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Comparative Analysis of Grid-Following (GFL) and Grid-Forming (GFM) Inverters: Control and Transition Capabilities

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Abstract: In recent years, interest in integration of renewable energy (RE) sources (particularly Wind Energy Systems - WES) into the electrical grid for sustainable, innovative solutions and a greener future continues to grow exponentially. To date, most RE sources have been connected to the grid through traditional grid-following inverters (GFL). Although this control method promises grid compatibility and lower complexity, the unpredictable variability of these eco-friendly RE sources leads to undesirable effects when taken into account. With the increasing interaction of renewable energy sources in today's grid, new challenges arise—such as voltage/frequency regulation and the reduction of overall system inertia—that cannot be resolved with conventional grid-following inverters (GFL). Therefore, the concept of grid-forming inverters (GFM) has been adopted.

The aim of this study is to examine the comparison between grid-forming inverters and traditional grid-following inverters, particularly focusing on droop control, and to regulate the simulated test results with appropriate control systems. For this purpose, the study first compares GFM—based on different control techniques (droop, virtual synchronous generator, and synchronverter control) in the literature—with the conventional GFL technique. The circuit tested in this study involves a 40 kVA-rated inverter supplying relevant loads and the grid, with GFL and GFM control modes analyzed separately. Finally, the potential effects of inverters on load variation and grid outages will be considered.

Keywords: Grid-Following Inverter (GFL), Grid-Forming Inverter (GFM).

1. Introduction

When examining the market shares of wind and solar systems—the two main drivers of renewable energy globally—2022 will be remembered as a significant milestone. That year, renewables hit a record high, accounting for 12% of global electricity generation. Another noteworthy point was that fossil-based generation declined for the first time ever. For Türkiye, in 2023, solar energy's share rose from 4.9% (2022) to 5.7% (2023), while wind energy contributed approximately 34 TWh, securing a 10.5% share (2023) of total electricity production. This marked a crucial milestone in the transition from fossil-based generation to clean energy (Serkan Aslan, 2023; Wiatros-Motyka, 2023).

Considering these developments, it no longer seems far away for grid models powered solely by renewable energy—rather than traditional synchronous generator (SG)-based systems—to become part of modern power networks. However, this potential shift requires a transition period. Because the declining share of SG-based energy in favor of wind and solar sources leads to grid control challenges that must be addressed. First, power systems were originally designed around traditional synchronous generators (SGs). The quality indicators of power systems rely on the behaviour and control of these machines, summarized in four key requirements:

- Constant frequency (e.g., 50 Hz or 60 Hz);
- Constant voltage amplitude;
- System protection during faults;
- A sinusoidal voltage source with low harmonic content and limited harmonic interactions.

For grid-connected Wind Energy Systems (WES)—a type of renewable energy source—four additional requirements apply (Mandrile et al., 2021):

- Renewable power plants (RES) must be equipped with appropriate controllers to withstand multiple fault events.
- Higher inertia is needed to limit the Rate of Change of Frequency (RoCoF) and enable protective relay intervention.
- Static converter-based plants (e.g., RES-PV) must exchange reactive power with the grid per Grid Code Regulations.
- Synchronous Generators (SGs) can operate under symmetrical and asymmetrical faults, injecting both positive and negative sequence fault currents. However, static converters cannot inject high short-circuit currents, so they require additional control algorithms to meet Fault Ride-Through (FRT) requirements by enabling positive/negative sequence current injection.

The dominance of modern power electronics-based renewable generation plants has raised concerns about sustaining these mentioned 4+4 fundamental specifications. Traditional SG systems benefit from inertia and Automatic Voltage Regulators (AVR), which are crucial for grid stability. In contrast, power electronics-based systems lack these features, making conventional grid-following inverters (GFL) insufficient for ensuring stability. Two key inverter designs—grid-forming (GFM) and grid-following (GFL) inverters—have been extensively studied. One reason for this focus is that while the input-side converter topology and control vary depending on the renewable source (e.g., WES & PV), the grid-side inverter (dc-ac) remains the same. Thus, grid integration has become a critical research area with diverse control techniques. The input side typically consists of a rectifier or dc-dc converter, both providing a dc output, allowing the input converter to be modeled as a dc link (Ali et al., 2024).

2. Grid-Following Inverter (GFL)

Currently, most renewable energy sources (RES) are connected to the grid via traditional current-controlled grid-following inverters (GFL). Utilizing the phase-locked loop (PLL) concept, GFL inverters must detect the grid frequency and synchronize themselves to it. Additionally, they primarily inject active power by following the maximum power point tracking (MPPT) algorithm dictated by the input-side converter topology. As their name implies, GFL systems inherently follow the grid under all conditions and cannot contribute to grid stability (Rathnayake et al., 2021). The increasing dominance of renewable energy systems in the grid exacerbates this issue, as power electronics-based inverters—with their limited voltage-frequency regulation—replace synchronous generators (SGs) with high rotational inertia. Notably, the energy stored in the DC-link capacitors of inverters is significantly smaller compared to the inertial energy provided by the large masses of traditional systems.

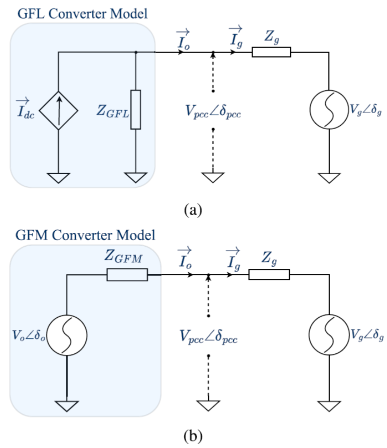

Figure 1 Circuit models of (a) grid-following (GFL) and (b) grid-forming (GFM) systems

The GFL converter can be approximated as a controlled current source with high parallel impedance, as illustrated in Figure 1-a. GFL-based inverter systems regulate currents to inject power or adjust voltage. This is achieved by transforming the three-phase (abc) system into active and reactive components (dq) using Park and Clark transformations (Ali et al., 2024). Active and reactive power are thus regulated via Id and Iq current control. The measured grid voltages and currents feed into the PLL block (Figure 2-a), generating a grid reference angle for these transformations (abc-dq). In the inverter connection circuit (Figure 3), Kirchhoff's voltage law (Equation 1) is applied in the dq-frame to decouple active and reactive power dynamics. As evident, the objective is active-reactive power (PQ) control. However, this PQ-controlled converter system lacks grid regulation capability and exhibits limited small-signal stability performance, particularly in weak grids (Gullu et al., 2024).

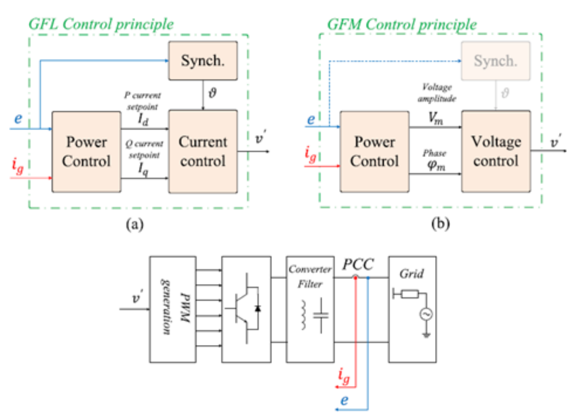

Figure 2 Grid-Following (GFL) (a) and Grid-Forming (GFI) (b) control models (Rosso et al., 2021)

$$\begin{cases} V_d = R \cdot I_d + L \cdot \frac{dI_d}{d_t} - \omega L \cdot I_q + E_d \\ V_q = R \cdot I_q + L \cdot \frac{dI_q}{d_t} + \omega L \cdot I_d + E_q \end{cases} \quad (1)$$

- V_d,V_q : Inverter output voltages (d-q axes)
- I_d,,I_q : Inverter output currents
- R,L : Resistance and inductance of the grid coupling reactance
- w : Grid angular frequency ($\omega = 2\pi f$)
- E_d,E_q : d-q components of the grid voltage (typically E_q=0, E_d =V_{grid})

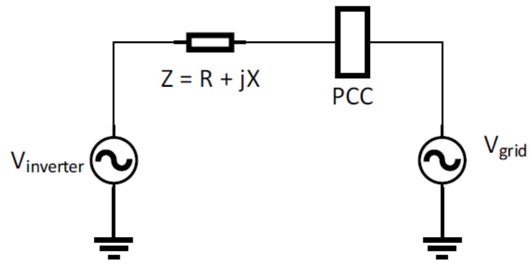

Figure 3 The main electrical interface between the inverter and utility grid (Gullu et al., 2024)

3. Grid Forming Inverter (GFM)

The GFM converter, as illustrated in Figure 1-b, can be represented as a voltage source with low series impedance, symbolizable via Norton or Thevenin equivalents. Unlike grid-following inverters (GFL), grid-forming inverters operate autonomously without grid dependency and possess inherent grid regulation capabilities. While GFL systems regulate power through current control, GFM achieves power control via direct voltage regulation. Crucially, this enables voltage-frequency regulation at the point of common coupling (PCC), compensating for voltage fluctuations (see Figure 2-b). Initially developed to address GFL converter limitations, GFM technology gained early adoption in uninterruptible power supplies (UPS) and microgrid operations due to its control flexibility. Recent studies highlight its stability benefits in both infinite-bus and weak grid applications, making it a focal point in modern power systems research (Ali et al., 2024).

Unlike GFL converters reliant on phase-locked loops (PLLs), many proposed GFM implementations eliminate PLLs, mimicking synchronous machine behaviour to achieve self-synchronization with the grid. Studies demonstrate that PLL-based synchronization in GFL converters adversely affects small-signal stability, particularly under variable grid frequencies (Sevilmiş & Karaca, 2019; Urtasun et al., 2022). Detailed performance comparisons reveal that PLL methods exacerbate stability issues in weak grids. Selecting an appropriate control strategy is critical for GFM operation. Prominent methods include (Rosso et al., 2021):

- Droop control
- Virtual synchronous generator (VSG) control
- Synchronverter
- Power synchronization control (PSC)
- Power balance (matching) control
- Virtual oscillator control (VOC)

3.1 Droop Control

According to Equations (2)-(4), droop control is a simple and highly implementable technique. However, its lack of inherent inertia means it may fail to ensure frequency stability in scenarios with high Rate of Change of Frequency (RoCoF) (Tozak et al., 2024). A key advantage of this method is its ability to regulate voltage and frequency based on measured active and reactive power values without requiring additional synchronization units. Recent observations suggest the need for an adaptive droop control system capable of dynamically adjusting its coefficients to maintain grid synchronization under varying conditions.

$$\dot{\theta}^{ref} = \omega \tag{2}$$

$$\omega = \omega^{*} + K_{Qv}^{droop}(P^{ref} - P) \tag{3}$$

$$v_{pcc,d}^{ref} = v^{*} + K_{Qv}^{droop}(Q^{ref} - Q) \tag{4}$$

3.2 Virtual Synchronous Generator (VSG) Control

As previously discussed (Urtasun et al., 2022), grid-forming inverters (GFMs) are fundamentally designed to naturally emulate the capabilities of synchronous generators (SGs) used in conventional systems. This control technique specifically addresses the rotor dynamics of SGs through the swing equation and adapts it for grid control. Equations (5)-(8) describe:

- The frequency output of the SG (Eq. 6),
- The induced voltage (Eq. 7), and
- The excitation current (Eq. 8) for voltage regulation.

Here, the parameters J (inertia constant) and D_p (damping ratio) correspond to the virtual inertia moment required by the grid and the damping coefficient, respectively. By adjusting these values, the virtual synchronous generator (VSG) control can exhibit characteristics similar to droop control (Tozak et al., 2024).

$$\dot{\theta}^{ref} = \omega \tag{5}$$

$$\dot{w} = \frac{1}{Jw}(P^{ref} - P) + \frac{D_P}{J}(w^{*} - w) \tag{6}$$

$$v_{pcc,abc}^{ref} = 2wM_f i_o \begin{bmatrix} \sin(\theta) \\ \sin(\theta - \frac{2\pi}{3} \\ \sin(\theta - \frac{4\pi}{3} \end{bmatrix} \tag{7}$$

$$i_o = \frac{k_p}{M_f}(v^{*} - \|v_{pcc,dq}\| + \frac{k_i}{M_f}\int(v^{*} - \|v_{pcc,dq}(\tau)\|)d\tau \tag{8}$$

3.3 Synchronverter

Another control method that emulates synchronous machines is the Synchronverter. Unlike the previously discussed Virtual Synchronous Generator (VSG) control—which primarily focuses on rotor dynamics—the Synchronverter replicates the complete behaviour of a synchronous generator through comprehensive modelling of key parameters, including:

- Electromagnetic torque (T_e)
- Electromotive force (u)
- Reactive power (Q)

These dynamics are formally expressed in Eq. (9). The Synchronverter distinguishes itself through its grid-synchronization capability in grid-connected mode, while offering adjustable parameters, such as inertia damping coefficient and mutual inductance. This adaptability enhances its performance in diverse grid conditions (Rathnayake et al., 2024; Rathnayake et al., 2022).

$$\begin{aligned} T_e &= M_f i_f \langle i, \widetilde{\sin(\theta_r)} \rangle \\ u &= \dot{\theta}_r M_f i_f \widetilde{\sin(\theta_r)} \\ Q &= -\dot{\theta}_r M_f i_f \langle i, \widetilde{\cos(\theta_r)} \rangle \end{aligned} \tag{9}$$

4. Test Results

4.1 GFL Inverter Control Performance Test

The inverter output current and voltage control described by Equation (1) for traditional GFL operation has been implemented in the circuit shown in Figure 9 using MATLAB/Simulink. Figure 4 examines the point of common coupling (PCC) for both islanded and grid-connected scenarios. Current regulation for harmonics is achieved through the LCL filter mentioned previously. The measured grid voltage undergoes axis transformation to the dq-frame for simplified control implementation. As illustrated in Figure 6, synchronization with the grid is established through a synchronous reference frame-based phase-locked loop (SRF-PLL) circuit, which generates the reference angle for output synchronization (Blaabjerg et al., 2006).

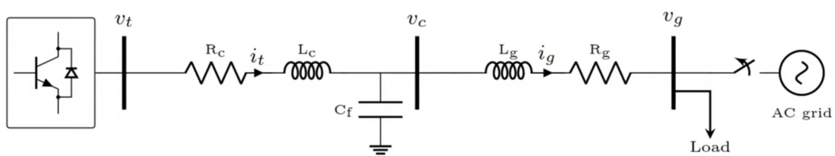

Figure 4 Grid-connected configuration of the comparative inverter topology

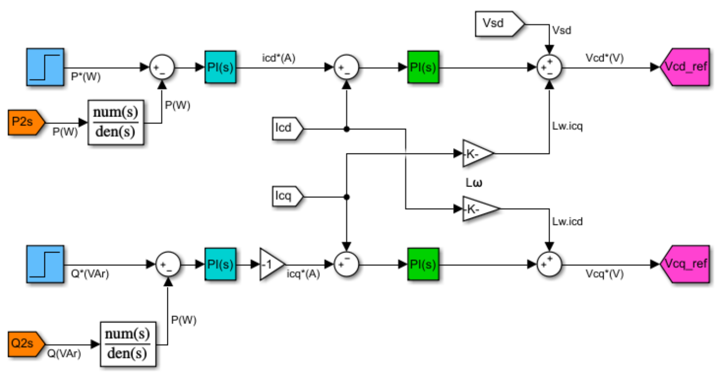

Figure 5 Dual control loops for GFL

The control methodology for the circuit presented in Figure 4 employs a dual-loop control structure. As shown in Figure 5, the outer loop control determines the inverter's active and reactive power by processing the reference power values (P, Q). The current reference values generated by the outer loop enable precise d-axis and q-axis current regulation of the inverter output. Following the inner loop control, the obtained voltage reference values are processed through sinusoidal pulse-width modulation (SPWM) to generate gate signals for the IGBT semiconductors, thereby regulating the inverter output.

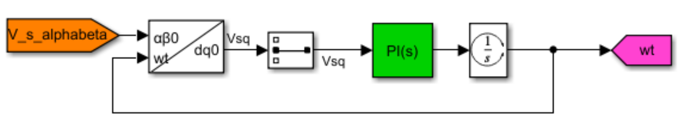

Figure 6 PLL synchronization unit

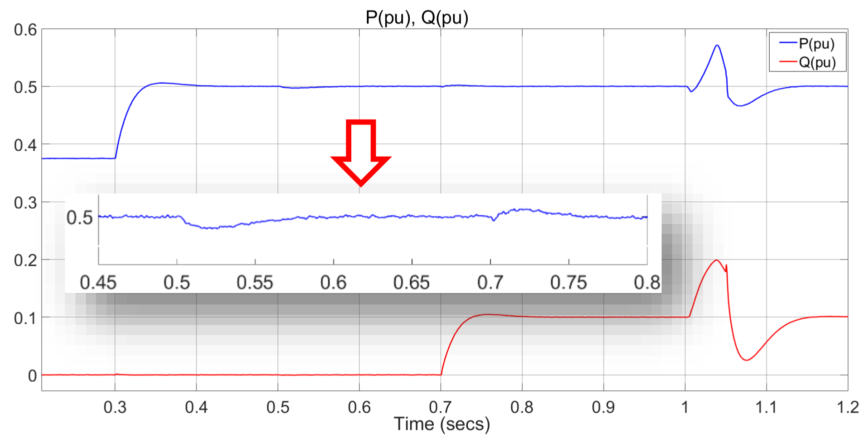

Figure 7 GFL's Active P(pu) and Reactive Q(pu) Power Change

As illustrated in Figure 7, the system demonstrates distinct power response characteristics: the active power rises to 0.5 pu at 0.3 s, followed by reactive power increase at 0.7 s. Notably, the grid-connected mode maintains minimal power fluctuations ($\Delta P < 2\%$, $\Delta Q < 3\%$) during load transitions at t = 0.5 s. However, during the intentional 50 ms islanding event initiated at t = 1 s, the GFL control system exhibits three critical behaviors: (1) unstable active/reactive power regulation with ±15% oscillations, (2) significant power quality degradation, and (3) successful resynchronization within 2 cycles post-grid reconnection. These observations validate the inherent limitations of GFL inverters in maintaining power stability during grid disturbances while confirming their capability for automatic re-synchronization.

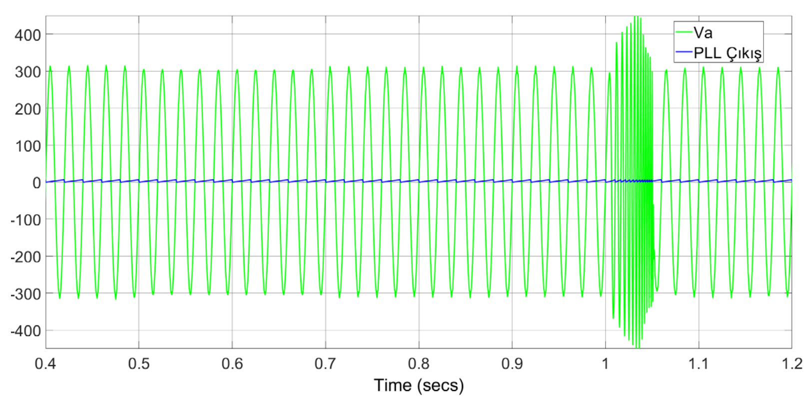

Figure 8 Grid Voltage (V_a) ve PLL Output (w_t)

Figures 8-9 demonstrate the synchronization performance between the PLL output (ωt) and grid voltage (V_a) under different operational conditions. The results show:

- Successful phase locking during normal grid-connected operation
- Immediate loss of synchronization upon grid disconnection, accompanied by frequency deviation exceeding ±2 Hz and transient frequency spikes reaching approx. 250 Hz (for 50 Hz nominal)
- Full synchronization recovery within 3 cycles after grid restoration (50 ms reconnection)

Also, this behaviour quantitatively confirms:

- The PLL's effective tracking capability during stable conditions
- The inherent vulnerability to grid disturbances
- The fast resynchronization characteristic (<100 ms) post-fault.

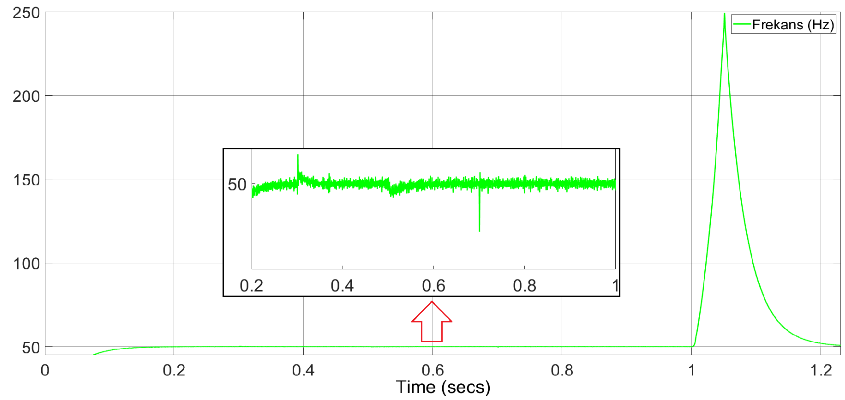

Figure 9 Grid Frequency (Hz)

4.2 GFM Inverter Control Performance Test

In synchronous generators, increased power demand necessitates rotor speed reduction (Salem et al., 2023), consequently inducing frequency decline to provide additional power support. This consistent power-frequency relationship inherent to synchronous machines has been systematically incorporated into grid-forming (GFM) inverters through droop control development (Mohammed et al., 2024). As demonstrated in Figure 10, the implemented droop control mechanism—constructed using Equations (2)-(4)—generates both reference voltage (U_{abc}) and frequency (ω_t) signals.

The governing equations establish two fundamental relationships that the active power (P) is directly regulated through frequency variation, where frequency effectively substitutes the phase angle in power equations. Reactive power (Q) is also controlled via voltage. Accordingly, P and Q represent the measured active and reactive power values, while P_{ref} and Q_{ref} denote their respective reference values. K_p and K_q are the droop gain parameters. If these droop parameters are set to low values, the system responds more slowly; conversely, higher values enable a faster dynamic response.

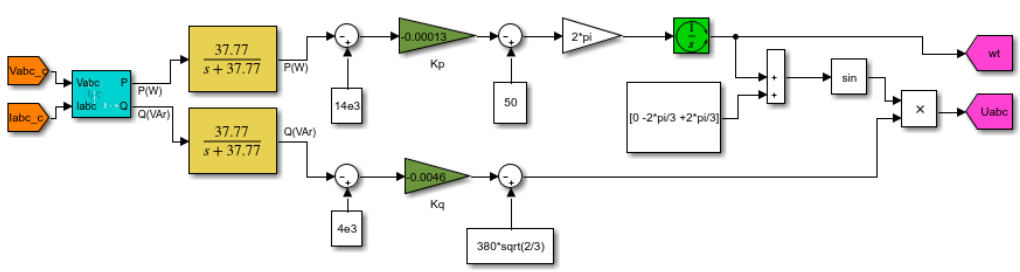

Figure 10 Droop frequency and sinusoidal waveform generation

As illustrated in Figure 10, the calculated input power values are first subjected to filtering and then compared with their respective reference values based on predefined droop coefficients. Subsequently, the resulting control signals are evaluated against the nominal system frequency and terminal voltage. An increase (or decrease) in the measured active power results in a corresponding decrease (or increase) in the output frequency. A similar droop characteristic governs the relationship between reactive power and terminal voltage.

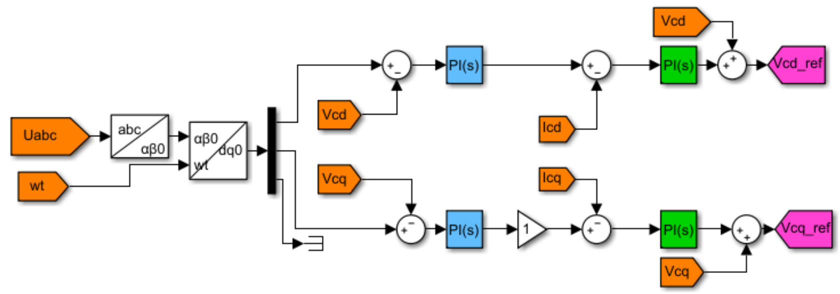

Figure 11 Droop control loops

The obtained terminal voltage (U_{abc}) and the angular frequency (ω_t), which is used for the dq-axis transformations, are fed into the control block illustrated in Figure 11. These signals sequentially pass through the voltage and current control loops, ultimately generating the reference voltages required for PWM signal synthesis. Notably, no Phase-Locked Loop (PLL) block is present in this structure, indicating that synchronization with an existing grid is not required.

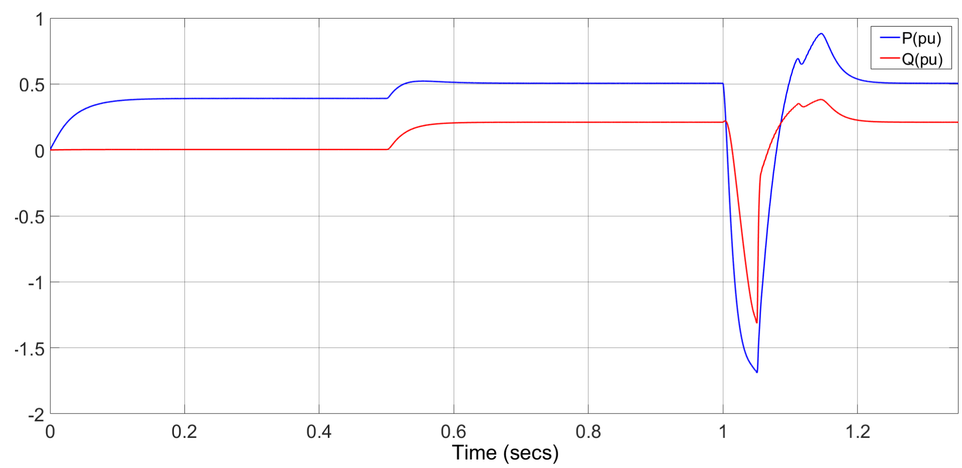

Figure 12 Active and Reactive Power Dynamics in GFM Inverter

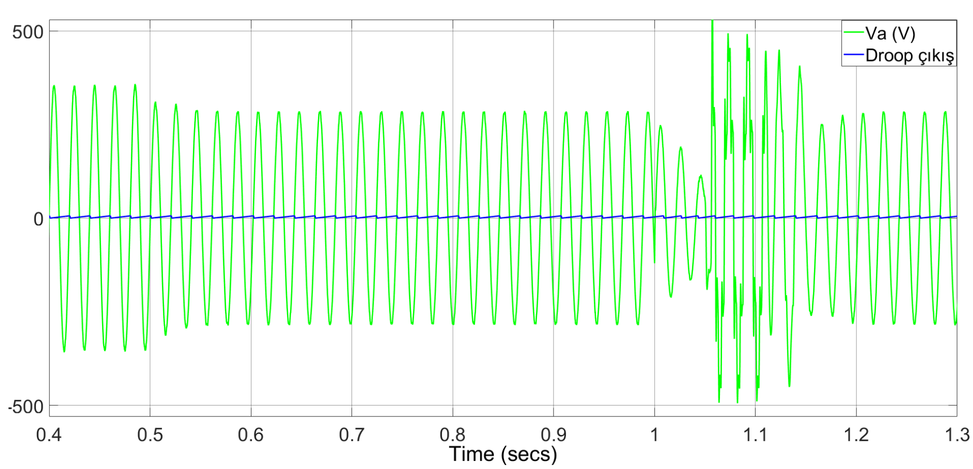

Figure 13 GFM inverter PCC voltage (V_a) and Droop output (w_t)

Initially, the inverter—rated at 14 kW and 4 kVAr (see Figure 10)—supplies a 12 kW load. At t = 0.5 s, an additional load of 12 kW and 10 kVAr is introduced into the system, similar to the scenario in GFL operation. As shown in Figure 12, this additional loading results in an increase in both the active and reactive power output of the GFM inverter. Correspondingly, Figure 14 illustrates a drop in frequency at t = 0.5 s, reflecting the droop mechanism response. This frequency reduction represents the system's dynamic adjustment to accommodate and share the increased load. Furthermore, Figure 15 shows a decrease in terminal voltage due to the increased reactive power demand.

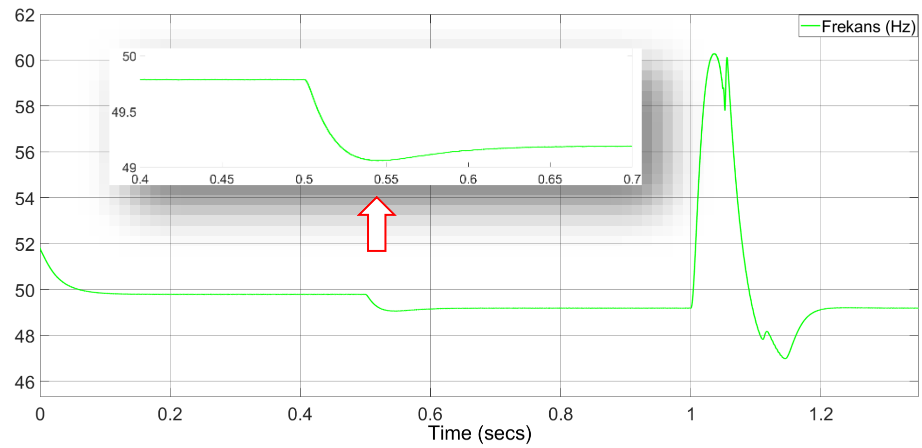

Figure 14 Frequency Deviation Curve (Hz)

Unlike to previous inverter scenario, at t = 1 s, the grid connection is established at the PCC (Point of Common Coupling) within a 50 ms interval; however, in this case, the transition occurs in the opposite direction, i.e., from islanded to grid-connected mode. As observed in the GFL case, the resulting unstable and oscillatory waveforms indicate that both control methods—summarized in Table 1—are complementary in nature, each compensating for the other's limitations under different operating conditions.

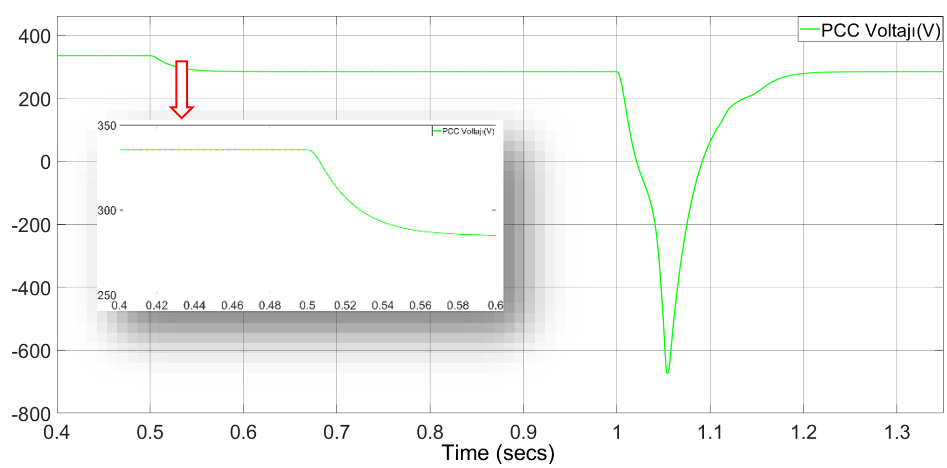

Figure 15 Point of Common Coupling (PCC) voltage deviation profile (V)

Table 1. Detailed Comparison of GFM and GFL Inverters (Mohammed et al., 2024)

Specifications	*Grid-Forming Inverter (GFM)*	*Grid-Following Inverter (GFL)*
Operation	Can operate in islanded mode; generates voltage and frequency independently.	Requires an external grid reference to operate.
Grid Dependency	Operates independently of the grid; can initiate the grid from scratch.	Dependent on the grid for voltage and frequency references.
Control Objective	Regulates voltage and frequency.	Tracks grid voltage and frequency (typically using a PLL).
Inertia	Provides synthetic (virtual) inertia.	Has no inherent inertia; relies on grid inertia.
Applications	Microgrids, islanded systems, weak grids.	Grid-connected systems under stable grid conditions.
Stability	More suitable for weak grids or systems with high renewable energy penetration.	May struggle in weak grids or systems with low inertia.

5. Results and Discussion

Based on the data collected from the literature, the comprehensive Table 1 presents a feature-by-feature comparison of the two main inverter control strategies. In this context, this study simulates droop-based Grid-Forming (GFM) and conventional vector-controlled Grid-Following (GFL) inverters under both islanded and grid-connected scenarios, taking into account various load conditions using MATLAB/Simulink. The respective advantages and limitations of each control method are examined through graphical results under different grid conditions. Notably, the issue of grid dependency highlighted in the table is validated through this study. The inverter control structure, designed to operate either grid-connected or isolated, needs to be carefully designed. Specifically, it is observed that a hybrid control model combining GFM for islanded systems and GFL for grid-connected systems would be beneficial. This model should not be limited to droop control alone but should also incorporate other GFM control strategies available in the literature. Moreover, ensuring smooth and stable transitions between different grid states is identified as a target for future work. Finally, the inclusion of weak grids or rural networks located far from centralized infrastructure is also considered a potential focus in upcoming research.

Declaration of Ethical Standards

As the authors of this study, we declare that he complies with all ethical standards.

Credit Authorship Contribution Statement

F. Burak: Conceptualization, Methodology, Software, Validation, Formal analysis, Writing -Original Draft, Visualization, Writing, Investigation
H. Karaca: Review & Editing, Supervision.

Declaration of Competing Interest

The authors declared that they have no conflict of interest.

Data Availability

No datasets were generated or analyzed during the current study.

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