

Article

Modeling and Control of Multiple-Parallel Grid-Forming Active Power Filters for Scalable Harmonic Attenuation

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Abstract

Grid-forming converters have gained significant attention for their ability to form grid voltage and provide essential grid-supportive services. However, managing harmonics generated by nonlinear loads remains a critical challenge in weak grids. A single grid-forming converter active power filter offers limited compensation capacity, and under heavy nonlinear loading its performance is restricted by converter ratings, leading to reduced stability margins, higher harmonic distortion, and weakened voltage/frequency regulation. To overcome these limitations, this paper presents a novel distributed control approach for multiple-parallel grid-forming converters active power filters that integrates voltage and frequency regulation with scalable harmonic attenuation. The proposed method extracts harmonic components at the point of common coupling and generates harmonic voltage commands to each unit so the parallel units collectively create a near short-circuit impedance for harmonics, preventing harmonic currents from propagating into the grid. Beyond improved harmonic performance, the multi-unit system enhances effective inertia, damping, and short-circuit capacity while avoiding complex parameter tuning, enabling a simple and scalable deployment. Simulation results demonstrate effective harmonic attenuation at the point of common coupling and accurate active/reactive power sharing.

Keywords: active power filter; grid-forming converter; harmonic suppression; parallel operation; power sharing

1. Introduction

The rapid penetration of renewable energy sources (RESs) and power electronic interfaced generation has fundamentally reshaped modern distribution networks, transitioning the conventional power grid from a centralized, synchronous-machine-dominated system into a converter-dominated, decentralized, and low-inertia power system [1,2]. While this transformation improves efficiency, flexibility, and sustainability, it also introduces significant challenges related to system stability, voltage regulation, and power quality. In particular, the reduced inertia and damping in converter-dominated grids amplify voltage and frequency fluctuations and increase the system's sensitivity to disturbances, especially under weak-grid conditions [3].

Grid-forming converters (GFMCS) have emerged as a key enabling technology to address these challenges. Unlike grid-following converters, GFMCs can autonomously establish grid voltage and frequency and provide essential grid-supportive services, such as



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voltage regulation, frequency stabilization, virtual inertia, and improved fault response [4,5]. As a result, GFMCs are increasingly viewed as foundational building blocks for future low-inertia power systems. However, despite their advantages, GFMC-based systems remain vulnerable to power quality degradation caused by nonlinear loads, which inject harmonic currents into the grid and distort voltage waveforms at the point of common coupling (PCC). These harmonic distortions can degrade equipment lifetime, reduce system efficiency, and compromise overall grid stability, particularly in weak grids where impedance interactions are more pronounced.

Active power filters (APFs) have long been established as an effective solution for harmonic mitigation and power quality enhancement. Conventional shunt APFs, typically operating in grid-following mode, detect load-generated harmonic currents and inject compensating currents at the PCC to suppress harmonic propagation [6,7], as illustrated in Figure 1. Although widely adopted, their performance relies heavily on accurate grid voltage synchronization and phase-locked loop (PLL) operation, which become unreliable in weak or distorted grids [8]. Moreover, single APF units are inherently constrained by converter power ratings and switching frequency limits, making it challenging to compensate for large harmonic currents or wide-band harmonic spectra without increasing switching losses, thermal stress, or system cost [9,10].

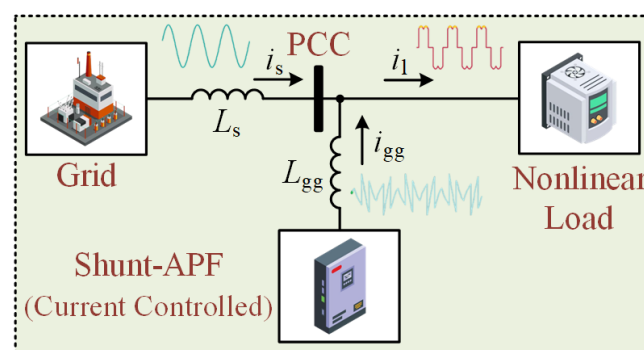


Figure 1. Shunt active power filter connected in parallel with the grid and nonlinear load.

To overcome these limitations, the parallel operation of multiple APFs has been proposed as a scalable and modular solution. Parallel APF configurations can increase harmonic compensation capacity, enhance redundancy, and improve system reliability [11]. Various coordination strategies have been reported in the literature, including frequency splitting and center-mode control, power sharing and distributed control, and capacity limitation or master–slave schemes [12,13]. These approaches define how harmonic compensation tasks and current sharing are distributed among multiple units to ensure stable operation under diverse loading conditions. Nevertheless, the majority of these solutions remain grid-following in nature and therefore inherit the fundamental drawbacks associated with grid dependence, limited stability support, and reduced robustness in low-inertia grids [14–18].

Recently, grid-forming active power filters (GFMC-APFs) have been introduced as an advanced alternative that integrates the grid-support capabilities of GFMCs with the harmonic mitigation functionality of APFs [9]. By operating in grid-forming mode, GFMC-APFs can regulate voltage and frequency while simultaneously presenting a low-impedance path for harmonic components, effectively suppressing harmonic propagation into the upstream grid. This dual functionality not only improves power quality but also enhances system stability by contributing virtual inertia, damping, and short-circuit capacity. However, existing GFMC-APF implementations are predominantly limited to single-unit

systems, which restrict their scalability and practical deployment in networks with high harmonic content or increasing load demand.

Motivated by these challenges, this paper proposes a novel distributed control framework for multiple-parallel GFMC-APFs aimed at achieving scalable harmonic attenuation while preserving grid-forming functionality. Unlike conventional parallel APF solutions, the proposed approach enables each GFMC-APF unit to actively participate in voltage and frequency regulation as well as harmonic mitigation through harmonic voltage reference generation at the PCC. The distributed nature of the control strategy eliminates the need for centralized coordination, high-bandwidth communication, or extensive parameter tuning, thereby maintaining modularity, plug-and-play capability, and scalability. This makes the proposed solution particularly suitable for modern low-inertia and weak-grid environments where robustness and simplicity are critical.

The main contributions of this work can be summarized as follows:

- a. A distributed grid-forming control strategy for multiple-parallel GFMC-APFs that simultaneously enables harmonic attenuation and autonomous voltage and frequency regulation without relying on grid synchronization mechanisms.
- b. An impedance-based dynamic modeling framework for multiple-parallel GFMC-APFs, providing analytical insight into system interactions and stability characteristics under harmonic and nonlinear loading conditions.
- c. Comprehensive simulation-based validation, demonstrating scalable harmonic mitigation, improved power quality, and stable operation under nonlinear load scenarios.

The remainder of this paper is organized as follows. Section 2 introduces the configuration of the multiple-parallel GFMC-APFs system. Section 3 details the proposed distributed control architecture and harmonic voltage reference generation method. Section 4 presents the impedance-based modeling and stability analysis. Section 5 validates the effectiveness of the proposed approach through simulation studies. Finally, Section 6 concludes the paper.

2. System Configuration

The schematic diagram in Figure 2 illustrates the configuration of the proposed multiple-parallel GFMC-APFs system. Each GFMC-APF unit operates as an independent voltage source supplied by a regulated dc-link voltage v_{gdc} , which can be obtained from a battery, dc bus, or renewable interface. The converters are controlled through pulse-width modulation (PWM) to generate the desired output voltage waveforms. Each unit is connected to the grid through an LCL filter, consisting of the converter-side inductor L_{gi} , the filter capacitor C_{gf} , and the grid-side inductor L_{gg} . The primary control objective of each GFMC-APF is to regulate the capacitor voltage v_{gfabc} to control the phase and magnitude of its output, thereby forming a stable voltage at the PCC while compensating harmonic distortions. The nonlinear load connected at the PCC generates harmonic currents i_{labc} , which are detected and compensated by the parallel GFMC-APFs, ensuring harmonic-free grid-injected currents i_{ggabc} . The nonlinear load is modeled as a three-phase diode bridge with a series combination of resistance R_{load} and inductance L_{load} , representing its dynamic behavior. The grid is modeled as a voltage source v_{sabc} in series with grid inductance L_{s} , representing grid impedance. Voltages at the PCC v_{gabc} are measured for synchronization, and the compensating currents are regulated through the control of v_{gfabc} . The parallel operation of multiple GFMC-APFs enhances the total compensation capacity, improves grid stiffness, and enables scalable harmonic attenuation while maintaining voltage and frequency regulation at the PCC.

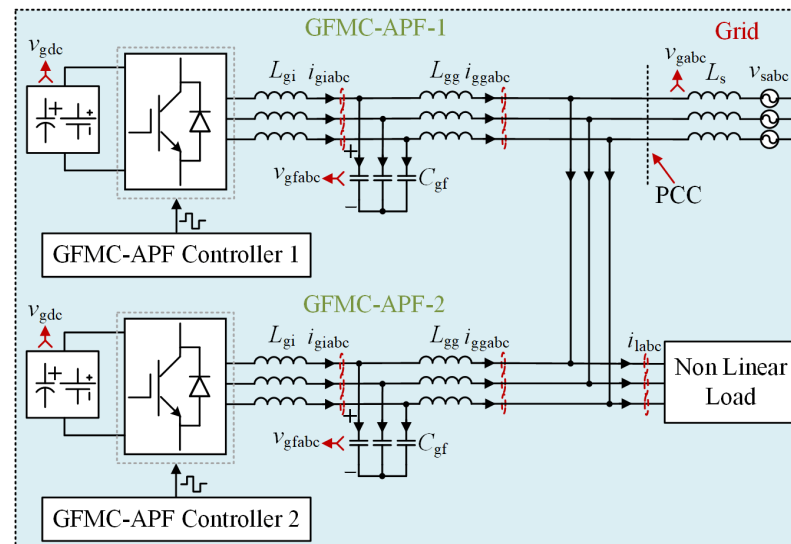


Figure 2. Configuration of the multiple-parallel GFMC-APFs system connected to the grid and nonlinear load through LCL filters.

3. Control Architecture of the Multiple-Parallel GFMC-APF System

The detailed control architecture of the proposed multiple-parallel GFMC-APF system is shown in Figure 3. Compared with conventional grid-following APF control schemes, the proposed structure integrates grid-forming power control, voltage–current regulation, and harmonic reference generation within a unified distributed framework. Each GFMC-APF unit operates autonomously using only local measurements, enabling scalable parallel operation without communication links.

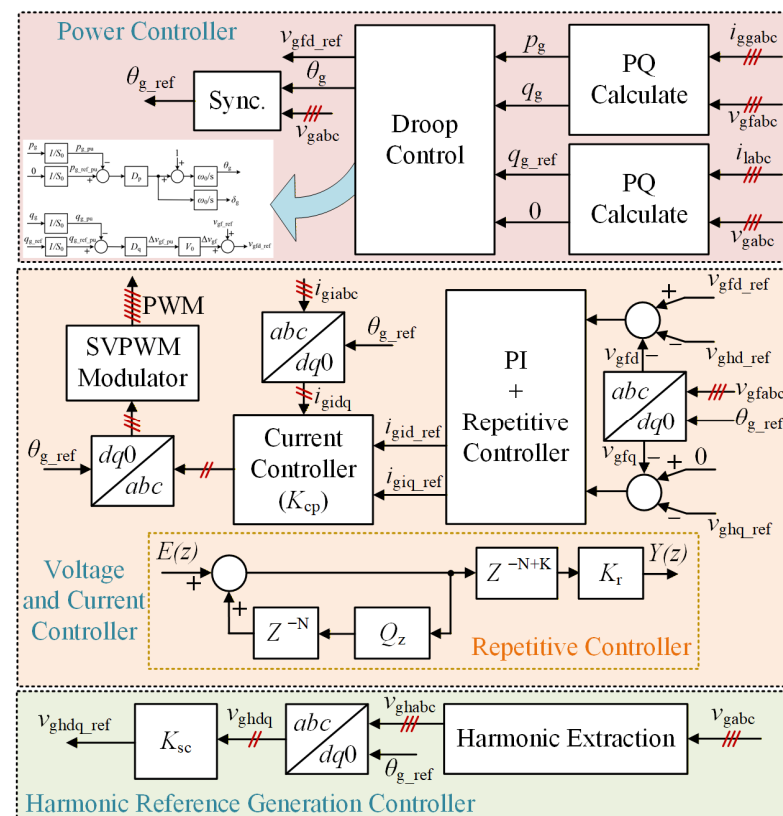


Figure 3. Control structure of the multiple-parallel GFMC-APF system.

The overall control system is composed of three coordinated layers:

- the power controller,
- the voltage and current controller, and
- the harmonic reference generation controller.

3.1. Power Controller

The power controller establishes the grid-forming behavior of each GFMC-APF unit. As shown in the upper part of Figure 3, this controller consists of a synchronization (Sync.) block, active and reactive power calculation (PQ Calculate), and a droop control loop.

The instantaneous active and reactive powers p_g and q_g are computed from the measured filter capacitor voltages v_{gfabc} and grid-side currents i_{ggabc} . These quantities are then compared with the reference values p_{g_ref} and q_{g_ref} to generate the droop-based voltage and frequency commands.

The droop control block implements conventional p - f and q - v droop characteristics, allowing multiple parallel GFMC-APFs to share power proportionally without communication. The control equation for the d -axis reference voltage and dynamic phase shift is given by

$$v_{gfd_ref} = V_0 D_q (q_{g_ref} / S_0 - q_g / S_0) + v_{gfd_ref} \quad (1)$$

$$d\delta_g / dt = \omega_0 D_p (-p_g / S_0) \quad (2)$$

where D_p and D_q are the active and reactive power droop coefficients, respectively. S_0 is the system's base power, ω_0 is the nominal grid frequency and V_0 is the base voltage.

The synchronization block ensures consistent reference frame alignment between the measured PCC voltage and the internally generated phase angle, enabling grid-forming operation without relying on PLL. As a result, each GFMC-APF can independently establish voltage and frequency at the PCC while naturally achieving power sharing under parallel operation.

3.2. Voltage and Current Controller

The voltage and current controller, shown in the middle section of Figure 3, regulates the converter output voltage and current to accurately track the references generated by the power controller and harmonic controller.

The outer voltage control loop regulates the filter capacitor voltages v_{gfabc} , which directly determines the PCC voltages. The measured voltage is transformed into the synchronous dq reference frame using the angle θ_{g_ref} . The fundamental voltage reference v_{gfd_ref} generated by the droop controller is applied on the d -axis, while the q -axis reference is set to zero to ensure unity power factor operation under normal conditions.

To achieve both accurate fundamental voltage regulation and effective harmonic suppression, a combined proportional–integral (PI) and repetitive controller (RC) is employed. The PI controller ensures zero steady-state error and adequate dynamic response for the fundamental component. However, since the PI controller alone has limited gain at harmonic frequencies, a repetitive controller is added in parallel.

The repetitive controller exploits the periodic nature of harmonic disturbances by introducing high gain at integer multiples of the fundamental frequency. Its structure, illustrated in the lower part of Figure 3, consists of a delay operator Z^{-N} , a low-pass filter Q_z , and a gain K_r . This configuration enables selective amplification of periodic error components while maintaining stability. Consequently, the PI–RC voltage controller can simultaneously regulate the fundamental voltage and suppress periodic harmonic distortions at the PCC.

The output of the voltage controller generates the current references $i_{\text{gid_ref}}$ and $i_{\text{giq_ref}}$ for the inner current loop. The inner current control loop regulates the converter-side inductor currents i_{giabc} . The measured currents are transformed into the dq frame and compared with the reference currents from the voltage controller. A proportional current controller with gain K_{cp} is used to ensure fast dynamic response and accurate current tracking.

The decoupled current control structure improves system robustness, limits overcurrent during transients, and reduces the interaction between voltage and current loops. The resulting voltage commands are transformed back to the abc frame and fed into the space vector pulse-width modulation (SVPWM) block. The SVPWM modulator generates the switching signals for the converter, ensuring fixed switching frequency and efficient utilization of the dc-link voltage.

3.3. Harmonic Reference Generation Controller

The harmonic reference generation controller, shown in the bottom section of Figure 3, is a key component distinguishing the proposed GFMC-APF from conventional grid-forming converters. Its primary role is to actively shape the converter's harmonic impedance at the PCC.

The measured PCC voltages v_{gabc} is processed by a harmonic extraction module, which separates the harmonic components from the fundamental voltage. These extracted harmonic voltages are transformed into the synchronous dq frame using the same reference angle $\theta_{\text{g_ref}}$, ensuring consistent phase alignment with the main control loops.

The extracted harmonic voltage components are scaled by the short-circuit coefficient K_{sc} to generate the harmonic voltage reference $v_{\text{ghdq_ref}}$. This coefficient determines the effective harmonic impedance synthesized by each GFMC-APF. A higher K_{sc} corresponds to a lower harmonic impedance, enabling stronger harmonic attenuation.

The harmonic voltage reference is then superimposed on the fundamental voltage reference within the voltage controller. By injecting harmonic voltages with opposite phase to those present at the PCC, each GFMC-APF actively absorbs harmonic currents, effectively behaving as a low-impedance path for harmonic frequencies. When multiple GFMC-APFs operate in parallel, their combined effect significantly reduces the equivalent harmonic impedance at the PCC, preventing harmonic currents from propagating into the upstream grid.

4. Stability Analysis of Multiple-Parallel GFMC-APFs

This section presents an impedance-based stability analysis of the multiple-parallel GFMC-APF system, focusing on the impact of controller parameters and parallel operation on small-signal stability and harmonic interaction between the converters and the grid.

4.1. Impedance Modeling

The simplified control structure of a single GFMC-APF, as shown in Figure 4, consists of a voltage controller, current controller, PWM delay, and an LCL filter. The voltage controller $G_v(s)$ includes both a proportional–integral (PI) and a repetitive controller (RC), expressed as:

$$G_v(s) = G_{\text{PI}}(s) + G_{\text{RC}}(s) \quad (3)$$

$$G_{\text{PI}}(s) = K_{\text{vp}} + \frac{K_{\text{vi}}}{s} \quad (4)$$

$$G_{\text{RC}}(s) = \frac{K_r \cdot e^{-(N_{\text{RC}} - K)sT_s}}{1 - Q_s \cdot e^{-N_{\text{RC}}sT_s}} \quad (5)$$

where K_{vp} and K_{vi} are the proportional and integral gains of the PI controller, respectively; A scaling factor K adjusts the amplitude of harmonic compensation; K_r is the repetitive

controller gain; Q_s is the RC filter coefficient; T_s is the sampling period; and N_{RC} represents the number of samples per fundamental cycle. The PI controller regulates the fundamental voltage, while the RC compensates for periodic harmonic disturbances.

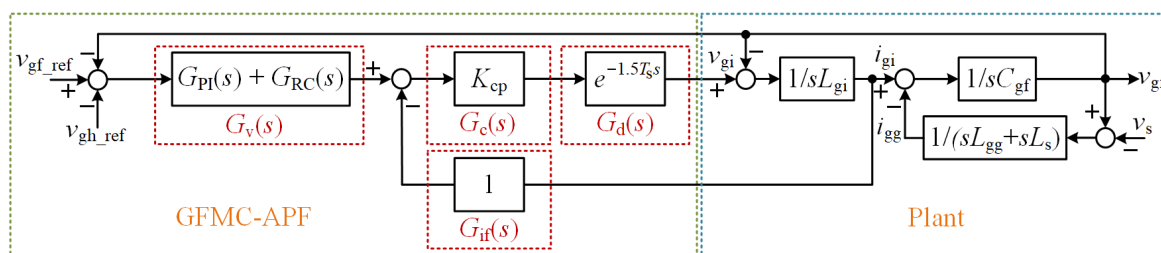


Figure 4. Small-signal impedance model of a single GFMC-APF.

The inner current controller is modeled as $G_c(s) = K_{cp}$, and the total system delay due to computation and PWM modulation is approximated as $G_d(s) = e^{-1.5T_s s}$ [19]. The current control loop also includes a current feedback filter $G_{if}(s)$, set to 1. This allows the current feedback to be directly utilized without additional filtering, ensuring precise and efficient control [20].

The transfer functions of the LCL filter, representing the converter–grid dynamics, are given as:

$$G_{vgf}(s) = \frac{v_{gf}(s)}{v_{gi}(s)} = \frac{L_{gg} + L_s}{s^2(L_{gg} + L_s)L_{gi}C_{gf} + (L_{gi} + L_{gg} + L_s)} \quad (6)$$

$$G_{igg}(s) = \frac{i_{gg}(s)}{v_{gi}(s)} = \frac{s^2(L_{gg} + L_s)C_{gf} + 1}{s^3(L_{gg} + L_s)L_{gi}C_{gf} + s(L_{gi} + L_{gg} + L_s)} \quad (7)$$

when N GFMC-APF units are connected in parallel at the PCC, each converter shares the same grid voltage but contributes its own compensation current. The total injected current is expressed as:

$$i_{gg,total}(s) = \sum_{n=1}^N i_{gg,n}(s) = N \cdot G_{igg}(s) v_{gi}(s) \quad (8)$$

Hence, the equivalent impedance of the multiple-parallel GFMC-APFs becomes:

$$Z_{GFMC,total}(s) = \frac{Z_{GFMC}(s)}{N} \quad (9)$$

This relationship indicates that as the number of GFMC-APF units increases, the equivalent harmonic impedance decreases proportionally, thereby improving harmonic attenuation capability.

The open-loop transfer function for a single GFMC-APF can be written as:

$$G_{ol}(s) = \frac{G_v(s)K_{cp}G_d(s)s(L_{gg} + L_s)}{s^3(L_{gg} + L_s)L_{gi}C_{gf} + s^2K_{cp}G_d(s)C_{gf}(L_{gg} + L_s) + s(L_{gg} + L_s + L_{gi}) + K_{cp}G_d(s)} \quad (10)$$

The corresponding closed-loop transfer function can be written in the standard control form as:

$$G_{cl}(s) = \frac{G_{ol}(s)}{1 + G_{ol}(s)} \quad (11)$$

Therefore, the open-loop transfer function of the multi-unit configuration can be approximated as:

$$G_{ol,total}(s) = N \cdot G_{ol}(s) \quad (12)$$

Although this enhances harmonic suppression, it simultaneously reduces the system's gain margin and phase margin, potentially leading to oscillatory behavior when multiple units operate in parallel if the control parameters are not properly coordinated.

4.2. Stability Analysis

The stability behavior of the multiple-parallel GFMC-APF system is examined using the impedance-based open-loop model. The analysis is performed for different numbers of parallel converters ($N = 1$ – 5) to observe the variation in system stability as additional units are introduced. The current controller proportional gain, voltage controller proportional gain, and voltage controller integral gain are set to $K_{cp} = 0.1$, $K_{vp} = 0.14$, and $K_{vi} = 60$, respectively. These parameters are chosen to ensure stable operation with adequate bandwidth for harmonic compensation and voltage regulation.

Figure 5 presents the open-loop Bode response of the system using only the PI-based voltage controller. As the number of GFMC-APFs increases, the overall system impedance decreases and the loop gain proportionally rises, resulting in reduced gain and phase margins. This occurs because parallel operation amplifies the collective feedback interaction among converters, increasing sensitivity to control delay and parameter mismatch. The current-loop gain K_{cp} defines the system bandwidth, while the integral gain K_{vi} governs the low-frequency gain and phase margin. A higher K_{vi} improves steady-state voltage accuracy but narrows the phase margin, whereas a lower K_{vi} enhances small-signal stability and damping. After systematic tuning, the gains $K_{cp} = 0.1$, $K_{vp} = 0.2$, and $K_{vi} = 10$ are selected. These values provide sufficient low-frequency gain for accurate voltage regulation while preserving an acceptable phase margin and ensuring stable small-signal behavior across all paralleled GFMC-APFs.

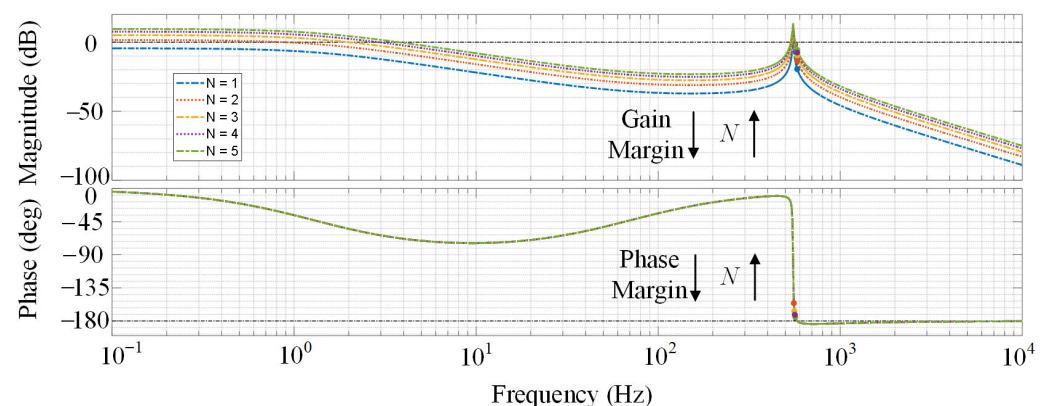


Figure 5. Open-loop Bode plot with PI control showing reduced gain and phase margins as parallel units increase.

Figure 6 presents the open-loop Bode response of the system when the RC is incorporated alongside the PI-based voltage controller. Without the RC, the system exhibits limited harmonic compensation; however, activating the RC introduces distinct harmonic peaks at integer multiples of the fundamental frequency, demonstrating selective gain enhancement and effective suppression of periodic disturbances. As the RC gain K_r increases from 0.1 to 0.3 and 0.5, harmonic rejection improves accordingly, but the gain margin decreases, indicating increased sensitivity of the system to stability constraints. Moreover, using $Q_z = 1$ as the internal filter is unsuitable because it integrates the error and drives the controller toward instability. To mitigate excessive gain near the critical frequency, Q_z must be selected slightly below unity; therefore, $Q_z = 0.99$ is chosen to ensure adequate filtering without compromising dynamic response. Based on this analysis, and to achieve an optimal balance between harmonic suppression and small-signal stability, $K_r = 0.22$ is

selected after careful consideration. With these tuned values of K_r and Q_z , the combined PI–RC structure delivers accurate voltage regulation, robust harmonic attenuation, and stable parallel operation of the GFMC–APF system.

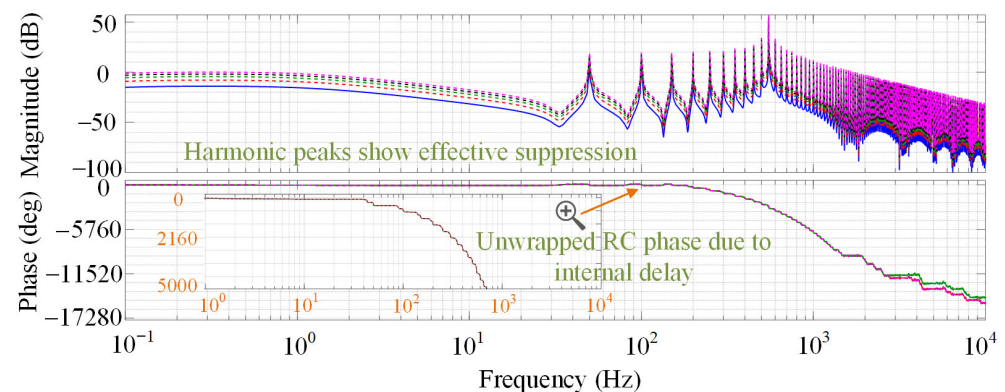


Figure 6. Open-loop Bode plot with PI–RC control exhibiting harmonic peaks at integer multiples of the fundamental frequency.

In Figure 7, the Bode plot shows the closed-loop frequency response of multiple-parallel grid-forming active power filters as the number of units increases from $N = 1$ to $N = 5$. At low frequencies (<100 Hz), all cases display a flat magnitude response with minimal phase shift, indicating strong tracking performance independent of N . At higher frequencies, the single-unit case exhibits a clear resonant peak, reflecting limited damping. As additional units are added, this resonance is progressively suppressed: the peak amplitude decreases, the response becomes smoother, and high-frequency attenuation improves. The phase behavior also steadies, with $N = 4$ and $N = 5$ showing notably higher phase margins. Overall, increasing the number of parallel units enhances damping, reduces resonance effects, and improves closed-loop stability while maintaining good low-frequency performance.

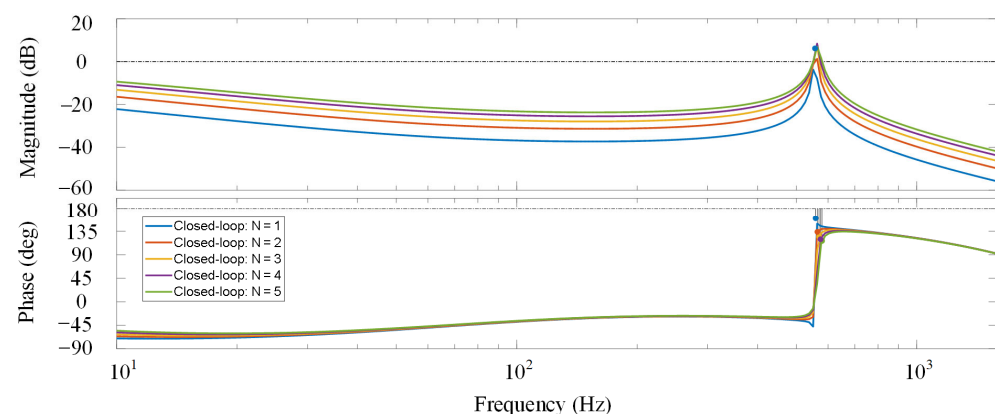


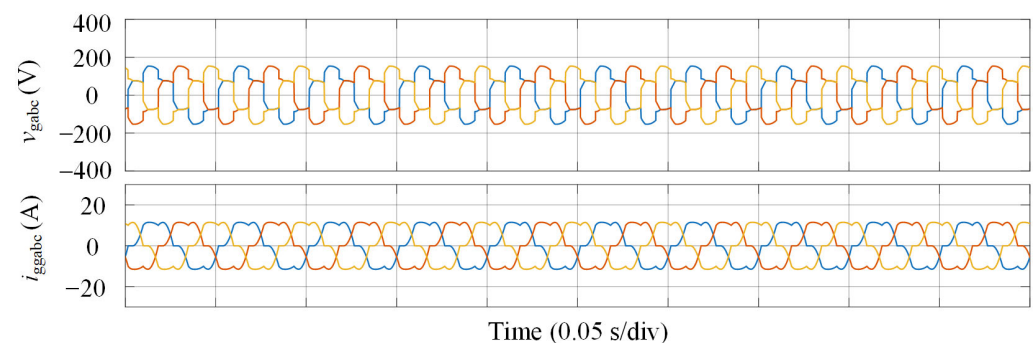
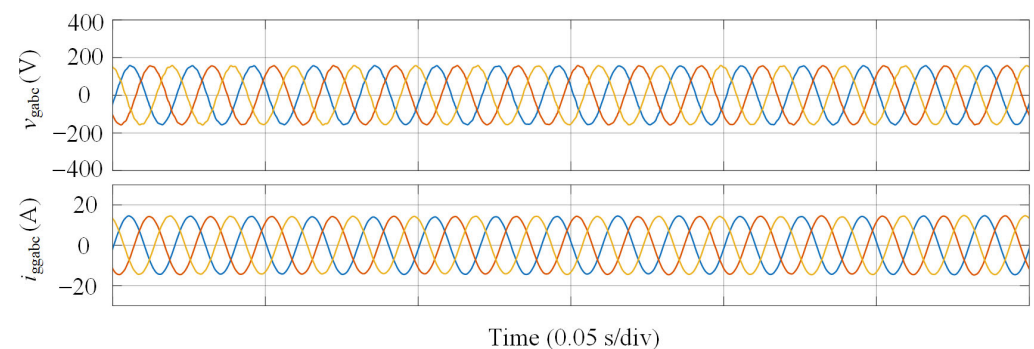
Figure 7. Closed-loop dynamics for varying numbers of multiple-parallel GFMC–APFs with PI Control.

5. Simulation Results

Simulations in MATLAB/Simulink (R2024a) validate the performance of the proposed multiple-parallel GFMC–APFs in harmonic suppression, power regulation, and improvement of PCC voltage and grid current quality, as shown in Figures 8–13. The system and control parameters used in the analysis are listed in Table 1.

Table 1. System and Control Parameters.

Description	Symbol	Value
Nominal dc voltage	V_{dc}	400 V
Grid voltage	V_s	110 Vrms
Nominal frequency	f_0	50 Hz
Switching frequency	f_{sw}	10 kHz
Line inductor	L_s	10 mH
Grid resistance	R_s	0.1 Ω
Load inductor	L_{load}	1 mH
Load resistance	R_{load}	20 Ω
Active power reference	P_{g_ref}	0 W
Filter Parameters for Inverter 1 & 2		
Converter-side inductor	L_{gi}	2 mH
Grid-side inductor	L_{gg}	4 μ H
Filter capacitance	C_{gf}	50 μ F
Control Parameters for Inverter 1 & 2		
Active power droop gain	D_p	2.85×10^{-3}
Reactive power droop gain	D_q	14.2×10^{-3}
Voltage controller P gain	K_{vp}	0.2
Voltage controller I gain	K_{vi}	10
Current controller P gain	K_{cp}	0.1
RC scaling factor	K	6
RC gain	K_r	0.22
RC filter coefficient	Q_z	0.99
Short-circuit coefficient	K_{sc}	0.1

**Figure 8.** PCC voltage and current waveforms before activating multiple-parallel GFMC-APFs, showing distortion from nonlinear load.**Figure 9.** PCC voltage and current waveforms after activation of multiple-parallel GFMC-APFs, showing harmonic suppression and waveform restoration.

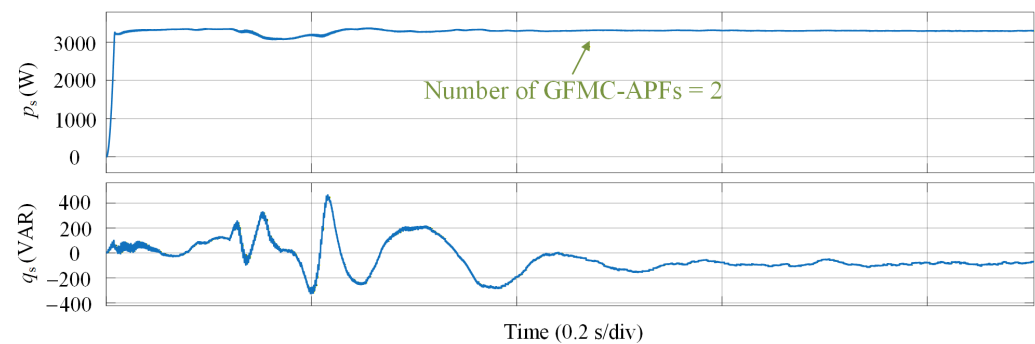


Figure 10. Active and reactive power responses of the two-parallel GFMC-APFs showing stable power regulation after transient disturbances.

Figure 8 presents the grid voltage v_{gabc} and grid current i_{ggabc} waveforms before activating the multiple-parallel GFMC-APFs. Significant distortion can be observed in both voltage and current due to the nonlinear load injecting harmonic currents into the grid. The grid voltages exhibit notches and waveform irregularities, while the grid currents show strong low-order harmonic distortion, mainly from the 3rd, 5th, and 7th components. These results highlight the degraded power quality and the necessity for coordinated operation of multiple-parallel GFMC-APFs to achieve effective harmonic attenuation and maintain grid voltage quality.

Figure 9 shows the grid voltage v_{gabc} and grid current i_{ggabc} waveforms after activation of the multiple-parallel GFMC-APFs. Once the APFs operate, both voltage and current waveforms become nearly sinusoidal, indicating effective harmonic compensation. The distortions observed earlier are eliminated as the multiple-parallel GFMC-APFs inject compensating voltages at the PCC, creating a near short-circuit path for harmonic currents. As a result, the grid current becomes balanced and synchronized with the grid voltage, confirming improved power quality.

Figure 10 illustrates the dynamic performance of a system utilizing two parallel GFMC-APFs. The top graph shows active power stabilizing around 3000 W after an initial drop, demonstrating the multiple-parallel GFMC-APFs ability to maintain precise active power regulation despite initial disturbances. The bottom graph depicts reactive power fluctuating between approximately -400 VAR and $+400$ VAR before stabilizing at around -100 VAR, highlighting the multiple-parallel GFMC-APFs effective regulation of reactive power. This stabilization enhances system efficiency and reduces the grids burden.

Figure 11 depicts the semi-logarithmic harmonic spectra of v_{gabc} and i_{ggabc} , illustrating the performance of multiple-parallel GFMC-APFs in ensuring compliance with IEEE Std. 519-2014 [21]. The top graph shows the harmonic spectrum for v_{gabc} with a fundamental frequency of 50 Hz and a THD of 1.25%, which is well below the allowable 8% limit. The bottom graph presents the harmonic spectrum for i_{ggabc} with a fundamental frequency of 50 Hz and a THD of 0.35%, significantly under the 4% threshold. These results highlight the effectiveness of the multiple-parallel GFMC-APFs in harmonic suppression, ensuring high power quality by effectively reducing harmonic distortions compared to the unmitigated case.

Figure 12 demonstrates the grid-forming capabilities of the multiple-parallel GFMC-APFs, maintaining stability while suppressing harmonics from the nonlinear load and responding effectively to load changes. The voltage loop with a slow dynamic response will cause coupling between the outer power control loop and the inner voltage control loop, which is visible in the first interval of operation. When the nonlinear load is applied, the GFMC-APFs inject compensating currents that suppress harmonic distortion and preserve the grid-forming voltage waveform. During the load-change interval, the transient current

response and rapid settling show strong disturbance rejection and continued harmonic mitigation. Overall, the behavior confirms stable grid-forming operation supported by virtual inertia and damping.

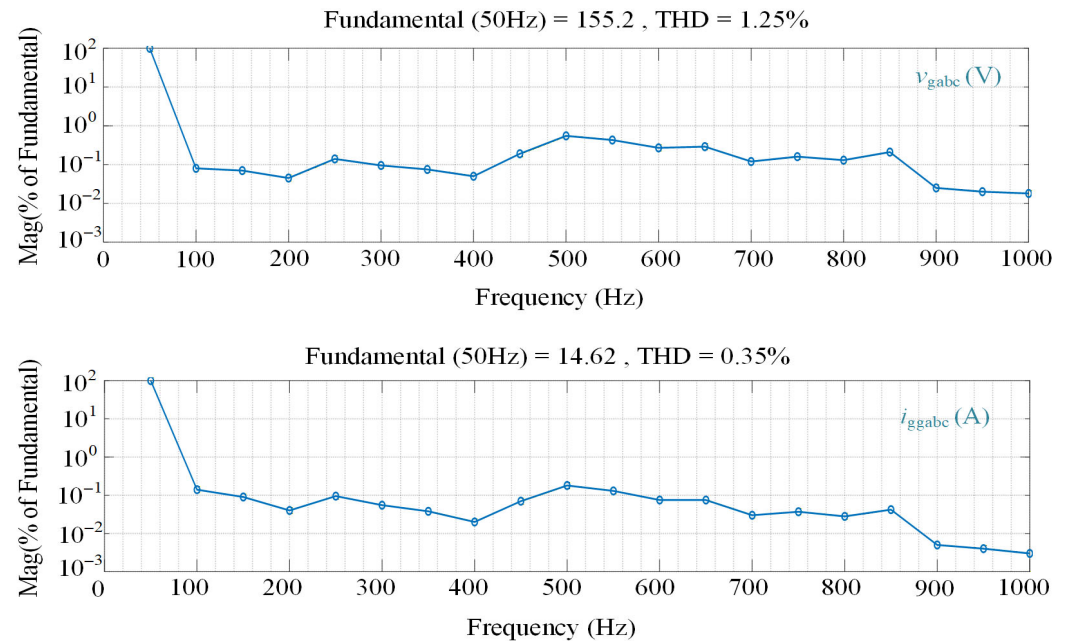


Figure 11. Semi-logarithmic harmonic spectra of grid voltage and current showing effective harmonic suppression by multiple-parallel GFMC-APFs in compliance with IEEE Std. 519-2014.

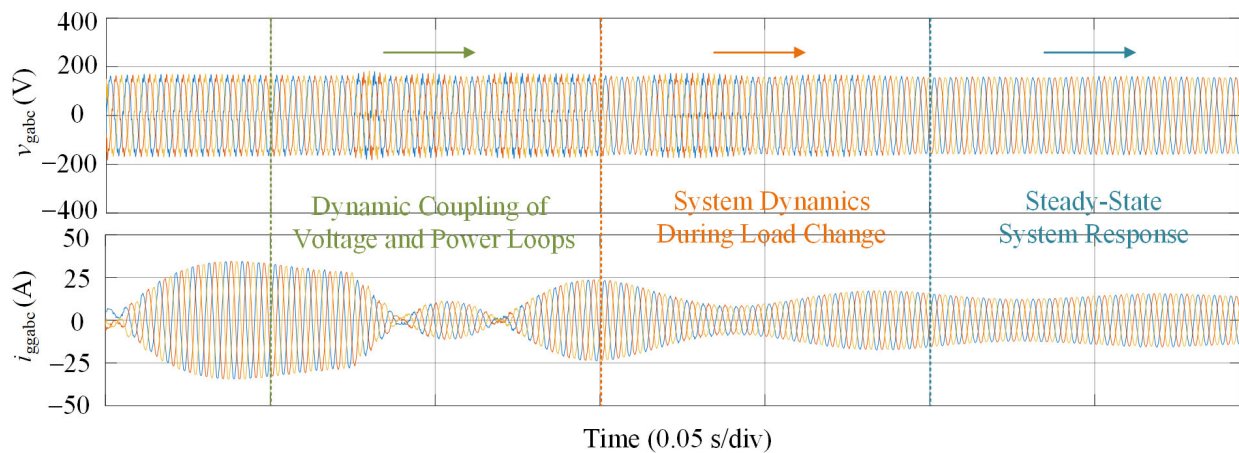


Figure 12. Grid-forming response of multiple-parallel GFMC-APFs under loop coupling and load disturbances.

Figure 13 shows the harmonic spectrum of v_{gabc} , highlighting both harmonic and supra-harmonic components. The 50 Hz fundamental is dominant, while low-order harmonics remain well suppressed. The clusters appearing between roughly 1–4 kHz represent supra-harmonic emissions associated with converter switching and nonlinear load interaction. These components contribute only slightly to the overall distortion, resulting in a low THD of 1.28%. Above 5 kHz, the supra-harmonic content decays rapidly and remains negligible up to 20 kHz, demonstrating effective high-frequency filtering by the GFMC-APF system.

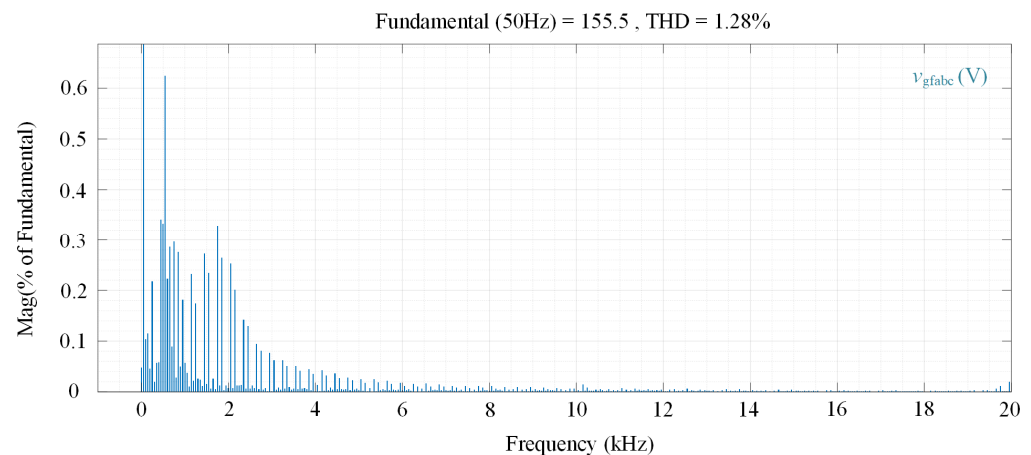


Figure 13. Harmonic spectrum of v_{gfabc} with supra-harmonic components.

6. Conclusions

This paper presents a distributed control strategy for multiple-parallel GFMC-APFs to mitigate harmonic distortion in low-inertia grids with nonlinear loads. The proposed method enables each parallel unit to extract harmonic components at the PCC and generate compensating voltage references, such that the parallel GFMC-APFs collectively synthesize a near short-circuit equivalent impedance for harmonic frequencies while simultaneously regulating voltage, frequency, and power sharing. Unlike conventional grid-following APFs or single-unit GFMC-APFs, the harmonic mitigation capability of the proposed system scales naturally with the number of parallel units without requiring communication or centralized coordination. An impedance-based analytical model is developed to characterize the stability behavior of the parallel configuration. Simulation results verify effective power regulation and significant power quality improvement, with PCC voltage and grid current THDs reduced to 1.25% and 0.35%, respectively, fully complying with IEEE Std. 519-2014. The proposed approach provides a modular, scalable, and robust solution for harmonic suppression in future converter-dominated and weak-grid power systems.

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