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# Transient Synchronization Stability in Grid-Following Converters: Mechanistic Insights and Technological Prospects—A Review

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**Abstract:** This paper investigates the transient synchronization stability mechanisms and technological advancements associated with grid-following (GFL) converters, providing a systematic review of the current research landscape and future directions in this field. The current literature lacks a comprehensive understanding of how outer-loop control dynamics and grid-converter interactions critically influence transient stability mechanisms. This oversight often leads to incomplete or overly simplistic stability assessments, particularly under high penetration of renewable energy sources. Furthermore, existing stability criteria and analytical methodologies do not adequately address the compounded challenges arising from multi-control-loop coupling effects and systems with multiple parallel converters. These limitations underscore the inability of conventional methodologies to holistically model the transient synchronization behavior of GFL converters in modern power-electronics-dominated grids. To address these gaps, this work synthesizes a comprehensive review of modeling frameworks, analytical methodologies, transient stability mechanisms, and influence factors specific to GFL converters. First, based on the fundamental differences between synchronous generators and GFL, this paper summarizes the second-order equivalent model derived from phase-locked loop (PLL) dynamic. It conducts a comparative analysis of the applicability and limitations of conventional stability assessment methods, such as the equal-area criterion, phase portrait method, and Lyapunov functions, within power-electronics-dominated systems. It highlights potential mechanistic misinterpretations arising from neglecting outer-loop control and grid interactions. Second, the paper delineates the principal challenges inherent in the transient synchronization stability analysis of GFL converters. These challenges encompass the dynamic influences of multi-control-loop coupling effects and the imperative for advancing stability criterion research in systems with multiple parallel converters. Building on existing studies, the paper further explores innovative applications of artificial intelligence (AI) in transient stability assessment, including stability prediction based on deep learning, data-physics hybrid modeling, and human–machine collaborative optimization strategies. It emphasizes that enhancing model interpretability and dynamic generalization capabilities will be critical future directions. Finally, by addressing these gaps, this work provides theoretical foundations and technical references for transient synchronization stability analysis and control in high-penetration inverter-based resources (IBRs) grids.

**Keywords:** grid-following converters; transient synchronization stability; mechanistic insights; artificial intelligence

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## 1. Introduction

With the gradual depletion of global fossil fuel reserves and the increasing severity of environmental issues, green and environmentally friendly renewable energy technologies have attracted widespread attention and rapid development [1–4]. Over the past two decades, power grids globally have undergone a significant transformation, and energy production has experienced revolutionary changes. Among these advancements, wind and solar power generation based on IBRs has become the cornerstone of power generation. However, this shift has introduced new challenges to power systems' operation and control, particularly in transient stability [5–7].

Unlike traditional synchronous generators, which rely on mechanical rotation, IBRs employ advanced converters as interfaces. Through voltage source converters (VSCs) and sophisticated controls, IBRs provide rapid and continuous responses, demonstrating exceptional flexibility and power regulation capability. The rapid proliferation and deep integration of IBRs have spurred innovations in power system modeling and have also catalyzed extensive research into power system stability analysis. However, with the increasing penetration of IBRs in power systems, transient stability issues have become increasingly prominent, presenting unprecedented challenges in accurately characterizing system dynamics, assessing security, and designing control strategies for modern power systems.

The academic community has undertaken comprehensive studies in response to the system stability challenges posed by the large-scale grid integration of IBRs. These efforts include redefining and reclassifying system stability concepts, characteristics, and categories, as detailed in [8,9]. Numerous studies [10–13] have investigated model construction, stability analysis, instability mechanisms, and control strategies tailored to the technical characteristics of IBRs. Notably, the dynamic interactions introduced by inverter controls have received considerable attention, particularly in the newly added resonance and converter-driven stability categories. Despite these advancements, the challenges associated with the large-scale deployment of inverters and their control systems on transient stability remain inadequately addressed. Given the scope of the proposed research, this paper focuses on the critical issue of transient synchronization stability in IBR-integrated power systems. Meanwhile, it systematically reviews the latest research progress and key technologies in this field and outlines future research directions in light of emerging technologies such as AI.

In the context of widespread IBR integration, accurate and rapid transient stability assessment has become a critical concern for power system planning and operation. Broadly defined, power system transient stability can refer to the ability of the system to return to a stable state within a reasonable time after a major disturbance while maintaining key parameters such as frequency and voltage within acceptable limits. Based on the electrical quantities of interest, it can be further divided into rotor angle stability, voltage stability, and frequency stability. More narrowly, power system transient synchronization stability pertains to the ability of synchronous generators to maintain synchronous operation after a major disturbance, ensuring that all rotors maintain the same electrical angular velocity and constant relative rotor angles [14].

In traditional power systems dominated by synchronous generators, the core of transient synchronization stability lies in the generators' rotor motion dynamics and power angle characteristics. Existing research [14] has systematically elucidated the mechanisms underlying transient synchronization instability in such systems, and the essence of transient instability is the imbalance between rotor mechanical power and electromagnetic power. Following a disturbance, the rotor of a synchronous generator accelerates or decelerates, causing a change in the power angle. The equal area criterion or the Lyapunov energy function is employed to quantify these power angle changes and identify potential instability risks.

The equal-area criterion and Lyapunov methods demonstrate effectiveness in simplified single-machine power systems. However, their application faces significant limitations in highly nonlinear multi-machine systems [15–17]. These limitations primarily arise from the dimensional explosion in system modeling and an inherent inability to fully account for the complex dynamic coupling effects induced by the high penetration of power electronic devices [18].

In contrast, IBRs fundamentally differ from synchronous generators in structure and operational characteristics, particularly due to the absence of a physical rotor angle. For example, both permanent magnet synchronous generators (PMSGs) and photovoltaic (PV) systems use back-to-back inverters as grid interfacing, where the rotor angle dynamics of PMSGs are isolated by the grid-side inverter, and PV systems do not rely on mechanical rotation, thus lacking the physical quantity of the generator rotor angle. From a physical perspective, the synchronization mechanism of IBRs shifts from rotor dynamics to control algorithms. For example, both permanent magnet synchronous generators (PMSGs) and photovoltaic (PV) systems use back-to-back inverters as grid interfacing, where the grid-side inverter isolates the rotor angle dynamics of PMSGs, and PV systems do not rely on mechanical rotation, thus lacking the physical quantity of the generator rotor angle. From a problem-oriented perspective, existing research primarily focuses on small-signal stability in IBR grid integration, while a unified understanding of transient synchronization instability mechanisms under large disturbances is still lacking. This limitation is particularly evident in the absence of a generalized synchronization state variable analogous to the power angle and stability criteria for multi-IBR cluster interactions. Although the traditional synchronization stability theory is well established, its physical foundation fundamentally differs from the electromagnetic transient-dominated characteristics of IBRs, making it difficult to apply classical rotor motion equations to power-electronics-dominated systems [19]. Therefore, for new-type power systems dominated by renewable energy, it is essential to redefine transient synchronization stability and investigate its underlying mechanisms, constituting this paper’s central objective.

The dynamic characteristics of IBRs are intrinsically linked to their control strategies, which can be divided into GFL and GFM control [20–22]. In the context of transient synchronization stability, IBRs employing these two control strategies exhibit distinctly different dynamic behaviors. It is generally believed that the synchronization mechanism of GFL inverters lies in accurately tracking grid voltage, with PLL detecting the voltage at the point of common coupling (PCC) in real time to obtain phase information. Based on this phase information, the outer loop control is divided into independent d-axis and q-axis controls, which regulate active power/DC voltage and reactive power/AC voltage, respectively. The inner loop generates modulation voltage references based on the current orders outputted by the outer loop control, which are then used to drive insulate-gate bipolar transistors (IGBTs) via pulse width modulation (PWM) [20,21]. In contrast, GFM control actively constructs the inverter’s voltage amplitude and phase angle. When using virtual generator control for GFL, IBRs simulate the operation of synchronous generators through equivalent rotor angles, demonstrating robust performance in weak grids or islanded operation modes. The well-established theories of synchronous generators remain applicable for transient synchronization stability analysis of IBRs with GFM control [22]. Given the scope and focus of this paper, the discussion will center on GFL, as it is the predominant control strategy in current IBR deployments. While equally significant, the intricacies of GFM control will not be explored in detail herein.

A comprehensive understanding of the transient synchronization behavior of GFL inverters necessitates the development of accurate object models and stability evaluation methods. Existing research [23] has established that the coordination between the inner and outer loops of GFL inverters relies on the precise phase information of the PCC voltage provided by PLL. Consequently, the dynamic of PLL can be analogized to the second-order rotor motion equation of synchronous generators, enabling the application of the equal area criterion and the second method of Lyapunov for synchronization mechanism analysis. Ref. [24] investigates the impact of reactive power control methods on grid-supporting inverters (GSIs). A single-input single-output (SISO) model is developed to explicitly reveal how PLL interacts with other components of the converter system in grid synchronization. Ref. [25] analyzes the effects of PLL parameters, positive/negative sequence currents, and circuit parameters on PLL synchronization stability during asymmetric AC faults. Ref. [26] establishes quantitative indices for GFL synchronization stability equilibrium points from the perspective of small-signal synchronization stability. It should be noted that existing research on transient synchronization stability analysis has often adopted simplified assumptions, primarily focusing on PLL while neglecting the coupling influences with other control loops.

These above methods facilitate the exploration of instability mechanisms, identification of influencing factors, quantification of stability boundaries, and validation through time-domain simulations. However, recent research indicates that the interactions within inverter control loops and between inverters and the grid can significantly impact dynamics. This discovery implies that considering only PLL dynamics is inadequate for fully capturing the transient synchronization process of GFL inverters. For example, Refs. [27,28] conduct preliminary explorations into the transient synchronization stability of VSCs with coupled control loops, proposing that in addition to PLL, outer loop control should be retained in transient synchronization analysis, and the role of nonlinear current limiting during transients must be considered. Ref. [29] identifies coupling characteristics between the current control loop and PLL and proposes a voltage feedforward control method to enhance system damping. Ref. [30] reveals that in multi-converter systems, some converters may lose synchronization stability under grid faults while others remain stable. The study proposes a coherency-based aggregated modeling approach for transient stability analysis in multi-converter systems. As a result, understanding the coupling mechanisms among different control loops and investigating the impact of multi-loop coupling on GFL transient synchronization stability have become critical research directions.

In recent years, AI technologies have been increasingly applied in power systems, showing great potential in studying the transient synchronization stability of IBRs. Many machine learning algorithms have been successfully applied to the dynamic stability analysis of GFL inverters, achieving significant advances in inverter control strategy optimization, stability prediction, and fault diagnosis [31]. AI technologies help enhance transient synchronization stability and simulative efficiency and provide novel theoretical frameworks and technical tools for ensuring the secure operation of power systems. This paper also reviews the current applications of AI technologies in studying the transient synchronization stability of IBRs and explores future development directions.

The above review shows significant progress in the research on the transient synchronization stability of IBR grid-connected systems. However, many challenges remain. This paper aims to systematically organize the current research landscape, deeply analyze key scientific issues, and provide future research directions, offering theoretical support and technical guidance for the secure and stable operation of new-type power systems.

The remaining chapters of the paper are organized as follows: Section 2 builds a transient synchronous analytical model of a GFL under large disturbances and derives the second-order equations of motion based on PLL dynamics, compared with the traditional synchronous generators. Section 3 introduces the synchronous stability analysis methods used in the current investigation, including equal-area criterion, phase diagram method, Lyapunov method, and time-domain simulation method. This section further explores the synchronization stability mechanism of GFL converters by adapting power angle stability analysis methods from synchronous generator theory. The analysis reveals that PLL governs the dynamic behavior of the entire converter during transient events, and the dynamic characteristics of the converter are explained analogously to those of the synchronous generator. Additionally, this section examines the impact of equivalent damping terms on converter transient characteristics, highlighting their inherent complexity and unpredictability. It concludes with a comprehensive review of existing research findings and unresolved issues concerning the interaction dynamics of shunt converters. Section 4 investigates AI applications and future directions in transient synchronization stability analysis. It introduces transient stability assessment and prediction methods based on AI technologies, including deep Bayesian active learning, deep imbalance learning, artificial neural networks, etc. The section also examines these methods' challenges and practical applications in the transient stability assessment of power systems. Furthermore, it explores trends in the fusion of physical modeling and data-driven approaches, including strategies to enhance model interpretability, incorporate human cognitive models, and enable human–machine collaboration to overcome the limitations of data-driven methods in the transient stability analysis of power grids. A summary is given in Section 5.

## 2. Model of GFL for Transient Analysis

A typical grid-connected configuration of a GFL is shown in Figure 1a. The grid is represented using an infinite bus in series with grid impedance, where $U_{\mathrm{g\_abc}}$ denotes the infinite bus voltage, $R_{\mathrm{g}}$ and $L_{\mathrm{g}}$ represent the grid resistance and inductance, respectively. $U_{\mathrm{t\_abc}}$ and $I_{\mathrm{abc}}$ indicate the PCC voltage and grid current, $V_{\mathrm{dc}}$ represents the DC-link voltage, and $L_{\mathrm{f}}$ denotes the filter inductance. Based on Kirchhoff's voltage law, the PCC voltage can be expressed as:

$$U_{\mathrm{t\_abc}} = U_{\mathrm{g\_abc}} + L_{\mathrm{g}} \frac{dI_{\mathrm{abc}}}{d\omega_0 t} + I_{\mathrm{abc}} R_{\mathrm{g}} \quad (1)$$

where $\omega_0$ is the system base grid angular frequency.

The control system of a GFL converter primarily consists of a PLL, voltage outer loop, and current inner loop. The GFL converter synchronizes with the grid through the PLL. Figure 1b shows a typical PLL control structure, where $U_{\mathrm{td}}$ and $U_{\mathrm{tq}}$ represent the d-axis and q-axis components of PCC voltage, $\omega_{\mathrm{g}}$ and $\omega_{\mathrm{pll}}$ denote the grid angular frequency and PLL angular frequency, respectively. The intermediate variable $\omega_{\mathrm{p}}$ satisfies $\omega_{\mathrm{p}} = \omega_{\mathrm{pll}} - \omega_{\mathrm{g}}$, and $\theta_{\mathrm{pll}}$ represents the output phase angle of PLL.

As PLL critically influences the transient synchronization characteristics of converters, numerous studies [32,33] have investigated its modeling and stability analysis under large disturbances. Under large disturbances, PLL plays a central role by tracking the voltage phase angle at the PCC in real time. This enables coordinate transformation from the stationary frame abc to the synchronous rotating frame dq, thereby establishing a reference phase for decoupled power control [32].

Under nominal grid voltage conditions, the $U_{tq}$ is regulated to zero via the closed-loop phase feedback of PLL. Consequently, the PI controller output stabilizes at $\omega_{\mathrm{p}} = 0$, locking the PLL frequency to the grid fundamental frequency. In this steady state, the active power output of converter is predominantly governed by $I_d$, ensuring synchronized operation with the grid.

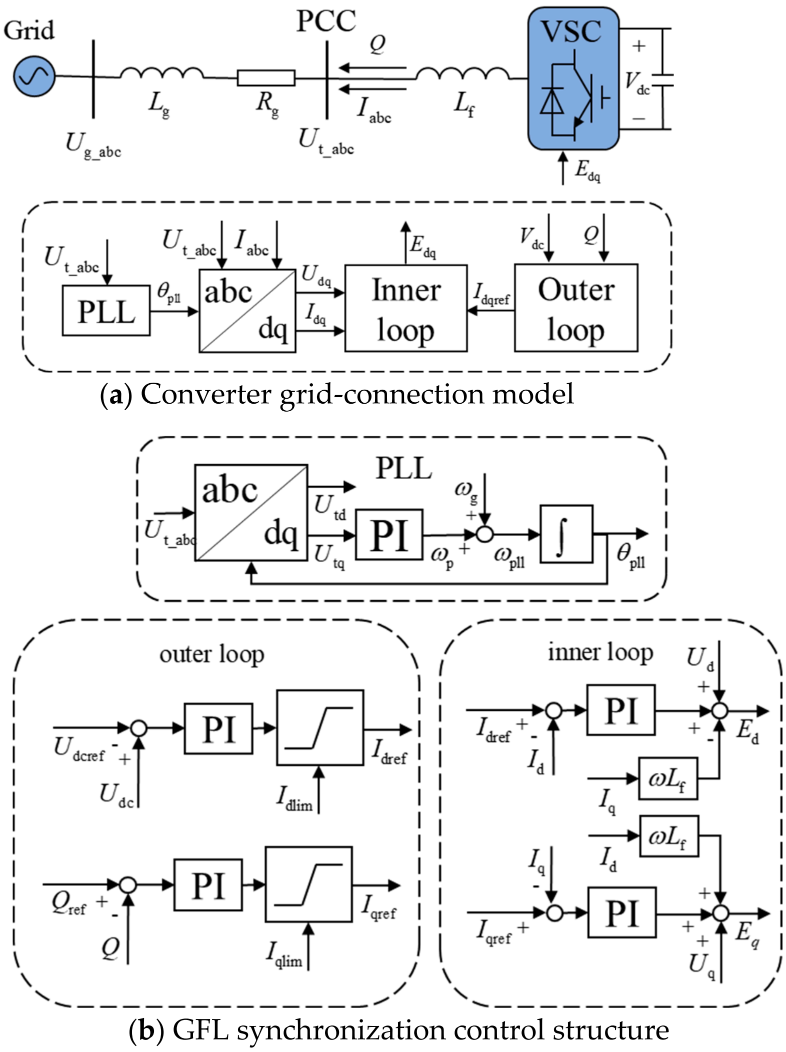


**Figure 1.** GFL and its control scheme.

During grid voltage disturbances, deviations in $U_{tq}$ from zero trigger the dynamic response of the PI controller. The $\omega_{\text{pll}}$ is integrated to generate a phase correction $\theta_{\text{pll}}$, which updates the rotating frame via Park transformation. This closed-loop mechanism dynamically adjusts the phase–frequency–voltage amplitude triad, enabling the converter to maintain phase synchronization during grid faults. By mitigating phase mismatches, the system avoids power oscillations that could otherwise destabilize grid operations [33]. The PLL dynamics can be described as:

$$\begin{aligned} \omega_{\text{p}} &= k_{\text{ppll}} U_{\text{tq}} + k_{\text{ipll}} \int U_{\text{tq}} dt \\ \theta_{\text{pll}} &= \int (\omega_{\text{p}} + \omega_{\text{g}}) dt \end{aligned} \tag{2}$$

In the PLL reference frame, the PCC voltage equation becomes:

$$U_{\text{t}} = (U_{\text{g}} e^{j\theta_{\text{g}}} + IZ) e^{-j\theta_{\text{pll}}} \tag{3}$$

where $Z = R_{\text{g}} + j\frac{\omega_{\text{pll}}}{\omega_0} L_{\text{g}}$, $I = (I_d + jI_q) e^{j\theta_{pll}}$.

The PLL angular speed and synchronization phase depend on $U_{\text{tq}}$ in the PLL reference frame. $U_{tq}$, obtained through the rotational coordinate transformation of $U_{\text{t}}$, can be expressed as:

$$U_{\text{tq}} = \text{Imag}(U_{\text{t}}) \tag{4}$$

Combining Equations (1), (3) and (4), $U_{\mathrm{tq}}$ is derived as:

$$\begin{cases} U_{\mathrm{tq}} = U_{\mathrm{g}} \sin \delta_{\mathrm{p}} + \frac{\omega_{\mathrm{pll}}}{\omega_0} I_{\mathrm{d}} L_{\mathrm{g}} + I_{\mathrm{q}} R_{\mathrm{g}} \\ \delta_{\mathrm{p}} = \theta_{\mathrm{pll}} - \theta_{\mathrm{g}} \end{cases} \quad (5)$$

Substituting Equation (5) into Equation (2) yields:

$$M \frac{d^2 \theta_{\mathrm{pll}}}{dt^2} = P_{\mathrm{m}} - P_{\mathrm{e}} - (P_{\mathrm{d1}} + P_{\mathrm{d2}})$$
$$\begin{cases} M = 1 - k_{\mathrm{ppll}} I_{\mathrm{d}} \frac{L_{\mathrm{g}}}{\omega_0} \\ P_{\mathrm{m}} = k_{\mathrm{ipll}} I_{\mathrm{d}} \frac{L_{\mathrm{g}}}{\omega_0} + k_{\mathrm{ipll}} I_{\mathrm{q}} R_{\mathrm{g}} \\ P_{\mathrm{e}} = k_{\mathrm{ipll}} U_{\mathrm{g}} \sin \delta_{\mathrm{p}} \\ P_{\mathrm{d1}} = \omega_{\mathrm{p}} k_{\mathrm{ppll}} U_{\mathrm{g}} \cos \delta_{\mathrm{p}} \\ P_{\mathrm{d2}} = -\frac{\omega_{\mathrm{p}} k_{\mathrm{ipll}} I_{\mathrm{d}} L_{\mathrm{g}}}{\omega_0} \end{cases} \quad (6)$$

where $M$ is the equivalent rotational inertia, $P_{\mathrm{m}}$ is the equivalent mechanical power, $P_{\mathrm{e}}$ is the equivalent electromagnetic power, and $P_{\mathrm{d1}}$, $P_{\mathrm{d2}}$ represent equivalent damping terms.

The synchronization stability of GFLs is fundamentally governed by the temporal interplay between control loops. Critical components, including the PLL, voltage outer loop, current inner loop, and saturation logic, operate across time scales spanning $10^{-6}$ s to 1 s, while the transient synchronization stability time scale predominantly resides in the $10^{-2}$ s to 1 s range. This substantial overlap between the dynamic response window of PLL and the synchronization stability time scale induces direct dynamic coupling, positioning the PLL as the linchpin of GFL synchronization stability.

Extensive research based on these fundamental equations has yielded significant insights into converter synchronization dynamics. Notably, Ref. [34] proposed a voltage space vector-based dynamic criterion for converters, establishing a large-disturbance synchronization stability assessment method centered on PLL dynamics. This work investigates the qualitative impact of system parameters on equilibrium points, providing crucial theoretical foundations for stability analysis. Subsequently, Ref. [35] reveals the synchronization behavior between the PLL angular frequency and grid voltage, demonstrating how grid voltage dynamics perturb PLL behavior and consequently propagate power angle and frequency instability. These studies focus on the equivalent swing equation derived from the PLL dynamics, emphasizing its dominant role in converter synchronization. However, two critical aspects remain:

(1) Coupling terms between the PLL and other control loops (e.g., product terms of reference currents and PLL parameters) exist in the equations.
(2) Nonlinear components (e.g., voltage outer loop saturation, current limiting) induce complex transient variations in system variables.

Existing works [34,35] primarily consider PLL dynamics while neglecting interactions with other control loops, which may obscure subtle synchronization stability characteristics. For example, ref. [36] shows that the current inner loop adversely affects the transient synchronization characteristics of the PLL by changing the voltage reference value, while ref. [37] finds that the dynamics of the voltage outer loop and the limiting link feed back to the PLL through the grid impedance, thus affecting the system synchronization characteristics. Recognizing this gap, recent studies have investigated PLL interactions with other control loops. Building upon these developments, we present a systematic analysis in Section 3 that comprehensively examines PLL dynamics and multi-loop interactions, offering new insights into their collective impact on synchronization stability.

## 3. Understanding Transient Synchronization Stability in GFL Converters

GFL converters constitute complex nonlinear systems with multiple interacting control loops and intricate dynamic behaviors. Extensive research efforts have yielded significant theoretical and practical advancements in the small-signal stability analysis. Foundational works by refs. [38,39] have established comprehensive small-signal models of converters around their operating points, employing methods like the impedance-based or eigenvalue method to evaluate system stability. These studies have systematically addressed critical stability challenges, including resonant instability and inadequate stability margins while proposing effective mitigation strategies through PLL parameter optimization, enhanced structural design, and innovative feedforward compensation schemes [40]. Collectively, these contributions have established a robust theoretical framework for small-signal stability challenges in converters.

However, when examining the transient synchronization characteristics of GFL converters, conventional small-signal analysis methods become inadequate due to their inherent limitations in handling significant operating point deviations and large disturbances. Although researchers have made notable progress in understanding the underlying mechanisms and developing stability assessment methodologies, comprehensive solutions remain elusive. From a theoretical perspective, methodologies adapted from power angle stability analysis of synchronous machine have facilitated synchronization stability studies based on PLL dynamics [41]. However, these studies are typically limited to individual control loops or a single converter unit, failing to capture the full complexity of practical systems. The intricate interactions, encompassing multi-loop control dynamics, inter-converter coordination, and grid-converter coupling effects, operate across multiple temporal and spatial scales, resulting in highly complex grid dynamic behaviors that lack comprehensive theoretical explanations and systematic analytical frameworks.

This section first introduces methodologies suitable for transient synchronization stability analysis of converters, then investigates PLL-based transient synchronization stability challenges, and subsequently examines existing research approaches addressing interactions among control loops or converters. This systematic exploration aims to elucidate current strategies for managing synchronization issues in practical applications while identifying critical research gaps that require further investigation.

### *3.1. Analysis Methods for Transient Synchronization Stability of GFL*

Since the model of GFL can be formulated analogously to the rotor swing equations of the synchronous machines, methodologies for power angle stability assessment in synchronous machines can be adapted to evaluate converter transient synchronization stability. In general, the equal-area criterion and phase plane analysis excel in visualizing system stability mechanisms and estimating stability boundaries, making them particularly suitable for low-order models. While time-domain simulations are computationally intensive, they accommodate complex interaction scenarios and are widely adopted for stability analysis in more sophisticated systems. Additionally, time-domain methods can leverage hardware-in-the-loop (HIL) platforms to construct physical or semi-physical models, thereby enhancing the fidelity of results [42]. The energy function method offers computational efficiency for multi-converter systems by avoiding iterative numerical integration. However, its neglect of damping effects limits applicability to multi-swing instability scenarios and yields conservative outcomes. Despite this limitation, it remains a practical tool for assessing synchronization stability in multi-machine systems. Table 1 compares the advantages and limitations of common analytical approaches.

**Table 1.** Comparison of transient synchronization stability determination methods for GFL.

| Method | Principle and Characteristic | |
|---|---|---|
| Equal area criterion | Principle | Determination of system stability by comparison of acceleration area and deceleration area based on second-order equations of motion |
| | Applicable Scenarios | Single machine infinite bus system |
| | Computational Complexity | Low |
| | Adaptability to Multi-Converter Systems | Poor |
| | Data Dependency | No simulation data required |
| | Interpretability | High |
| | Advantages | It is capable of portraying the system stability boundary; it can reveal the mechanism of converter instability more clearly, which is easy to understand. It is capable of portraying the system stability boundary; it can reveal the mechanism of converter instability more clearly, which is easy to understand; it requires fewer computational resources and is faster. |
| | Disadvantages | Lack of effective treatment of the equivalent damping term, uncertainty about the conservatism and optimism of the results; difficulty in considering Lack of effective treatment of the equivalent damping term, uncertainty about the conservatism and optimism of the results; difficulty in considering more stability influences and expanding to higher order systems. |
| | Reference | Refs. [17,27,33,43–48] |
| Phase portrait | Principle | Inscribing power system trajectory images based on numerical scoring methods. |
| | Applicable Scenarios | Single machine infinite bus system |
| | Computational Complexity | Moderate |
| | Adaptability to Multi-Converter Systems | Poor |
| | Data Dependency | Dependent on initial conditions |
| | Interpretability | Moderate |
| | Advantages | The description of the stabilization mechanism is intuitive and easy to understand; the computation requires fewer resources and is faster. |
| | Disadvantages | Stabilizing the domain of attraction is difficult to determine when the system order is high. |
| | Reference | Refs. [24,49–52] |

**Table 1.** *Cont.*

| Method | Principle and Characteristic | |
|---|---|---|
| Time domain simulation | Principle | Based on the numerical integration method, the system state motion process is simulated to determine the stability of the system under a given operation mode. The system state motion process is simulated to determine the stability of the system under a given operation. |
| | Applicable Scenarios | Any system with detailed modeling |
| | Computational Complexity | Very High |
| | Adaptability to Multi-Converter Systems | Good |
| | Data Dependency | Full model parameters needed |
| | Interpretability | Low |
| | Advantages | Suitable for complex systems, it provides detailed system dynamic processes and allows direct observation of system stabilization or destabilization processes. It provides detailed system dynamic processes and allows direct observation of system stabilization or destabilization processes. |
| | Disadvantages | It can only obtain the stability of the system under a given operating condition, and cannot portray the stability domain of the system; and the simulation requires more resources and is slow in computation. |
| | Reference | Refs. [28,48,53] |
| Lyapunov energy function | Principle | The stabilization problem is transformed into a problem of comparing function values with critical values by constructing a Lyapunov function and determining the critical values of the function. |
| | Applicable Scenarios | Systems with analytical models |
| | Computational Complexity | High |
| | Adaptability to Multi-Converter Systems | Moderate |
| | Data Dependency | Model-based |
| | Interpretability | High |
| | Advantages | Accurate results of attraction domain calculations; applicable to higher-order system stability judgments; capable of assessing transient. Accurate results of attraction domain calculations; applicable to higher-order system stability judgments; capable of assessing transient stability margins. |
| | Disadvantages | There is no general construction method for Lyapunov functions, and proper Lyapunov functions are difficult to obtain. |
| | Reference | Refs. [36,54–56] |

### *3.2. Synchronization Mechanism of GFL*

Under large disturbances such as grid voltage sags, the outer loop of the converter could be blocked, causing the control mode to switch to constant current control. Meanwhile, the time scale of the inner current loop response is significantly shorter than that of the PLL, and the dynamic effects of the current loop are typically neglected during transient processes. Therefore, regarding the synchronization stability of converters, it is generally accepted that the PLL dominates the dynamic behavior of the entire converter. As a result, the converter can be regarded as a current source controlled by the PLL [57].

Equation (1) indicates that GFL converters exhibit dynamic characteristics analogous to those of synchronous generators. A mapping relationship exists between the parameters and variables in grid-connected converter systems and those in the dynamic equations of synchronous generator grid-connected systems. Therefore, when analyzing converter dynamics, their operational behavior is often compared to the dynamics of synchronous generators [58]. The dynamic characteristics of these two types of power sources are compared in Figure 2. Figure 2a shows the grid-connected model of a synchronous generator and its motion analysis model. Both GFL and the synchronous generator grid-connected system adopt the same grid model, where $U_g$ represents the grid voltage and $X_g$ denotes the grid equivalent impedance. For synchronous generator parameters, $E\prime$ represents the generator's internal voltage, $X_d\prime$ is the d-axis transient reactance of the generator, and $\delta\prime$ denotes the internal voltage angle of the synchronous machine. And $M_{SG}$ represents the moment of inertia of the synchronous generator, $P_{m\_SG}$ denotes the mechanical power, $\frac{E\prime U_g \sin\delta\prime}{X_d\prime + X_g}$ is the maximum electromagnetic power, and $P_{D\_SG}$ corresponds to the damping coefficient. These parameters are mapped to the equivalent moment of inertia, equivalent mechanical power, equivalent maximum electromagnetic power, and equivalent damping of the converter.

In generators' transient synchronization stability analysis, the power angle $\delta\prime$ plays a critical role, characterizing the relative spatial position between generator rotors. The analytical process must consider energy conversion, response, and damping characteristics. The variation of $\delta$ is essentially a conversion process between potential and kinetic energy, determined by the difference between electromagnetic power and mechanical power. When mechanical power equals electromagnetic power, the system reaches a stable equilibrium point. If they are unequal, the rotor accelerates or decelerates under the unbalanced torque, driving the system toward equilibrium or instability. The power angle response speed is related to $M_{SG}$. Due to the large and constant mass of the rotor, $M_{SG}$ remains unchanged, resulting in a relatively slow power angle response. Damping originates from the frictional torque experienced during rotor rotation. The direction of friction always opposes the motion of the rotor, making the damping term consistently positive. It is generally approximated as proportional to the rotor's angular velocity and independent of the power angle magnitude.

In understanding the synchronization mechanisms of converters, insights from the power angle stability analysis of synchronous generators can be effectively referenced. Existing studies further examine the unique characteristics of converters, including controllability, nonlinearity, and fast dynamics, to refine mechanistic explanations and strengthen theoretical frameworks.

Figure 2b illustrates the grid-connected system with GFL and the corresponding motion equations. In transient synchronization studies, the response time scale of the PLL is significantly faster than the rotor motion speed. Therefore, special attention should be paid to instability arising from the transient response of the converter, especially in cases where severe faults cause large deviations from the system's original stable equilibrium point [59]. Ref. [59] investigates the existence of stable equilibrium points under post-fault conditions. By assuming a steady-state operation, the PLL achieves accurate grid voltage synchronization, satisfying the condition $\omega_p = 0$, where the equivalent damping term becomes zero. This simplification reduces the system dynamics to a second-order differential equation. Experiences from power angle stability analysis of synchronous generators can be referenced to determine the existence of equilibrium points. If no equilibrium point exists, post-fault instability is inevitable. Even when equilibrium points exist, instability risks persist if the system fails to transition to these states due to transient energy barriers. Ref. [60] further examines the transient characteristics of the converter under various equilibrium points and proposes a parameter optimization method for PLL to enhance stability margins. Additionally, Ref. [53] develops a reduced-order model of the PLL, decomposing the nonlinear dynamics into weighted linear sub-models. This approach employs parallel distributed compensation techniques to design stabilizing controllers, thereby improving synchronization stability.

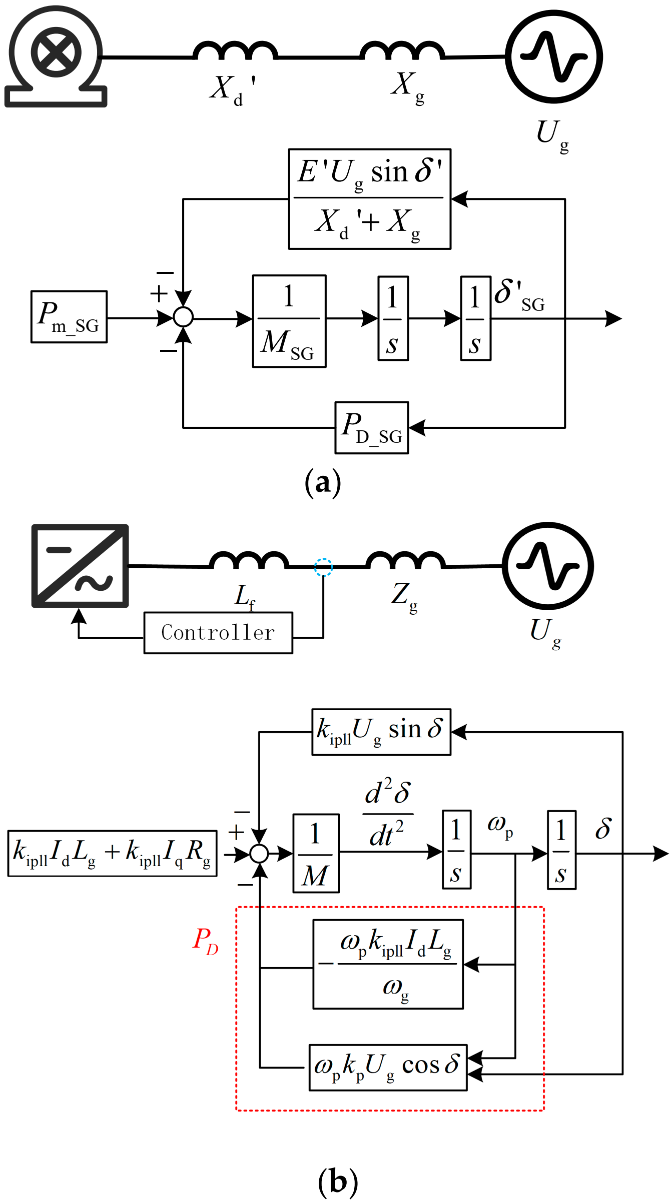


**Figure 2.** Comparison of dynamic characteristics of grid-connected system with synchronous generator and GFL. (**a**) Synchronous generator grid-connected modes and their equations of motion. (**b**) Grid-connected model of a GFL and its equations of motion.

During transient processes, the equivalent mechanical power and equivalent electromagnetic power can rapidly stabilize due to the fast action of the current loop. However, the equivalent damping term introduces significant nonlinearities, making the converter's transient behavior highly complex and challenging to predict. This complexity arises because multiple factors influence the equivalent damping term, and its dynamic characteristics remain unclear and require urgent quantitative interpretation. Unlike physical damping in synchronous generators, the equivalent damping term in converters is a virtual parameter, lacks a corresponding physical component and is jointly determined by the control loop of the PLL and grid strength. Its magnitude is not only proportional to the angular velocity of the PLL but also depends on PLL parameters and grid strength. When the system is subjected to disturbances, changes in the PLL angle dynamically alter the equivalent damping term, further complicating its behavior. Under extreme operating conditions, such as severe grid faults, the equivalent damping term may become negative, introducing uncertainty into stability assessment results and increasing the risk of misjudgment.

In studies on the equivalent damping term, ref. [61] compares the similarities and differences between synchronous machines' power angle stability and converters' synchronization stability. It further extends the equal-area criterion to define stability boundaries for converters. Ref. [35] argues that system instability is related to the balance of energy absorption and release. Under different current control strategies, the equivalent damping term exhibits varying values, and negative damping is identified to increase the potential energy of the converter, thereby raising the risk of transient instability. Ref. [61] employs a numerical iteration method to progressively approximate the actual operating conditions of the converter. Although this approach increases algorithmic complexity, it enables accurate determination of system stability. Furthermore, ref. [62] proposes a method for converters to calculate the equivalent angular velocity during post-fault transients. This method achieves a favorable balance between computational accuracy and efficiency.

Converters exhibit significantly faster and more complex dynamic characteristics than synchronous generators. While current research has established PLL-based synchronization stability frameworks for single-converter systems, critical gaps remain in understanding multi-loop interactions and complex grid conditions. The following parts will categorize and discuss future work focusing on interactions among control loops and complex grid operating conditions.

### 3.3. Impact of Control Loop Interactions on GFL Synchronization Stability

Section 3.1 analyzes synchronization characteristics originating from PLL under the assumption of negligible influence from outer loops, inner loops, and auxiliary control modules in converters. However, the studies in ref. [36] have shown that even when multi-loop control architectures are designed with time-scale decoupling principles to simplify analysis, simplified assumptions, i.e., ignoring non-PLL control loops, prove inadequate in meeting practical accuracy demands for high-precision applications or under complex grid operating conditions. In some scenarios involving minor disturbances that do not induce control mode transitions (e.g., voltage control to current control), the voltage outer loop retains dominance in regulating reference current magnitude. Under these conditions, the influence of the outer loop cannot be dismissed. This realization has prompted a paradigm shift in research focus toward holistic analysis of multi-loop interactions within converter control architectures, moving beyond the traditional PLL-centric dynamic modeling framework.

Beyond the PLL, the synchronization of grid-connected converters can be significantly influenced by the outer loop, inner loop, and limiters. For example, ref. [63] proposes a reduced-order fast-slow subsystem modeling framework based on the multi-time-scale dynamics of converters. With this model, the authors comprehensively analyze the impacts of the outer loop, inner loop, and PLL on synchronization stability by constructing energy functions. Their findings indicate that larger proportional and smaller PLL integral coefficients enhance transient stability. Furthermore, the study reveals that system stability initially increases but then decreases with the growth of DC-link capacitance. Ref. [28] extends this analysis by incorporating the DC voltage outer loop and the limiter into the dynamic equations of converters. The study explores the existence of regions of equilibrium points under varying fault severity levels and investigates the influence of PI controller parameters and limit control strategies on synchronization stability. From the perspective of interactions in multi-converter grid-connected systems, ref. [52] examines how the angle and magnitude of injected currents during low-voltage ride-through (LVRT) affect transient synchronization stability. This work delivers practical engineering solutions for LVRT's current injection design and the selection of IBR-rated capacities, offering practical guidelines for system-level stability enhancement.

Building on these insights, we conduct a comprehensive review of the converter control structure, focusing on their impact on synchronization stability during grid transients and highlighting key findings and unresolved challenges in this domain.

(1) The Outer Loop

Based on the model provided in Section 2, when disturbances are sufficiently small to avoid triggering limiters or voltage ride-through actions, the outer loop generates reference values for d-axis and q-axis current. These references drive the converter output current through the inner current loop, which subsequently affects the PCC voltage via grid impedance, thereby altering the dynamic characteristics of the PLL. Current research focuses on how including outer loop control modifies system stability, how different the outer loop modifies system stability, and how different outer loop strategies influence synchronization behavior. Ref. [64] investigates the impact of DC voltage control on the transient synchronization stability of GFL. By analyzing large-disturbance models of grid-connected converters, the study characterizes the system's steady-state and transient stability boundaries through the dynamic interactions between DC voltage and the PLL, resolving uncertainties in previous stability boundary definitions. Ref. [65] analyzes the minimum-phase characteristics of voltage source converters by adopting a constant AC voltage outer loop and DC voltage outer loop. It identifies that the PLL and outer loop dynamics jointly determine the minimum-phase behavior and systematically evaluates influencing factors. Ref. [66] employs a unified model considering different saturation modes. Two typical control limiters, hard and circular, are investigated. The study concludes that larger thresholds of hard limiters degrade synchronization stability, while circular limiter thresholds primarily affect the transient response of the PLL without significantly impacting synchronization stability.

(2) The Inner Loop

In converter control system design, dynamic decoupling between the inner current loop and the PLL is typically achieved through predefined rules. Existing transient synchronization stability analysis methods often assume an idealized current loop to maintain low-order system models. However, weak grid conditions intensify the coupling between converters and the grid, rendering simplified models potentially overly optimistic and unsuitable for stability predictions. Ref. [53] analyzes homoclinic bifurcation behaviors of GFL oscillating around equilibrium points under the influence of different current loop bandwidths. This study proposes that high or low current loop bandwidths can trigger saddle-node bifurcations of periodic orbits or avoid homoclinic bifurcations to ensure synchronization stability. Ref. [67] presents a dual-iterative equal-area criterion for stability analysis of grid-tied paralleled-converter systems. It provides insights into the impact of control parameters, including current loop bandwidth, on system stability. Ref. [68] employs the singular perturbation theory to develop fast/slow nonlinear models of GFL converters based on the time-scale separation between PLL and current loop dynamics. Using the Lyapunov indirect method, the study separately analyzes the transient synchronization stability of these two models. The results indicate that reducing the proportional coefficient of the current loop enhances stability in the fast subsystem. Furthermore, Ref. [69] utilizes second-order models to estimate initial conditions efficiently. Numerical continuation results demonstrate that full-order models capture complex bifurcation behaviors. The study establishes a parameter design principle to ensure transient synchronization stability, systematically incorporating the effects of current loop bandwidth and voltage feedforward weighting into the proposed framework.

(3) Other Control Loops

Due to computational resource constraints and simulation scale limitations, current research remains limited in fully characterizing practical nonlinear systems, such as PWM saturation and nonlinear limiters. PWM, a critical component of converters, represents a typical saturated nonlinear part. When the absolute value of the modulated voltage exceeds thresholds, PWM enters saturation, resulting in output voltage magnitudes below the theoretical predictions. Ref. [70] notes that modulation signals may repeatedly switch between saturated and unsaturated operational regions during large disturbances, potentially inducing system resonance phenomena. Ref. [71] observes that PWM rapidly saturates when current reference values experience abrupt changes, though this analysis lacks a dynamic stability perspective. Ref. [72] further applies the time-domain methods to investigate the effects of current and circular limiters on the synchronization stability of grid-following converters. Additionally, Ref. [34] focuses on the PLL, outer loop, and current limiters of converters. Using an improved Lyapunov-based method, this study identifies critical constraint boundary violation points in system dynamics. It then proposes transient current designs to improve operational safety.

### *3.4. Synchronization Stability of Multi-Converter Systems*

In contrast to a single-converter grid-connected system, practical renewable energy plants typically employ multiple power electronic converters paralleled to the PCC. Under such configurations, the voltage at the PCC is governed by the output characteristics of individual converters and grid parameters and the operational states of adjacent converters. In other words, this introduces interactions between converters and the grid and among the converters themselves [73].

Figure 3 shows the architecture of a multi-inverter parallel system, where the controls align with the detailed in Figure 1. In the multi-converter systems, the grid voltage is modified as follows:

$$U_{\mathrm{k\_abc}} = U_{\mathrm{g\_abc}} + L_{\mathrm{g}} \frac{d \sum\limits_{\mathrm{j}=1}^{n} I_{\mathrm{abc,j}}}{d\omega_0 t} + \sum_{\mathrm{j}=1}^{n} I_{\mathrm{abc,j}} R_{\mathrm{g}} \tag{7}$$

The system comprises $n$ parallel-connected converters, where $I_{abc,j}$ denotes the output current of $k$-th converter. Consequently, Equation (6) is modified as follows:

$$M_{\mathrm{k}}\frac{d^2\theta_{\mathrm{pll},k}}{dt^2} = P_{\mathrm{m},k} - P_{\mathrm{e},k}\sin\delta_{\mathrm{p},k} + P_{\mathrm{m},jk} - (P_{\mathrm{d1},k} + \sum_{j=1}^{n} P_{\mathrm{d2},jk})$$

$$\begin{cases} M_k = 1 - k_{\mathrm{ppll},k}\dfrac{L_{\mathrm{g}}}{\omega_0}\sum\limits_{j=1}^{n} I_{\mathrm{d},jk} \\ P_{\mathrm{m},k} = k_{\mathrm{ipll},k}\dfrac{L_g}{\omega_0}I_{\mathrm{d},k} + k_{\mathrm{ipll},k}I_{\mathrm{q},k}R_{\mathrm{g}} \\ P_{\mathrm{m},jk} = k_{\mathrm{ipll},k}\dfrac{L_g}{\omega_0}\sum\limits_{\mathrm{j}=1}^{n} I_{jk}\sin\delta_{\mathrm{p},jk} \\ P_{\mathrm{e},k} = k_{\mathrm{ipll},k}U_{\mathrm{g},k} \\ P_{\mathrm{d1},k} = \omega_{\mathrm{p},j}k_{\mathrm{ppll},k}U_{\mathrm{g}}\cos\delta_{\mathrm{p},k} \\ P_{\mathrm{d2},jk} = \dfrac{\omega_k - \omega_j}{\omega_{\mathrm{g}}}k_{\mathrm{ppll},j}\dfrac{L_{\mathrm{g}}}{\omega_0}I_{\mathrm{d},jk} \end{cases} \tag{8}$$

$I_{\mathrm{d},k}$, $I_{\mathrm{q},k}$ are the d-axis and q-axis current components of $k$-th converter. $\theta_{\mathrm{pll},k}$ is the phase angle of the PLL output of $k$-th converter, $k_{\mathrm{ppll},k}$, $k_{\mathrm{ipll},k}$ are the PI controller parameters of the PLL of $k$-th converter, $M_{\mathrm{k}}$, $P_{\mathrm{m},k}$, $P_{\mathrm{e},k}$, $P_{\mathrm{d1},k} + \sum_{j=1}^{n} P_{\mathrm{d2},jk}$ are the equivalent rotating moment of inertia, the equivalent mechanical power, the maximum value of the equivalent electromagnetic power, and the equivalent damping of $k$-th converter, $P_{\mathrm{m},jk}$ is the coupling power, $\delta_{\mathrm{p},k} = \theta_{\mathrm{pll,k}} - \theta_{\mathrm{g}}$, and $I_{\mathrm{d},jk} = I_{\mathrm{d},k} - I_{\mathrm{d},j}$.

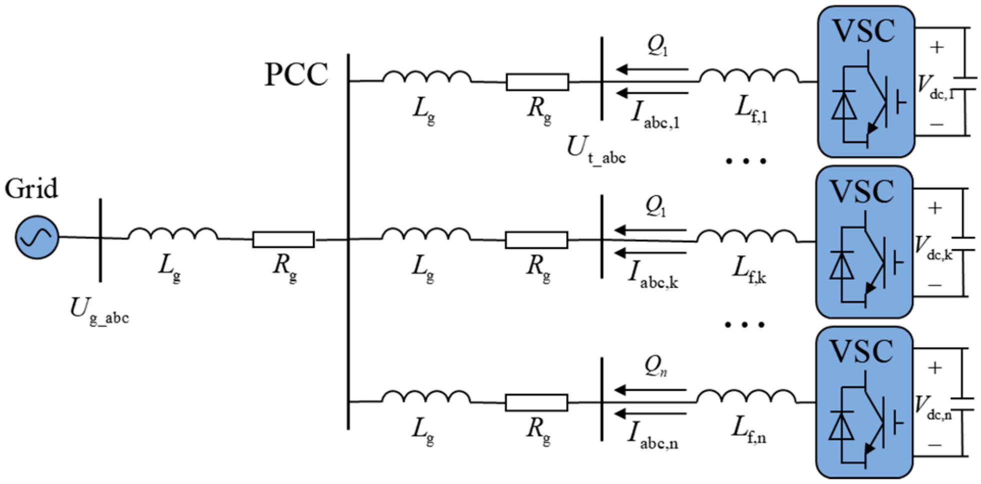


**Figure 3.** Structure of multi-converter parallel system.

The synchronization model of the $k$-th converter in a multi-converter parallel system is illustrated in Figure 4. Compared with the stand-alone model, the multi-converter configuration introduces coupled power terms and coupled damping terms, altering the system's equivalent rotational inertia. These modifications underscore the presence of dynamic interactions between PLL and current inner loops within individual converters [74]. The time scale of the power outer loop is orders of magnitude larger than those of the current inner loop and slightly larger than the time scale of the PLL, necessitating distinct analytical approaches. This temporal disparity enables the representation of interactions between GFM and other devices through the network impedance matrix, which quantifies their impact on both the self-impedance and mutual impedance of the system. In hybrid systems with GFL and GFM converters, analytical frameworks must prioritize interactions between GFL converters and other system components (e.g., energy storage, loads) or the grid itself.

Such analyses must account for the distinct operational modes of GFL and GFM converters, particularly their contrasting roles in voltage/frequency regulation and power-sharing [75].

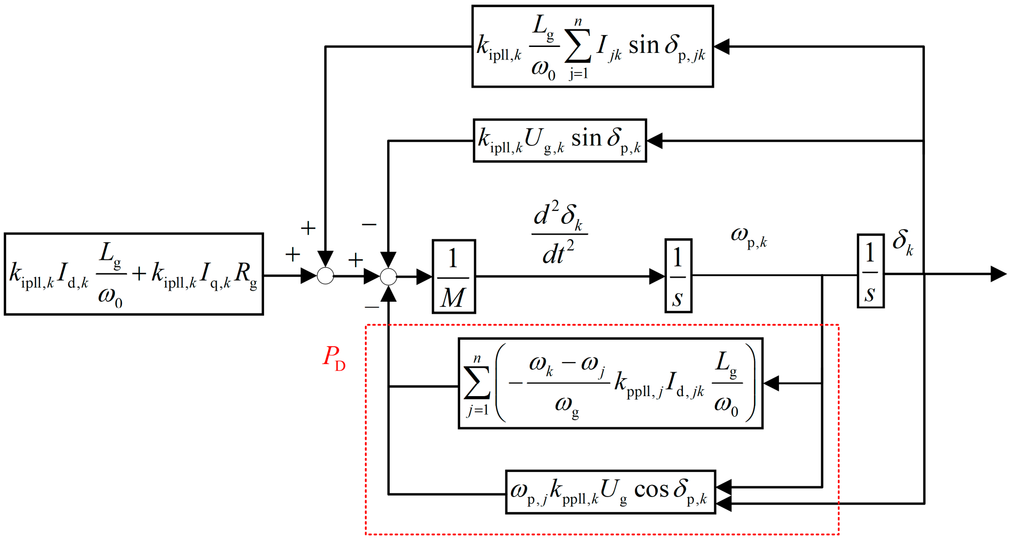


**Figure 4.** Synchronization model of the converter k in a multi-converter parallel system.

A prerequisite for the transient stability of multi-converter systems is the existence of stable equilibrium points for each individual converter. Due to interactions among multiple converters, the existence of equilibrium points depends interdependently on the operating states of all converters within the system. Ref. [30] establishes a set of nonlinear equations to solve for equilibrium points in multi-converter systems, demonstrating that ensuring stable equilibria in parallel configurations requires the output current of each converter to be subject to an upper bound. This bound is determined by both the network impedance and the current limitations of neighboring converters. Ref. [76] proposes a methodological framework to transform operational challenges, such as synchronization stability and power oscillations, into control problem objective functions. By reformulating converter control as a boundary parameter optimization problem at grid interfaces, the collective state variations implicit in power balance mechanisms are expressed as the sum of individual converter dynamics. This method enables synchronized cooperative control of converters under distributed resource conditions. Ref. [52] quantifies the impact of injected current angles and magnitudes on transient synchronization stability, providing guidelines for designing current injection references during LVRT and selecting the rated capacity of renewable energy sources. Ref. [17] focuses on parallel GFL systems and proposes the coupling mechanisms between power flows and synchronization stability control during LVRT scenarios.

Existing transient stability enhancement strategies for converters are predominantly designed for single-converter grid-connected systems, with uncertain applicability to multi-converter parallel configurations. Ref. [36] investigates the adverse interaction between PLLs and current inner loops, deriving a novel Lyapunov stability criterion via the extended invariance principle. This study quantifies the tolerance thresholds of converters to such interactions. Notably, replacing partial GFL converters with GFM control modes in multi-converter systems can enhance synchronization stability. Ref. [77] further establishes a hybrid GFL-GFM system model under grid faults, analyzing transient stability through nodal current laws and equal-area criteria. To mitigate power angle discrepancies between GFL and GFM converters, an auxiliary control strategy was proposed to improve hybrid system stability.

While existing studies have advanced the understanding of transient stability in multi-converter systems, the influence of multi-converter interactions on the transient stability margin of individual converters remains insufficiently characterized. This gap hinders the development of robust stability criteria in new-type power systems.

## 4. AI in Transient Synchronization Stability Analysis: Concepts, Applications and Future Prospects

Traditional stability analysis methods, originally designed for single-converter or single-machine systems, face significant challenges when applied to multi-converter or multi-machine configurations. These challenges stem from the inherent tension between the reliance on high-precision physical modeling and the computational intensity that hinders real-time assessment capabilities.

Recent advancements in AI, exemplified by innovations such as ChatGPT-4, Claude 2, and DeepSeek-R1, have inspired researchers to explore transformative solutions across various domains of power systems research. Among these, data-driven intelligent technologies have emerged as a pivotal approach for addressing transient synchronization stability analysis in complex, multi-converter systems. These methods utilize historical datasets to autonomously detect stability patterns, facilitating scalable and computationally efficient stability evaluations while preserving accuracy under dynamic operating conditions. The key findings, advantages, and limitations of the AI methods discussed below are summarized in Table 2.

These paradigm shifts enhance real-time decision-making and bridge the gap between theoretical precision and practical applicability in new types of power systems. For example, ref. [78] develops a deep Bayesian active learning (DBAL) framework using Bayesian Neural Networks (BNNs) for transient stability online assessment. This approach adaptively evaluates prediction confidence via posterior probability and employs uncertainty-based active learning to prioritize informative samples, reducing computational costs in time-domain simulations. It is validated in the IEEE 39-bus system and achieves high accuracy with minimal data requirements. Ref. [79] proposes a deep imbalanced learning framework where a modified denoising autoencoder (DAE) reduces data dimensionality in latent space. Synthesizing unstable samples via an adaptive synthetic sampling approach (ADASYN) and decoding them to the original space significantly enhances the recognition of unstable scenarios. To evaluate the scalability of the proposed approach, a larger power system—the South Carolina 500-bus system—was analyzed. Using the same database generation method as in the IEEE 39-bus system, a dataset containing 34,725 samples (including 1243 unstable samples) was constructed. The results demonstrate that the proposed framework significantly improves the generalization capability of transient stability assessment through nonlinear data synthesis and integrated cost-sensitive learning. Additionally, Ref. [80] also introduced an ANN-based hybrid model that combines diverse network architectures to deliver high classification performance with reduced training instances.

Despite their potential, these methods face critical challenges in power system transient stability analysis. The predictive performance of machine learning algorithms critically relies on the quality, quantity, and diversity of training data, often requiring extensive operational or simulated datasets. Furthermore, the black-box nature of deep learning models leads to a lack of interpretability, hindering their trustworthiness in safety-critical applications [81]. To address these limitations, hybrid approaches that synergize physics-based analytical models with AI technologies are imperative. Such integration compensates for individual weaknesses, enabling efficient, real-time, and reliable stability assessment [82]. For example, ref. [83] developed an enhanced transient stability prediction model combining minimum redundancy maximum relevance (MRMR) feature selection with Winner-Takes-

All (WTA) ensemble learning. It processes real-time data from Wide-Area Measurement Systems (WAMS) to enable rapid online stability prediction, offering actionable insights for emergency control in future power grids.

**Table 2.** AI methods applied to transient synchronization stability analysis.

| Method | Principle and Characteristic | |
|---|---|---|
| DBAL Framework | Input Data | Simulation data |
| | Key Findings | Uses BNNs to adaptively evaluate prediction confidence via posterior probability, reducing computational costs through uncertainty-based active learning |
| | Advantages | High accuracy with minimal data requirements; reduces simulation costs |
| | Disadvantages | Relies on simulated data; real-time performance limited by active learning iterations |
| Deep Imbalanced Learning Framework | Input Data | High-dimensional operational data |
| | Key Findings | Combines modified DAE for dimensionality reduction and ADASYN-synthesized unstable samples to enhance recognition |
| | Advantages | Improves unstable scenario detection; data compression enhances efficiency |
| | Disadvantages | Complex data balancing; synthetic samples may introduce noise |
| ANN Hybrid Model | Input Data | Multi-scenario operational data |
| | Key Findings | Integrates diverse architectures to boost classification performance with fewer training instances |
| | Advantages | High classification accuracy; reduced training data dependency |
| | Disadvantages | Black-box nature limits interpretability; requires substantial training data |
| Hybrid Methods | Input Data | Real-time WAMS data |
| | Key Findings | Combines physics-based stability equations with AI for real-time online prediction |
| | Advantages | Merges physical principles with data-driven insights; real-time reliability |
| | Disadvantages | High integration complexity; requires interdisciplinary collaboration |
| Physics-Data Integrated Modeling | Input Data | Physical equations |
| | Key Findings | Embeds PINNs to enforce physical constraints, improving credibility and interpretability |
| | Advantages | Enhances trustworthiness via physics compliance; semi-interpretable “grey-box” solutions |
| | Disadvantages | Requires domain expertise for constraint definition; higher computational costs |

Continuous algorithmic innovations have marked the evolution of AI in transient stability assessment. From early decision trees and support vector machines (SVMs) to advanced convolutional neural networks (CNNs), long short-term memory (LSTM) networks, and graph neural networks (GNNs), these emerging technologies and iterative advancements reflect both deepening AI integration and research frontiers. Emerging technologies such as diffusion models and multi-source data-model fusion are poised to enhance key performance metrics (e.g., accuracy, generalization), driving transformative upgrades in stability methodologies.

A pivotal breakthrough lies in physics-data integrated modeling, where physics-driven models (rooted in transient synchronization stability principles) and data-driven models (based on information mining) are cohesively combined. For instance, physics-informed neural networks (PINNs) embed governing physical equations into neural network architectures and training processes, transforming opaque black-box models into interpretable grey-box solutions. This approach improves credibility by ensuring predictions adhere to physical laws [84].

In practical applications, Ref. [85] demonstrates that the proposed nonlinear data synthesis method outperforms linear interpolation-based approaches in extracting transient characteristics for transient stability assessment using non-temporal data. When validated on the 102-bus system, it achieves a prediction mean absolute error of <1.2%, showcasing its enhanced capability to capture nonlinear dynamics critical for stability analysis. In ref. [86], a novel data-driven method analogous to image processing techniques is developed to accelerate $N - 1$ contingency screening. This method employs a deep CNN to compute AC power flows under $N - 1$ contingency conditions and uncertain operational scenarios, validated in a 1354-bus system.

Despite progress, the practical deployment of AI in power systems remains constrained by imperfect decision accuracy. For systems demanding ultra-high reliability, the consequences of erroneous AI decisions are prohibitive, resulting in a "trust gap" that impedes real-world adoption. Bridging this gap requires multidimensional strategies: leveraging interpretability techniques to demystify model decisions, integrating human expertise via human-in-the-loop feedback mechanisms, and advancing hybrid augmented intelligence systems. Such systems synergize human cognitive strengths with machine computational power, enabling rapid model updates and risk-mitigated online decision-making. Ultimately, these advancements enhance the precision and responsiveness of stability assessment, fortifying grid security through collaborative human-AI intelligence. Future research can prioritize scalable validation across diverse grid topologies and operational scenarios to translate theoretical innovations into field-ready solutions.

## 5. Conclusions

This paper systematically reviews the transient synchronization stability mechanisms and technological advancements of GFL, summarizes key achievements and challenges in current research, and outlines future development directions. The main conclusions are as follows:

(1) The second-order motion model based on PLL dynamic equations provides an important theoretical framework for analyzing the transient synchronization stability of GFL. Its similarity to rotor motion equations of synchronous generators allows partial applicability of traditional methods. However, existing models often neglect coupling effects between outer-loop controls, current limiters, and PLL, leading to deviations in mechanistic understanding. Interactions among multiple control loops (e.g., voltage outer loop, current inner loop, and nonlinear limiting) significantly influence transient synchronization stability. Studies reveal that current loop bandwidth, DC voltage

control strategies, and limiting modes alter the equivalent damping characteristics of the system, thereby affecting stability margins.

(2) Traditional methods (e.g., equal-area criterion, Lyapunov functions) offer intuitiveness and computational efficiency advantages in low-order single-converter systems but struggle to extend directly to multi-converter interaction scenarios. While time-domain simulations can handle complex systems, they demand high computational resources and fail to reveal intrinsic patterns of stability boundaries. In multi-converter parallel systems, coupled power and damping terms between converters cause dynamically varying equivalent inertia. Current research has yet to fully clarify quantitative laws governing multi-converter interactions, necessitating the development of aggregated models that balance accuracy and complexity.

(3) Data-driven methods (e.g., deep Bayesian learning, imbalanced sample optimization) demonstrate potential for rapid transient stability assessment but face challenges such as strong dependence on data quality and insufficient model interpretability. Physics-data fusion modeling (e.g., physics-informed neural networks), which embeds grid dynamic equations, enhances model generalization capabilities and credibility, offering new insights for stability prediction in complex scenarios.

Future work should prioritize improving the discrimination accuracy of transient synchronization stability boundaries for GFL, enhancing the computational speed and adaptability of methods under complex conditions, developing stability criteria that account for multi-control-loop coupling and multi-timescale interactions, and establishing stability criteria and control strategies compatible with high penetration of renewable energy integration. Additionally, advancing interpretability research of AI models, constructing human–machine collaborative hybrid-augmented intelligence frameworks, and realizing online stability assessment and adaptive optimization in dynamic scenarios represent another critical research direction.

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## Abbreviations

The following abbreviations are used in this manuscript:

| | |
|---|---|
| GFL | Grid-following |
| PLL | Phase-locked loop |
| AI | Artificial intelligence |
| IBR | Inverter-based resource |
| VSC | Voltage source converter |
| PMSG | Permanent magnet synchronous generator |
| PV | Photovoltaic |
| GFM | Grid-forming |

| | |
|---|---|
| PCC | Point of common coupling |
| IGBT | Insulate-gate bipolar transistor |
| PWM | Pulse width modulation |
| GSI | Grid-supporting inverter |
| SISO | Single-input single-output |
| HIL | Hardware-in-the-loop |
| LVRT | Low-voltage ride-through |
| DBAL | Deep Bayesian active learning |
| BNNs | Bayesian neural networks |
| DAE | Denoising autoencoder |
| ADASYN | Adaptive synthetic sampling approach |
| MRMR | Minimum redundancy maximum relevance |
| WTA | Winner-takes-all |
| WAMS | Wide-area measurement systems |
| SVM | Support vector machine |
| CNN | Convolutional neural network |
| LSTM | Long short-term memory |
| GNN | Graph neural network |
| PINN | Physics-informed neural network |

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