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Grid-Forming and Grid-Supporting Inverter Control in Modern Power Systems

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ABSTRACT

The increasing penetration of renewable energy sources such as solar photovoltaic and wind energy has transformed the structure of modern power systems. Unlike conventional synchronous generators, these renewable sources are connected through power electronic inverters which do not inherently provide inertia or voltage support to the grid. This has led to serious challenges in grid stability, especially in weak grids and microgrids. To address this issue, advanced inverter control strategies known as grid-forming (GFM) and grid-supporting (GFS) controls have emerged. Grid-forming inverters can establish voltage and frequency references, behaving similar to synchronous machines, while grid-supporting inverters assist the grid by providing ancillary services such as reactive power compensation and frequency regulation. This paper presents a comprehensive review of grid-forming and grid-supporting inverter control techniques, their principles, modeling approaches, control strategies, stability issues, and practical applications. Comparative analysis between both approaches is discussed along with future research directions.

KEYWORDS: *Grid-forming inverter, Grid-supporting inverter, Virtual inertia, Droop control, Microgrid, Renewable integration, Power electronics control.*

INTRODUCTION

The traditional power grid was dominated by large synchronous generators which naturally provided inertia, voltage regulation, and fault current capability. With rapid adoption of renewable energy systems, the grid is now increasingly populated by inverter-based resources (IBRs). These IBRs do not behave like synchronous machines and lack inherent grid-supporting characteristics.

Initially, most inverters were designed as **grid-following** devices, meaning they rely on the grid voltage and frequency for synchronization using Phase Locked Loop (PLL). However, in weak grids or islanded microgrids, this approach causes instability.

This situation has led to development of two important inverter categories:
- **Grid-Supporting (GFS) Inverters** – assist the grid but still depend on it.
- **Grid-Forming (GFM) Inverters** – capable of establishing grid voltage and frequency on their own.

These control strategies are essential for future low-inertia grids.

2. NEED FOR ADVANCED INVERTER CONTROL (ELABORATED)

The rapid integration of renewable energy resources such as solar photovoltaic (PV), wind turbines, and battery energy storage into modern power systems has significantly changed the dynamic behavior of the grid. Unlike conventional synchronous generators, these sources are connected through power electronic converters which **decouple the mechanical inertia from the electrical grid**. As a result, the natural stabilizing properties once provided by rotating machines are no longer present in sufficient amount. This transition has exposed several operational and stability challenges that cannot be handled effectively by traditional grid-following inverter control. Hence, advanced inverter control strategies such as **grid-forming (GFM)** and **grid-supporting (GFS)** have become necessary.

2.1 Reduction in System Inertia

Synchronous generators possess large rotating masses. During sudden disturbances such as load changes or faults, the stored kinetic energy in these rotating masses automatically resists rapid changes in frequency. This phenomenon is known as **inertia response**.

In inverter-based renewable plants:

- There is **no rotating mass** directly coupled to the grid.
- Frequency can change very rapidly during disturbances.
- The rate of change of frequency (RoCoF) becomes very high.
- Conventional protection and control schemes may fail to respond in time.

Without inertia, even small power imbalances can lead to large frequency deviations. Advanced inverter controls such as **Virtual Synchronous Machine (VSM)** and **Virtual Inertia Control** in GFM inverters artificially recreate this inertia by embedding the swing equation into the control algorithm.

2.2 Voltage Instability in Weak Grids

A weak grid is characterized by:

- Low short circuit ratio (SCR)
- High line impedance
- Poor voltage regulation capability

Grid-following inverters depend on Phase Locked Loop (PLL) to synchronize with grid voltage. In weak grids:

- Voltage waveforms are distorted and unstable.
- PLL loses synchronization or oscillates.
- Reactive power injection becomes ineffective.
- Voltage collapses or oscillations may occur.

GFM inverters solve this problem by acting as **controlled voltage sources** rather than current sources. They establish voltage magnitude and frequency themselves, thus stabilizing weak grids and microgrids.

2.3 Frequency Fluctuations

In conventional grids, frequency is tightly regulated by generator governors and inertia. With high renewable penetration:

- Sudden cloud cover in solar plants or wind variation leads to rapid power variation.
- Lack of inertia causes fast frequency swings.
- Load-generation imbalance is not automatically corrected.

GFS inverters can provide **droop-based frequency support**, while GFM inverters can directly regulate frequency through power–frequency droop and virtual inertia, similar to governor action in synchronous generators.

2.4 Protection Coordination Problems

Traditional protection systems are designed assuming high fault currents from synchronous generators (5–8 times rated current). However, inverter-based sources:

- Limit their current to 1.1–1.5 times rated value.
- Do not provide sufficient fault current for relays to detect faults.
- Cause maloperation of overcurrent and distance protection.

Advanced inverter controls allow:

- Controlled fault current injection.
- Better fault ride-through (FRT) capability.
- Improved coordination with protection schemes.

GFM inverters, due to their voltage source nature, can provide better fault response compared to GFS inverters.

2.5 Poor Fault Ride-Through (FRT) Capability

Grid codes require renewable plants to remain connected during short-term faults. However:

- Grid-following inverters trip due to PLL instability during voltage dips.
- Sudden disconnection of large renewable plants worsens grid disturbance.

GFM control enables:

- Stable operation during voltage sags.
- Continuous voltage support to the grid.
- Seamless transition between normal and fault conditions.

3. GRID-SUPPORTING (GFS) INVERTER CONTROL (ELABORATED)

Grid-Supporting (GFS) inverters represent an important evolution of the traditional **grid-following** inverter. While a pure grid-following inverter only injects current according to a reference, a grid-supporting inverter goes one step further by **actively assisting the grid** in maintaining voltage and frequency stability through ancillary services. However, it still **depends on the grid** for synchronization and reference, which distinguishes it from grid-forming control.

GFS control is widely used in present-day solar PV plants, wind converters, STATCOMs, and battery energy storage systems connected to strong utility grids.

3.1 Working Principle

The basic idea of GFS control is:

"Follow the grid, but support it whenever needed."

PLL-Based Synchronization

A Phase Locked Loop (PLL) continuously measures:

- Grid voltage phase angle (θ)
- Grid frequency (f)

This allows the inverter to transform measured quantities into the **dq synchronous reference frame**, where control becomes simpler and decoupled.

However, because the inverter relies on PLL:

- If grid voltage is distorted or weak, PLL performance degrades.
- Synchronization is fully dependent on the grid.

Current Injection Based on Reference

Once synchronized, the inverter behaves as a **controlled current source**. The reference current is generated from power commands:

- Active power reference → d-axis current (Id)
- Reactive power reference → q-axis current (Iq)

Thus, the inverter regulates how much power it injects into the grid by controlling output current.

Droop-Based Grid Support

To make the inverter "supportive" rather than passive, droop control is added:

- **P–f droop**: adjusts active power when frequency deviates.
- **Q–V droop**: adjusts reactive power when voltage deviates.

This allows the inverter to automatically respond to grid disturbances without communication.

3.2 Control Structure of a Typical GFS Inverter

The control structure of GFS inverter is hierarchical and consists of multiple loops operating at different time scales.

1. Phase Locked Loop (PLL)

- Measures grid voltage.
- Extracts phase angle and frequency.
- Enables transformation into dq frame.
- Most critical element for synchronization.

2. Inner Current Control Loop (dq Frame)

This is the fastest loop in the system.

- Regulates inverter output current.
- Ensures fast tracking of reference currents.
- Usually implemented using PI controllers with decoupling terms.
- Provides protection against overcurrent.

Because GFS behaves as a current source, this loop is the core of control.

3. Outer Power Control Loop

This loop generates current references from power commands.

- Compares measured P and Q with reference values.
- Generates Id* and Iq*.
- Slower than current loop.

This loop ensures correct power injection into the grid.

4. Droop-Based Support Layer

This layer modifies power references dynamically:

- If grid frequency drops → increase active power.
- If grid voltage drops → increase reactive power.

Thus, inverter contributes to **primary frequency and voltage regulation**.

3.3 Functional Behavior of GFS Inverter

With the above structure, a GFS inverter can:

- Inject precise active power from renewable source.
- Provide reactive power compensation like a STATCOM.
- Support grid frequency through active power modulation.
- Improve voltage profile through Q–V droop.
- Participate in ancillary services such as Volt-VAR and Frequency-Watt control.

Despite these capabilities, it still **does not create voltage**; it only responds to existing grid voltage.

4. GRID-FORMING (GFM) INVERTER CONTROL (ELABORATED)

Grid-Forming (GFM) inverters represent a paradigm shift from conventional grid-following control. Instead of behaving like controlled current sources that depend on the grid, GFM inverters operate as **controlled voltage sources** capable of establishing and regulating the grid voltage and frequency by themselves. This makes them essential for **weak grids, islanded microgrids, black-start operation, and future low-inertia power systems**.

4.1 Working Principle

No PLL Requirement

Unlike GFS inverters, GFM inverters **do not use a Phase Locked Loop (PLL)** for synchronization. This is because:

- The inverter itself generates the voltage waveform.
- Other inverters or loads synchronize to it.
- Stability does not depend on grid voltage quality.

This makes GFM control highly robust in weak grids where PLL-based systems fail.

Self-Establishment of Voltage and Frequency

A GFM inverter directly controls:

- Voltage magnitude (V)
- Frequency (f)
- Phase angle (θ)

These quantities are generated internally by the control algorithm. The inverter behaves similarly to an **ideal AC voltage source behind an impedance**, just like a synchronous generator.

Mimicking Synchronous Generator Dynamics

To replicate generator-like behavior, GFM control embeds dynamic relationships such as:

- Swing equation (inertia behavior)
- Droop characteristics (governor behavior)
- Damping effects (stability)

As a result, the inverter naturally responds to load changes and disturbances in a way similar to rotating machines.

4.2 Voltage Source Behavior of GFM Inverters

Because GFM inverters act as voltage sources, their behavior is fundamentally different from GFS.

Regulation of Output Voltage Amplitude

The inverter maintains a constant terminal voltage regardless of load variations by adjusting current automatically. When load increases:

- Current increases
- Voltage remains regulated

This is opposite to current-source behavior of GFS.

Frequency Regulation Based on Load

GFM inverters use **P–f droop control**:

- When active power demand increases → frequency slightly decreases.
- When load decreases → frequency increases.

This allows multiple GFM inverters to share load without communication, similar to multiple generators operating in parallel.

Power Sharing Using Droop Characteristics

Droop control enables decentralized power sharing:

- P–f droop → active power sharing
- Q–V droop → reactive power sharing

Thus, multiple GFM inverters can operate together stably in a microgrid.

4.3 Virtual Synchronous Machine (VSM) Concept

One of the most widely adopted GFM strategies is the **Virtual Synchronous Machine (VSM)**, also known as Virtual Synchronous Generator (VSG).

Swing Equation Emulation

The swing equation of a synchronous generator is:

Jdωdt=Pm−Pe−D(ω−ω0)J \frac{d\omega}{dt} = P_m - P_e - D(\omega - \omega_0)Jdtdω=Pm −Pe−D(ω−ω0)

Where:

- JJJ = moment of inertia
- DDD = damping factor
- PmP_mPm = mechanical power
- PeP_ePe = electrical power

In VSM control:

- Mechanical power PmP_mPm is replaced by power reference.
- Electrical power PeP_ePe is measured output power.
- Inertia JJJ and damping DDD are implemented virtually in software.

This provides **virtual inertia**, reducing rate of change of frequency (RoCoF) during disturbances.

Governor and AVR Emulation

VSM also includes:

- Governor action → implemented using P–f droop.
- Automatic Voltage Regulator (AVR) → implemented using Q–V droop.

Thus, the inverter behaves almost identical to a real synchronous generator.

5. CONTROL STRATEGIES FOR GFM AND GFS

5.1 Droop Control

Used in both GFM and GFS:

- P–f droop for frequency regulation
- Q–V droop for voltage regulation

5.2 Virtual Oscillator Control (VOC)

Nonlinear time-domain control inspired by oscillators. Provides fast synchronization without communication.

5.3 Virtual Synchronous Generator (VSG)

Imitates mechanical inertia and damping of synchronous machines.

5.4 Matching Control

Based on matching inverter dynamics with synchronous machine model for improved stability.

6. MODELING APPROACHES

Accurate modeling is important for analysis.

- State-space modeling in dq frame
- Small signal stability models
- EMT simulations for switching behavior
- Impedance-based modeling for stability studies

7. STABILITY ISSUES

7.1 In Weak Grids

PLL in GFS becomes unstable due to low short circuit ratio.

7.2 Power Sharing Instability

Improper droop settings lead to circulating currents.

7.3 Interaction between Multiple GFMs

Multiple grid-forming inverters require coordination.

8. COMPARISON BETWEEN GFM AND GFS

Feature	Grid-Supporting (GFS)	Grid-Forming (GFM)
Dependency on grid	High	Low
PLL required	Yes	No
Can operate islanded	No	Yes
Voltage source behavior	No	Yes
Suitable for weak grid	Limited	Excellent
Complexity	Moderate	High
Provides inertia	No	Yes (virtual)

9. APPLICATIONS

9.1 Microgrids

GFM inverters act as main voltage source in islanded microgrids.

9.2 Renewable Plants

Solar and wind farms using GFM improve grid stability.

9.3 Battery Energy Storage Systems

BESS with GFM control provides fast frequency response.

9.4 Black Start Capability

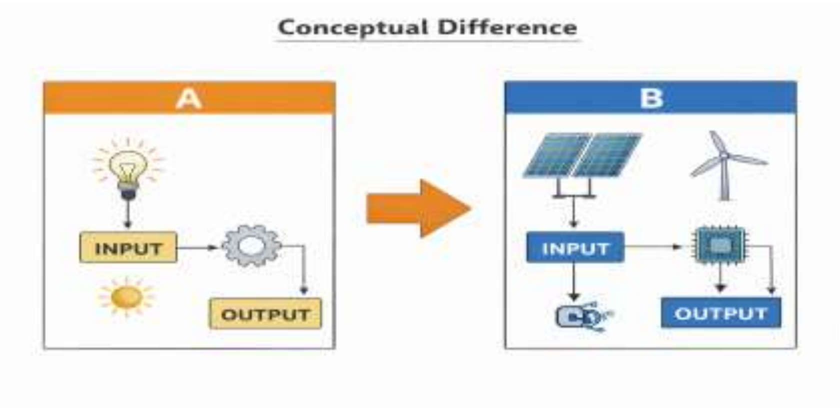
GFM inverters can start grid without external supply.

PRACTICAL CHALLENGES

- Parameter tuning of droop coefficients
- Protection coordination
- Standardization issues
- Hardware limitations
- Transition between GFS and GFM modes

FUTURE RESEARCH DIRECTIONS

- Adaptive droop control
- AI-based tuning of inverter parameters
- Standard grid codes for GFM
- Coordination of multiple GFM units
- Cyber-secure inverter control



12. Figure: Conceptual Difference

TABLE: CONTROL TECHNIQUES USED

Technique	Used in GFS	Used in GFM	Purpose
PLL	Yes	No	Synchronization
Droop Control	Yes	Yes	Power sharing
VSM/VSG	No	Yes	Virtual inertia
VOC	No	Yes	Fast sync
Current Control	Yes	Limited	Current regulation

CONCLUSION

The transition towards renewable dominated grids demands intelligent inverter control strategies. Grid-supporting inverters are useful for assisting existing strong grids but fail in weak or islanded conditions. Grid-forming inverters, on the other hand, provide a promising solution by emulating synchronous generator behavior and offering voltage and frequency reference. Though GFM control is more complex, it is essential for future low-inertia power systems. Proper coordination, modeling, and standardization are required to fully utilize these technologies. The evolution from grid-following to grid-forming marks a major step in power electronics and smart grid development.

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