans. Ind. Electron.* **2023**, *70*, 532–543. [\[CrossRef\]](#)
6. Hu, B.; Nian, H.; Li, H.; Chen, L.; Sahoo, S.; Blaabjerg, F. Impedance reshaping band coupling and broadband passivity enhancement for DFIG system. *IEEE Trans. Power Electron.* **2023**, *38*, 9436–9447. [\[CrossRef\]](#)
7. Xie, Z.; Gao, X.; Yang, S.; Zhang, X. Improved fractional-order damping method for voltage-controlled DFIG system under weak grid. *J. Mod. Power Syst. Clean Energy* **2022**, *10*, 1531–1541. [\[CrossRef\]](#)
8. Xie, Z.; Li, M.; Yang, S.; Zhang, X. Stability analysis of DFIG controlled by hybrid synchronization mode and its improved control strategy under weak grid. *IET Renew. Power Gener.* **2023**, *17*, 1940–1951. [\[CrossRef\]](#)
9. Huang, S.; Zhang, Z.; Chen, Z.; Huang, H.; Li, Z. Stability analysis and enhanced control of wind turbine generators based on hybrid GFL-GFM control. *Energies* **2025**, *18*, 4590. [\[CrossRef\]](#)
10. Li, M.; Xie, Z.; Xu, S.; Yang, S.; Zhang, X. Electromechanical oscillation analysis and suppression of grid forming DFIG-based wind turbines under weak grid. *IEEE Trans. Energy Convers.* **2025**, *40*, 1365–1377. [\[CrossRef\]](#)
11. Liu, C.; Xin, H.; Wu, D.; Gao, H.; Yuan, H.; Zhou, Y. Generalized operational short-circuit ratio for grid strength assessment in power systems with high renewable penetration. *IEEE Trans. Power Syst.* **2024**, *39*, 5479–5494. [\[CrossRef\]](#)

12. Zhou, Y.; Xin, H.; Wu, D.; Liu, F.; Li, Z.; Wang, G.; Yuan, H.; Ju, P. Small-signal stability assessment of heterogeneous grid-following converter power systems based on grid strength analysis. *IEEE Trans. Power Syst.* **2023**, *38*, 2566–2579. [[CrossRef](#)]
13. Xiao, Y.; Zhang, X.; Han, F. Neural network-based multiple-model adaptive control of grid-connected inverters in weak grids. *IET Power Electron.* **2025**, *18*, e70164. [[CrossRef](#)]
14. Leng, R.; Chen, H.; Wang, L.; Zhuang, K.; Chen, X.; Xin, H.; Huang, L. Small-signal stability assessment and enhancement of grid-following/grid-forming hybrid systems based on voltage and current strength. *IEEE Trans. Sustain. Energy* **2026**, *17*, 1755–1771. [[CrossRef](#)]
15. Huang, S.; Zhang, Z.; Chen, Z.; Huang, H.; Li, Z. Impedance-based criterion design for grid-following/grid-forming switching control of wind generation system. *Energies* **2025**, *18*, 4875. [[CrossRef](#)]
16. Qiu, Y.; Wang, Y.; Chen, Z. A reference current phasor-controlled seamless switching strategy between grid-following and grid-forming modes with multi-event integration. *Energy Rep.* **2025**, *14*, 2768–2781. [[CrossRef](#)]
17. Song, S.; Sun, K.; Li, K.-J.; Dong, Y.; Wen, Y.; Zhang, Z.; Li, M. An improved mixture ratio control strategy for zero-disturbance switching of grid-forming and grid-following inverters. *IEEE Trans. Ind. Appl.* **2025**, *61*, 8373–8382. [[CrossRef](#)]
18. Gao, X.; Zhou, D.; Anvari-Moghaddam, A.; Blaabjerg, F. Seamless switching method between grid-following and grid-forming control for renewable energy conversion systems. *IEEE Trans. Ind. Appl.* **2025**, *61*, 597–606. [[CrossRef](#)]
19. Ding, H.; Kar, R.; Miao, Z.; Fan, L. A novel design for switchable grid-following and grid-forming control. *IEEE Trans. Sustain. Energy* **2025**, *16*, 1301–1314. [[CrossRef](#)]
20. Cheng, Y.; Wu, W.; Koutroulis, E.; Orabi, M.; Chung, H.S.-H.; Blaabjerg, F. A cutting-edge dual-mode seamless switching method with fast phase locking for grid-connected inverter under distorted grid conditions. *IEEE J. Emerg. Sel. Top. Power Electron.* **2025**, *13*, 2188–2199. [[CrossRef](#)]
21. Ríos-Castro, D.; Pérez-Estévez, D.; Doval-Gandoy, J. Grid-connected converter with grid-forming and grid-following modes presenting symmetrical and asymmetrical fault ride-through capability. *IEEE J. Emerg. Sel. Top. Power Electron.* **2024**, *12*, 2082–2096. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.