

Innovative Coordination Control Approach for Enhancing Grid-Connected Inverters' Resilience to Voltage Unbalance

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Abstract:

Voltage unbalance in electrical grids presents a substantial challenge that directly impacts the operational efficiency and reliability of grid-connected inverters, which are integral for the seamless integration of renewable energy resources. In response to this issue, this paper develops a sophisticated coordinated control strategy that harnesses the dynamic synchronization capabilities of the d-q rotating coordinate system, specifically designed to counteract grid fluctuations. This innovative approach facilitates the meticulous regulation of both active and reactive power through a synergistic integration of advanced power management techniques and adaptive tuning mechanisms, thereby significantly enhancing the system's responsiveness and overall reliability. The strategy's effectiveness in substantially improving the fault ride-through capabilities of grid-connected inverters, even under conditions of marked voltage unbalance, is rigorously validated through a series of comprehensive experimental procedures. The findings represent a pivotal advancement in the field, underscoring the novel application of dynamic synchronization techniques within the context of grid-connected inverters. By offering an advanced control solution that markedly improves the resilience and stability of grid-connected inverters, this work makes a significant contribution to the existing body of knowledge, addressing a critical gap in the literature and paving the way for future research in this area. The implications of this study are far-reaching, providing a robust framework for enhancing the integration of renewable energy sources into the power grid, thereby supporting the global transition towards sustainable energy systems.

Keywords: grid-connected inverters, voltage unbalance, decoupled double synchronous reference frame, coordination control strategy, positive and negative sequence separation

INTRODUCTION

The inception of grid-connected inverters heralds a pivotal evolution in the energy landscape, underscored by their integral role in the seamless integration of renewable resources. These devices transcend conventional conversion functions, serving as the linchpin in the dynamic energy exchange between renewable sources and the grid, thus catalyzing a sustainable energy transition [1]. Central to the efficacy of the modern energy grid, grid-connected inverters adeptly transmute the variable direct current (DC) output from renewable sources, such as solar arrays and wind farms, into a consistent alternating current (AC), meticulously aligned with the grid's voltage and frequency specifications. Moreover, these inverters are paramount in upholding power supply integrity and reliability, significantly contributing to grid stabilization through power quality management, voltage regulation, and the provision of essential ancillary services, including frequency adjustment and reactive power compensation [2].

However, the assimilation of renewable energies, albeit favorable for sustainability, begets challenges to grid equilibrium, notably voltage unbalance. Manifested through disparities in the amplitude and phase angle of the grid's tri-phase voltage, voltage unbalance emerges as a common grid affliction, exacerbated by the disproportionate distribution of single-phase renewable installations and other loads [3]. Such imbalances impair grid-connected inverters, precipitating operational inefficiencies, escalated component wear, and premature failures, thereby compromising power infrastructure reliability. Furthermore, voltage unbalance aggravates power quality issues, inducing harmonic distortions, flicker, and diminishing the efficiency of grid-connected devices, culminating in heightened operational expenses and energy dissipation [4].

Traditional inverter control paradigms, though adept under balanced conditions, falter in addressing the multifaceted nature of unbalanced grid scenarios, often failing to ameliorate voltage unbalance effects, thus detrimentally impacting inverter functionality and grid stability [5]. This underscores the imperative for advanced

control mechanisms, adept at intelligently navigating and rectifying voltage imbalances, thereby bolstering inverter operation under unbalanced conditions and enhancing grid resilience, facilitating the sustainable integration of renewable energy sources [6].

Addressing voltage unbalance challenges, this study unveils an innovative control approach, leveraging the advanced capabilities of the d-q rotating coordinate system, aimed at reinforcing grid-connected inverters' fault ride-through capabilities and operational resilience amidst voltage imbalances. Anchored in dynamic synchronization and adaptive control principles, this strategy presents a state-of-the-art solution to mitigate voltage unbalance repercussions on inverter performance. This novel strategy's hallmark lies in its dynamic adaptability to fluctuating grid conditions, facilitated by continuous voltage parameter monitoring. Upon unbalance detection, it initiates a bespoke response, adjusting control parameters to counteract the unbalance. Enabled by the d-q rotating coordinate system, it adeptly decomposes grid voltage into direct and quadrature components, allowing precise management of voltage sequence components, crucial for addressing voltage unbalances.

Emphasizing fault ride-through enhancement, this strategy ensures inverter continuity and power delivery during voltage perturbations, significantly bolstering energy system resilience. This aspect is especially vital for grids with substantial renewable energy contributions, where supply intermittency further strains grid stability. Empirical validation, through comprehensive simulation and field trials, corroborates the control strategy's effectiveness in augmenting grid-connected inverters' fault ride-through capabilities. These findings highlight the strategy's potential in elevating inverter reliability and efficiency amidst pronounced voltage unbalances, thus marking a significant contribution to power electronics and grid management disciplines, offering a pragmatic resolution to a critical challenge in renewable energy source integration.

MATHEMATICAL MODEL OF LCL-TYPE GRID-CONNECTED INVERTERS UNDER UNBALANCED GRID VOLTAGE

Decomposition of Positive and Negative Sequences under Unbalanced Grid Voltage

The architectural design of a three-phase LCL grid-tied inverter is illustrated in Figure 1, showcasing the following components: The direct current (DC) voltage output from solar panels, after undergoing elevation through a Boost converter circuit, is denoted by u_{dc} . The inductor on the side of the inverter, labeled L_1 , is accompanied by its inherent resistance R_1 . Conversely, L_2 represents the inductance on the side connecting to the electrical grid, with R_2 indicating its intrinsic resistance. The capacitor employed for filtration purposes is represented by C , and R_d refers to a resistor utilized for passive damping. The switching elements within the three-phase inverter are identified as VT_1 through VT_6 , and the voltage across the three-phase electrical network is symbolized by u_g . This detailed description encapsulates the critical elements and their interconnections within the LCL inverter system designed for seamless integration with the power grid) [7-9].

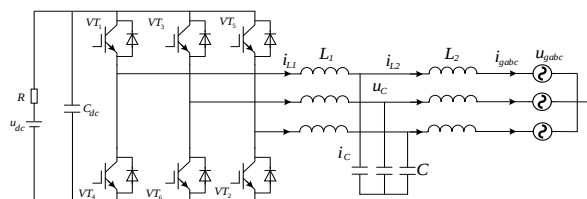


Figure 1. Main circuit of three-phase LCL type grid-connected inverter

In practical applications, the presence of voltage unbalances within three-phase electrical networks is a prevalent issue, exerting a profound influence on the operational efficiency of photovoltaic (PV) systems. Such imbalances are characterized by the presence of distinct positive and negative sequence components. Given the absence of zero-sequence components in three-phase systems devoid of a neutral conductor, it becomes imperative to decompose the unbalanced grid voltages into their respective positive and negative sequence constituents, as delineated in Equation (1) [10].

$$\begin{bmatrix} u_{ga} \\ u_{gb} \\ u_{gc} \end{bmatrix} = \begin{bmatrix} u_{ga}^p + u_{ga}^n \\ u_{gb}^p + u_{gb}^n \\ u_{gc}^p + u_{gc}^n \end{bmatrix} = E_m^p \begin{bmatrix} \cos(\omega t + \varphi^p) \\ \cos(\omega t + \varphi^p - 2\pi/3) \\ \cos(\omega t + \varphi^p + 2\pi/3) \end{bmatrix} + E_m^n \begin{bmatrix} \cos(\omega t + \varphi^n) \\ \cos(\omega t + \varphi^n + 2\pi/3) \\ \cos(\omega t + \varphi^n - 2\pi/3) \end{bmatrix} \quad (1)$$

In this context, E_m^p ; E_m^n respectively signify the peak values of the positive and negative sequence components of the grid voltage, while φ^p ; φ^n denote their initial phase angles. The symbol ω is utilized to represent the angular frequency of the grid.

In the context of three-phase AC power systems, where the system's variables are inherently alternating in nature, the physical significance of the model becomes clear within the static three-phase (abc) coordinate system. However, to convert these variables into direct current quantities, a coordinate transformation is essential. This becomes particularly crucial when addressing issues of voltage imbalance in the electrical grid, especially when it involves the positive and negative sequence components. An advanced approach to navigate these complex scenarios is imperative. This method encompasses two pivotal steps: initially, the unbalanced three-phase voltage of the grid is transformed into the static α - β coordinate system, facilitating subsequent analysis. Subsequently, the voltages within this α - β framework are further translated into two distinct rotating coordinate systems, specifically the positive and negative sequence d-q coordinate systems. Such transformations not only streamline the handling of unbalanced grid voltages but also clarify the separation and analysis of the positive and negative sequence components, enhancing the precision and clarity of the assessment [11].

Initially, Equation (1) is subjected to a Clark transformation, projecting it onto the two-dimensional stationary α - β coordinate system. Within this framework, the three-phase grid voltage is articulated as delineated in Equation (2), offering a streamlined representation conducive to further analytical processes.

$$\begin{bmatrix} u_{g\alpha} \\ u_{g\beta} \end{bmatrix} = \begin{bmatrix} u_{g\alpha}^p + u_{g\alpha}^n \\ u_{g\beta}^p + u_{g\beta}^n \end{bmatrix} = E_m^p \begin{bmatrix} \cos(\omega t + \varphi^p) \\ \sin(\omega t + \varphi^p) \end{bmatrix} + E_m^n \begin{bmatrix} \cos(-\omega t + \varphi^n) \\ \sin(-\omega t + \varphi^n) \end{bmatrix} \quad (2)$$

At this juncture, the voltage magnitudes remain in alternating current form. Subsequently, Equation (2) is transformed into the d-q coordinates of both positive and negative sequences within a dual synchronous rotating frame, thus allowing the representation of three-phase unbalanced grid voltage as depicted in Equation (3).

$$\begin{bmatrix} u_{gd}^p \\ u_{gq}^p \\ u_{gd}^n \\ u_{gq}^n \end{bmatrix} = E_m^p \begin{bmatrix} \cos(\omega t + \varphi^p - \theta) \\ \sin(\omega t + \varphi^p - \theta) \\ \cos(\omega t + \varphi^p + \theta) \\ \sin(\omega t + \varphi^p + \theta) \end{bmatrix} + E_m^n \begin{bmatrix} \cos(-\omega t + \varphi^n - \theta) \\ \sin(-\omega t + \varphi^n - \theta) \\ \cos(-\omega t + \varphi^n + \theta) \\ \sin(-\omega t + \varphi^n + \theta) \end{bmatrix} \quad (2)$$

In this context, θ denotes the angle between the positive sequence voltage vector of the grid and the d-axis of the positive sequence d-q coordinate system in the positively rotating reference frame with respect to the α axis. For simplification during stable system conditions, it is assumed that $\theta = \omega t$ and $\varphi^p = 0$, thereby reducing Equation (3) to a more simplified form as presented in Equation (4).

$$\begin{bmatrix} u_{gd}^p \\ u_{gq}^p \\ u_{gd}^n \\ u_{gq}^n \end{bmatrix} = E_m^p \begin{bmatrix} 1 \\ 0 \\ \cos(2\omega t) \\ \sin(2\omega t) \end{bmatrix} + E_m^n \begin{bmatrix} \cos(-2\omega t + \varphi^n) \\ \sin(-2\omega t + \varphi^n) \\ \cos(\varphi^n) \\ \sin(\varphi^n) \end{bmatrix} \quad (4)$$

In the dual synchronous rotating d-q coordinate system, the composite vector of the grid voltage is represented as shown in Equation (5), following the simplifications and transformations applied to the initial conditions.

$$\mathbf{U}_{gdq} = e^{j\omega t} \mathbf{u}_{gdq}^p + e^{-j\omega t} \mathbf{u}_{gdq}^n \quad (5)$$

In this formulation, $\mathbf{u}_{gdq}^p$ denotes the magnitude of the grid's positive sequence voltage vector, while $\mathbf{u}_{gdq}^n$ encapsulates the negative sequence vector, representing a refined understanding of the grid voltage dynamics in terms of its sequential components. To elaborate further, as illustrated in Equation (6), the positive and negative

sequence vectors can be expressed in terms of their respective components within the positive and negative sequence rotating coordinate systems.

$$\mathbf{u}_{gdq}^p = u_{gd}^p + ju_{gq}^p, \quad \mathbf{u}_{gdq}^n = u_{gd}^n + ju_{gq}^n \quad (6)$$

From Equations (4) ; (5) and (6), Equation (7) can be derived.

$$\begin{aligned} \mathbf{u}_{gdq}^p &= E_m^p \begin{bmatrix} 1 \\ 0 \end{bmatrix} + E_m^n \begin{bmatrix} \cos(-2\omega t) \cos \phi^n - \sin(-2\omega t) \sin \phi^n \\ \sin(-2\omega t) \cos \phi^n + \cos(-2\omega t) \sin \phi^n \end{bmatrix} \\ &= E_m^p \begin{bmatrix} 1 \\ 0 \end{bmatrix} + E_m^n \cos \phi^n \begin{bmatrix} \cos(-2\omega t) \\ \sin(-2\omega t) \end{bmatrix} + E_m^n \sin \phi^n \begin{bmatrix} -\sin(-2\omega t) \\ \cos(-2\omega t) \end{bmatrix} \end{aligned} \quad (7)$$

Similarly, Equation (8) can be obtained.

$$\mathbf{u}_{gdq}^n = E_m^n \begin{bmatrix} \cos(\phi^n) \\ \sin(\phi^n) \end{bmatrix} + E_m^p \begin{bmatrix} \cos(2\omega t) \\ \sin(2\omega t) \end{bmatrix} \quad (8)$$

Drawing from Equations (7) and (8), a decoupling network can be established to facilitate the extraction of positive and negative sequence components and the locking of the positive sequence phase. This technique is referred to as the Decoupled Double Synchronous Rotating Frame (DDSRF) method for sequence extraction, as depicted in Figure 2. The decoupling action effectively eliminates the second harmonics caused by three-phase asymmetry, achieving precise extraction and phase locking of the grid voltage's positive and negative sequences [12-16].

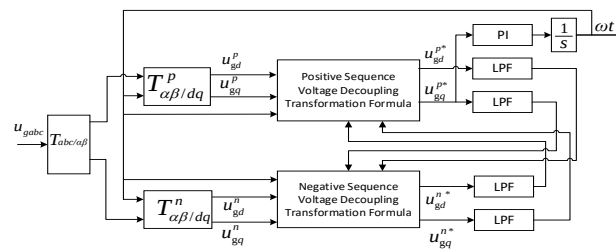


Figure 2. DDSRF-PLL structural block diagram

Similarly, the grid current equation (9) can be derived through analogous reasoning.

$$\begin{bmatrix} i_{gd}^p \\ i_{gq}^p \\ i_{gd}^n \\ i_{gq}^n \end{bmatrix} = I_m^p \begin{bmatrix} 1 \\ 0 \\ \cos(2\omega t) \\ \sin(2\omega t) \end{bmatrix} + I_m^n \begin{bmatrix} \cos(-2\omega t + \gamma^n) \\ \sin(-2\omega t + \gamma^n) \\ \cos(\gamma^n) \\ \sin(\gamma^n) \end{bmatrix} \quad (9)$$

In this formulation, γ^p, γ^n respectively denote the initial phase angles of the positive and negative sequence components of grid current. Consequently, within the dual-axis (dq) synchronous rotating coordinate system, the composite vector of grid current is represented as outlined in Equation (10).

$$\mathbf{I}_{gdq} = e^{j\omega t} \mathbf{i}_{gdq}^p + e^{-j\omega t} \mathbf{i}_{gdq}^n \quad (10)$$

$\mathbf{i}_{gdq}^p$ is the positive sequence vector of grid current, $\mathbf{i}_{gdq}^n$ is the negative sequence vector of grid current. To elaborate further, as illustrated in Equation (11), the positive and negative sequence vectors can be expressed in terms of their respective components within the positive and negative sequence rotating coordinate systems) [17,18].

$$\mathbf{i}_{gdq}^p = i_{gd}^p + ji_{gq}^p, \quad \mathbf{i}_{gdq}^n = i_{gd}^n + ji_{gq}^n \quad (11)$$

Mathematical Model of LCL-Type Grid-Connected Inverter under Unbalanced Grid Voltage Conditions

In the context of LCL-type inverters, the mathematical model within the two-phase (dq) synchronous rotating coordinate system is characterized by Equation (12), which represents the equation for the current on the inverter side.

$$\frac{d}{dt} \begin{bmatrix} i_{1dq}^p \\ i_{1dq}^n \end{bmatrix} = \frac{1}{L_1} \begin{bmatrix} u_{dq}^p - u_{cdq}^p - R_d(i_{1dq}^p - i_{2dq}^p) - R_1 i_{1dq}^p \\ u_{dq}^n - u_{cdq}^n - R_d(i_{1dq}^n - i_{2dq}^n) - R_1 i_{1dq}^n \end{bmatrix} + \begin{bmatrix} \pm\omega & 0 \\ 0 & \mp\omega \end{bmatrix} \begin{bmatrix} i_{1qd}^p \\ i_{1qd}^n \end{bmatrix} \quad (12)$$

In the framework of grid-connected systems, the current equation for the grid side is delineated by Equation (13), illustrating the dynamics of current flow from the perspective of the grid interface.

$$\frac{d}{dt} \begin{bmatrix} i_{2dq}^p \\ i_{2dq}^n \end{bmatrix} = \frac{1}{L_2} \begin{bmatrix} u_{cdq}^p - e_{dq}^p - R_d(i_{1dq}^p - i_{2dq}^p) - R_2 i_{2dq}^p \\ u_{cdq}^n - e_{dq}^n - R_d(i_{1dq}^n - i_{2dq}^n) - R_2 i_{2dq}^n \end{bmatrix} + \begin{bmatrix} \pm\omega & 0 \\ 0 & \mp\omega \end{bmatrix} \begin{bmatrix} i_{2qd}^p \\ i_{2qd}^n \end{bmatrix} \quad (13)$$

For the direct current (DC) side of the system, the voltage equation of the filtering capacitor C is methodically encapsulated in Equation (14), providing a mathematical representation of the voltage characteristics across the capacitor within the DC circuitry.

$$\frac{d}{dt} \begin{bmatrix} u_{cdq}^p \\ u_{cdq}^n \end{bmatrix} = \frac{1}{C} \begin{bmatrix} i_{1dq}^p - i_{2dq}^p \\ i_{1dq}^n - i_{2dq}^n \end{bmatrix} + \begin{bmatrix} \pm\omega & 0 \\ 0 & \mp\omega \end{bmatrix} \begin{bmatrix} u_{cdq}^p \\ u_{cdq}^n \end{bmatrix} \quad (14)$$

At low frequencies, the LCL converter exhibits similar filtering characteristics as the L-type converter. For mathematical analysis, the LCL converter is treated as an equivalent single inductor L-type filter, where $L=L_1+L_2$ represents the total inductance and $R=R_1+R_2$ denotes the aggregate parasitic resistance. The passive damping resistance R_d can be emulated through active damping techniques. In decoupling control, to simplify the control system complexity and to address low-frequency dynamics effectively, while ensuring high-frequency resonances are managed through built-in or external damping methods, the impact of the filtering capacitor C is often neglected, especially when the primary objective is to enhance current waveform quality through inductive components. Applying the Laplace transform to Equations (12), (13), and (14), the mathematical model of the LCL grid-connected inverter under unbalanced grid conditions can be derived, as depicted in Equation (15) [19,20].

$$\begin{cases} (sL + R)I_{gd}^p = U_d^p + \omega LI_{gq}^p - U_{gd}^p \\ (sL + R)I_{gq}^p = U_q^p - \omega LI_{gd}^p - U_{gq}^p \\ (sL + R)I_{gd}^n = U_d^n - \omega LI_{gq}^n - U_{gd}^n \\ (sL + R)I_{gq}^n = U_q^n + \omega LI_{gd}^n - U_{gq}^n \end{cases} \quad (15)$$

From Equation (15), it is possible to construct the structural block diagram of the LCL grid-connected inverter's mathematical model under conditions of grid voltage imbalance, as depicted in Figure 3.

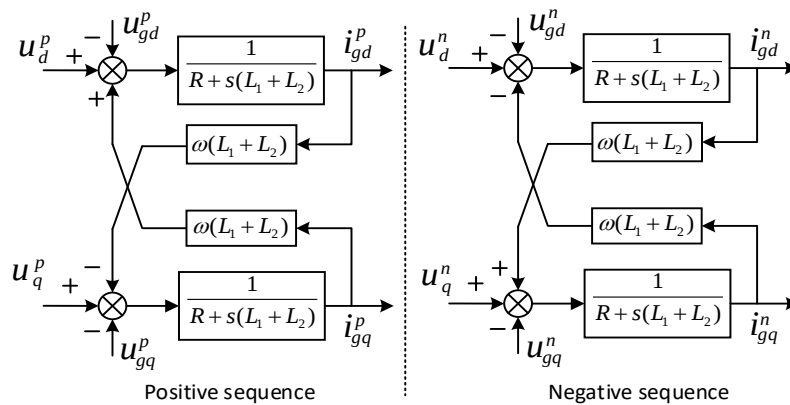


Figure 3. The block diagram of the LCL inverter's model for grid voltage imbalance

Due to the coupling present in the d-q axes, achieving control necessitates the application of decoupling control. Figure 4 presents the current decoupling control schematic relevant under conditions of voltage imbalance [21-23].

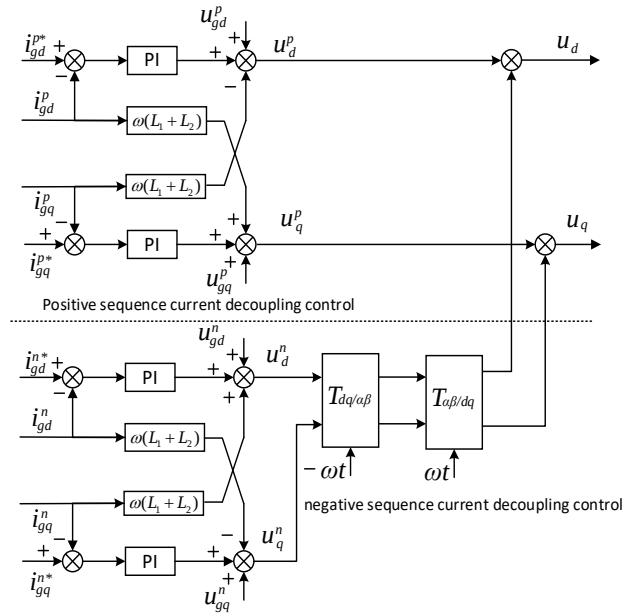


Figure 4. Positive and negative sequence current decoupling control block diagram

Damping Control of LCL-Type Grid-Connected Inverters

LCL filters possess a resonant frequency, which, when the system operates at or near this frequency, induces resonance as illustrated in Equation (16). This resonance significantly amplifies the output current of the filter, thereby impacting the stability and safety of the system.

$$G_{LCL}(s) = \frac{i_2(s)}{u_d(s)} = \frac{1}{Z_{L1} * \frac{Z_{L2}}{Z_C} + Z_{L1} + Z_{L2}} = \frac{1}{L_1 L_2 C s^3 + (L_1 + L_2)s} = \frac{1}{(L_1 + L_2)s} \frac{\omega_r^2}{(s^2 + \omega_r^2)} \quad (16)$$

To mitigate this resonance phenomenon, appropriate damping measures must be employed. By introducing damping, the transfer function of the LCL filter is modified as presented in Equation (17).

$$G_{LCL-d}(s) = \frac{i_2(s)}{u_d(s)} = \frac{1}{(L_1 + L_2)s} \frac{\omega_r^2}{s^2 + 2\zeta\omega_r s + \omega_r^2} \quad (17)$$

Damping can be categorized into active and passive damping. Passive damping is achieved by paralleling or serially connecting damping resistors across branches of the LCL filter. When a damping resistor R_d is inserted in series with the filter capacitor C branch, the transfer function is represented as shown in Equation (18) [24,25].

$$G_{LCL-d1}(s) = \frac{i_2(s)}{u_d(s)} = \frac{1 + R_d C s}{L_1 L_2 C s^3 + (L_1 + L_2)R_d C s^2 + s(L_1 + L_2)} \quad (18)$$

As illustrated in Figure 5, compared to the undamped state, the introduction of series damping effectively suppresses resonance peaks. At low frequencies, the capacitive impedance significantly exceeds that of the inserted damping resistor, thus not affecting its low-frequency characteristics. However, at high-frequency ranges, due to the reduced capacitive reactance, the damping resistor diminishes the LCL filter's attenuation capacity for higher-order harmonics [26,27].

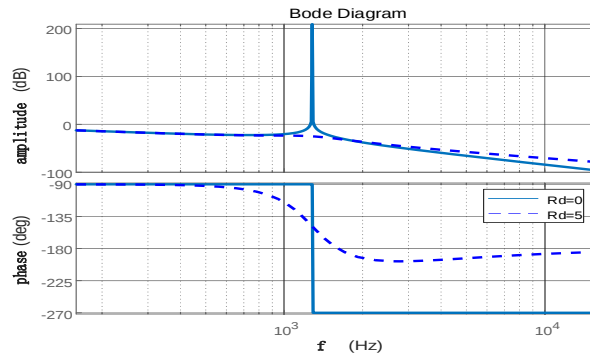


Figure 5. Resistor R_d inserted in series with the capacitor branch

When employing a passive damping strategy with a resistor R_d paralleled across the filtering capacitor C , the transfer function is represented as shown in Equation (19),

$$G_{LCL-d2}(s) = \frac{i_2(s)}{u_d(s)} = \frac{1}{L_1 L_2 C s^3 + \frac{L_1 L_2 s^2}{R_d} + (L_1 + L_2) C s} \quad (19)$$

As illustrated in Figure 6, this configuration exhibits the most effective suppression of resonance peaks, with negligible impact on low and high-frequency characteristics. However, grid-connected inverters typically avoid the use of passive damping with capacitors in parallel with resistors. This reluctance stems from the increased power consumption within the resistor branch, leading to reduced efficiency, heightened thermal management challenges, constrained system flexibility and adjustability, and potential compromises in filtering performance [28-31].

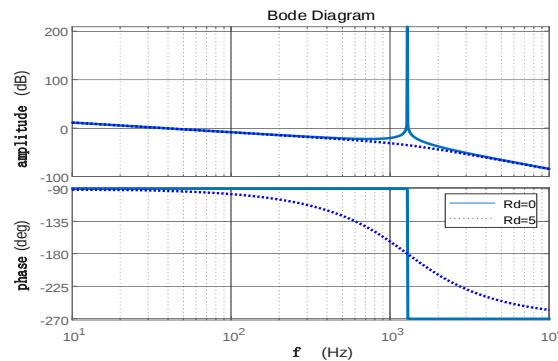


Figure 6. Resistor R_d paralleled with the capacitor branch

In summary, when implementing passive damping solutions, the preferred method is typically to connect a damping resistor in series with the capacitor branch. However, the energy dissipation through the passive damping resistor reduces system efficiency and increases operational costs. The inherent rigidity of passive damping limits the system's adaptability to varying operational conditions, lacking flexibility and adjustability. In contrast, active damping addresses the resonance issues of LCL filters through control strategies, circumventing energy loss and thermal management issues while offering greater flexibility and adjustability. This capability to enhance system stability without compromising filter performance makes active damping a more favored option [32-36].

Instantaneous Power Characteristics of Grid-Connected Inverters under Unbalanced Grid Voltage Conditions

Drawing upon the principles of instantaneous power theory within the two-phase rotating coordinate system, the apparent power output on the grid side of a grid-connected inverter can be articulated as Equations (20).

$$S_{dq} = \frac{3}{2} (\mathbf{U}_{gdq}^p e^{j\omega t} + \mathbf{U}_{gdq}^n e^{-j\omega t}) \cdot (\mathbf{I}_{gdq}^p e^{j\omega t} + \mathbf{I}_{gdq}^n e^{-j\omega t})^* \quad (20)$$

Incorporating Equations (5) and (10) into Equation (20), the real component of the complex power is identified as the instantaneous active power, while the imaginary component represents the instantaneous reactive power.

The formulations for both the instantaneous active and reactive power are delineated in Equation (21), showcasing their respective contributions to the overall power dynamics.

$$\begin{cases} p = p_0 + p_{s2} \sin(2\omega t + 2\varphi^n) + p_{c2} \cos(2\omega_0 t + 2\varphi^n) \\ q = q_0 + q_{s2} \sin(2\omega t + 2\varphi^n) + q_{c2} \cos(2\omega_0 t + 2\varphi^n) \end{cases} \quad (21)$$

The variables within Equation (21) are further elucidated in Equation (22), providing a comprehensive breakdown of their individual roles and interactions within the system's operational framework.

$$\begin{cases} p_0 = 1.5(u_{gd}^p i_{gd}^p + u_{gq}^p i_{gq}^p + u_{gd}^n i_{gd}^n + u_{gq}^n i_{gq}^n) \\ q_0 = 1.5(u_{gq}^p i_{gd}^p - u_{gd}^p i_{gq}^p + u_{gq}^n i_{gd}^n - u_{gd}^n i_{gq}^n) \\ p_{c2} = 1.5(u_{gd}^n i_{gd}^p + u_{gq}^n i_{gq}^p + u_{gd}^p i_{gd}^n + u_{gq}^p i_{gq}^n) \\ p_{s2} = 1.5(u_{gq}^n i_{gd}^p - u_{gd}^n i_{gq}^p - u_{gq}^p i_{gd}^n + u_{gd}^p i_{gq}^n) \\ q_{c2} = 1.5(u_{gq}^n i_{gd}^p - u_{gd}^n i_{gq}^p + u_{gq}^p i_{gd}^n - u_{gd}^p i_{gq}^n) \\ q_{s2} = 1.5(-u_{gd}^n i_{gd}^p - u_{gq}^n i_{gq}^p + u_{gd}^p i_{gd}^n + u_{gq}^p i_{gq}^n) \end{cases} \quad (22)$$

The above equation is articulated in matrix form as Equation (23), encapsulating the complex interrelations within a structured framework for enhanced clarity and analytical precision.

$$\begin{bmatrix} p_0 \\ q_0 \\ p_{c2} \\ p_{s2} \\ q_{c2} \\ q_{s2} \end{bmatrix} = \frac{3}{2} \begin{bmatrix} u_{gd}^p & u_{gq}^p & u_{gd}^n & u_{gq}^n \\ u_{gq}^p & -u_{gd}^p & u_{gq}^n & -u_{gd}^n \\ u_{gd}^n & u_{gq}^n & u_{gd}^p & u_{gq}^p \\ u_{gq}^n & -u_{gd}^n & -u_{gq}^p & u_{gd}^p \\ u_{gq}^n & -u_{gd}^n & u_{gq}^p & -u_{gd}^p \\ -u_{gd}^n & -u_{gq}^n & u_{gd}^p & u_{gq}^p \end{bmatrix} \begin{bmatrix} i_{gd}^p \\ i_{gq}^p \\ i_{gd}^n \\ i_{gq}^n \end{bmatrix} \quad (23)$$

UNIFIED CONTROL STRATEGY UNDER UNBALANCED GRID VOLTAGE CONDITIONS

To enhance the operational efficiency of grid-connected inverters under conditions of unbalanced grid voltage, several distinct control strategies can be employed to independently regulate the positive and negative sequence currents of the inverter. These strategies primarily involve: (1) implementing stable active power control by curbing the oscillations of the active power at twice the fundamental frequency, thereby maintaining the stability of the DC side voltage; (2) executing stable reactive power control by eliminating the second harmonic fluctuations in reactive power, aiming to provide a steady reactive power output to the grid; (3) effectively suppressing the negative sequence current to ensure the balanced output of three-phase currents from the inverter.

Constant Active Power Control

To ensure a stable output of active power, it is essential that the control system adheres to the conditions $p_{c2}=0$ and $p_{s2}=0$. By incorporating these conditions into equation (23), equation (24) can be derived.

$$\begin{bmatrix} p_0 \\ q_0 \\ 0 \\ 0 \\ q_{c2} \\ q_{s2} \end{bmatrix} = \frac{3}{2} \begin{bmatrix} u_{gd}^p & u_{gq}^p & u_{gd}^n & u_{gq}^n \\ u_{gq}^p & -u_{gd}^p & u_{gq}^n & -u_{gd}^n \\ u_{gd}^n & u_{gq}^n & u_{gd}^p & u_{gq}^p \\ u_{gq}^n & -u_{gd}^n & -u_{gq}^p & u_{gd}^p \\ u_{gq}^n & -u_{gd}^n & u_{gq}^p & -u_{gd}^p \\ -u_{gd}^n & -u_{gq}^n & u_{gd}^p & u_{gq}^p \end{bmatrix} \begin{bmatrix} i_{gd}^p \\ i_{gq}^p \\ i_{gd}^n \\ i_{gq}^n \end{bmatrix}^* \quad (24)$$

By transforming and solving equation (24), the command current can be determined to satisfy equation (25).

$$\begin{bmatrix} i_{gd}^p \\ i_{gq}^p \\ i_{gd}^n \\ i_{gq}^n \end{bmatrix}^* = \frac{2}{3} \begin{bmatrix} u_{gd}^p & u_{gq}^p & u_{gd}^n & u_{gq}^n \\ u_{gq}^p & -u_{gd}^p & u_{gq}^n & -u_{gd}^n \\ u_{gd}^n & u_{gq}^n & u_{gd}^p & u_{gq}^p \\ u_{gq}^n & -u_{gd}^n & -u_{gq}^p & u_{gd}^p \end{bmatrix}^T \begin{bmatrix} p_0 \\ q_0 \\ 0 \\ 0 \end{bmatrix} \quad (25)$$

By resolving equation (25), the expression for the command current corresponding to a constant active power output can be obtained as equation (26).

$$\begin{bmatrix} i_{gd}^p \\ i_{gq}^p \\ i_{gd}^n \\ i_{gq}^n \end{bmatrix}^* = \frac{2p_0^*}{3D_1} \begin{bmatrix} u_{gd}^p \\ u_{gq}^p \\ u_{gd}^n \\ u_{gq}^n \end{bmatrix} + \frac{2q_0^*}{3D_2} \begin{bmatrix} u_{gq}^p \\ -u_{gd}^p \\ u_{gq}^n \\ -u_{gd}^n \end{bmatrix} \quad (26)$$

Set:

$$\begin{cases} D_1 = (u_{gd}^p)^2 + (u_{gq}^p)^2 - (u_{gd}^n)^2 + (u_{gq}^n)^2 \\ D_2 = (u_{gd}^p)^2 + (u_{gq}^p)^2 + (u_{gd}^n)^2 + (u_{gq}^n)^2 \end{cases}$$

To maintain the stability of active power output from grid-connected inverters under conditions of unbalanced grid voltage, it is crucial for the inverter to mitigate fluctuations in its power output, thereby preserving the stability of the DC side voltage. According to equation (26), the inverter's capability to sustain a stable active power output is contingent upon its current command incorporating both positive and negative sequence components. The primary challenge here lies in the necessity to consider both positive and negative sequence components to ensure the stability of active power and DC side voltage; however, from the perspective of power quality and system stability, there is generally a preference to minimize the presence of the negative sequence component.

Substituting equation (26) into equation (24) allows for the derivation of the expression for the second harmonic fluctuations in reactive power (equation 27), which clearly indicates that the second harmonic ripples in reactive power, qc and qs, are uncontrollable.

$$\begin{bmatrix} q_c \\ q_s \end{bmatrix} = \frac{3p_0^*}{D_1} \begin{bmatrix} u_{gd}^p u_{gq}^n - u_{gd}^n u_{gq}^p \\ -u_{gd}^n u_{gd}^p - u_{gd}^p u_{gq}^n \end{bmatrix} + \frac{3q_0^*}{D_2} \begin{bmatrix} u_{gd}^n u_{gd}^p + u_{gd}^p u_{gq}^n \\ u_{gd}^n u_{gq}^p - u_{gd}^p u_{gq}^n \end{bmatrix} \quad (27)$$

Constant Control of Reactive Power

To ensure a constant output of reactive power, it is essential that the control system fulfills the conditions $q_c=0$ and $q_s=0$. By applying these conditions to equation (23), equation (24) can be derived.

$$\begin{bmatrix} p_0 \\ q_0 \\ 0 \\ 0 \\ q_{c2} \\ q_{s2} \end{bmatrix} = \frac{3}{2} \begin{bmatrix} u_{gd}^p & u_{gq}^p & u_{gd}^n & u_{gq}^n \\ u_{gq}^p & -u_{gd}^p & u_{gq}^n & -u_{gd}^n \\ u_{gd}^n & u_{gq}^n & u_{gd}^p & u_{gq}^p \\ u_{gq}^n & -u_{gd}^n & -u_{gq}^p & u_{gd}^p \\ u_{gd}^p & -u_{gd}^p & u_{gq}^p & -u_{gq}^n \\ -u_{gd}^n & -u_{gq}^n & u_{gd}^p & u_{gq}^p \end{bmatrix} \begin{bmatrix} i_{gd}^p \\ i_{gq}^p \\ i_{gd}^n \\ i_{gq}^n \end{bmatrix}^* \quad (28)$$

By transforming and solving equation (28), the command current is found to conform to equation (29).

$$\begin{bmatrix} i_{gd}^p \\ i_{gq}^p \\ i_{gd}^n \\ i_{gq}^n \end{bmatrix}^* = \frac{2}{3} \begin{bmatrix} u_{gd}^p & u_{gq}^p & u_{gd}^n & u_{gq}^n \\ u_{gq}^p & -u_{gd}^p & u_{gq}^n & -u_{gd}^n \\ u_{gd}^n & u_{gq}^n & u_{gd}^p & u_{gq}^p \\ -u_{gd}^n & -u_{gq}^n & u_{gd}^p & u_{gq}^p \end{bmatrix}^T \begin{bmatrix} p_0 \\ q_0 \\ 0 \\ 0 \end{bmatrix} \quad (29)$$

Solving equation (25) yields the expression for the command current during constant reactive power output as given in equation (26).

$$\begin{bmatrix} i_{gd}^p \\ i_{gq}^p \\ i_{gd}^n \\ i_{gq}^n \end{bmatrix}^* = \frac{2p_0^*}{3D_2} \begin{bmatrix} u_{gd}^p \\ u_{gq}^p \\ u_{gd}^n \\ u_{gq}^n \end{bmatrix} + \frac{2q_0^*}{3D_1} \begin{bmatrix} u_{gq}^p \\ -u_{gd}^p \\ -u_{gq}^n \\ u_{gd}^n \end{bmatrix} \quad (30)$$

Analysis based on equation (30) reveals that the command value for the current includes both positive and negative sequence components of the current, without any cross-multiplication terms between positive and negative sequence components of the voltage. When the command value from equation (30) is substituted into equation (28), an expression for the second harmonic fluctuations in active power (equation 31) can be derived. It is evident that the second harmonic ripples in active power, p_c and p_s , are uncontrollable.

$$\begin{bmatrix} p_c \\ p_s \end{bmatrix} = \frac{3p_0^*}{D_2} \begin{bmatrix} u_{gd}^n u_{gd}^p - u_{gq}^n u_{gq}^p \\ -u_{gd}^p u_{gq}^n - u_{gd}^n u_{gq}^p \end{bmatrix} + \frac{3q_0^*}{D_1} \begin{bmatrix} u_{gd}^n u_{gd}^p - u_{gd}^n u_{gq}^p \\ u_{gd}^n u_{gd}^p + u_{gq}^n u_{gq}^p \end{bmatrix} \quad (31)$$

In the context of calculating the active power output of an inverter, a noticeable phenomenon is the presence of second harmonic fluctuations in the inverter's active power output under the conditions of this control strategy. The existence of these second harmonic fluctuations stems from the insufficient neutralization of the unbalanced grid voltage effects by the positive and negative sequence current components during their interaction with the grid voltage, leading to variations in the output power in accordance with the unbalanced grid voltage conditions. Therefore, despite the current command considering both positive and negative sequence components, the absence of consideration for the interaction between voltage components limits the effectiveness of this control strategy in suppressing the active power fluctuations caused by grid imbalances, thereby affecting the overall system performance and power quality. This insight underscores the importance of integrating the interactions between grid voltage and inverter current in the design of grid-connected inverter control strategies to ensure stable active power output and reduce potential power fluctuations under unbalanced grid conditions.

Negative Sequence Current Suppression Control

To ensure that grid-connected inverters can deliver balanced three-phase currents to the grid, it is essential to effectively eliminate the negative sequence component from the inverter's output current. Achieving this goal not only contributes to the improvement of power quality but also helps to prevent adverse effects on grid stability. This requires the inverter control system to precisely identify and compensate for the negative sequence component in the current, aiming for a balanced three-phase current output. This is achieved by satisfying the condition $i_{gd}^n = i_{gq}^n = 0$, and by substituting into equation (23), equation (32) can be derived

$$\begin{bmatrix} p_0 \\ q_0 \\ p_{c2} \\ p_{s2} \\ q_{c2} \\ q_{s2} \end{bmatrix} = \frac{3}{2} \begin{bmatrix} u_{gd}^p & u_{gq}^p & u_{gd}^n & u_{gq}^n \\ u_{gq}^p & -u_{gd}^p & u_{gq}^n & -u_{gd}^n \\ u_{gd}^n & u_{gq}^n & u_{gd}^p & u_{gq}^p \\ u_{gq}^n & -u_{gd}^n & -u_{gq}^p & u_{gd}^p \\ u_{gq}^p & -u_{gd}^p & u_{gq}^n & -u_{gd}^n \\ -u_{gd}^n & -u_{gq}^n & u_{gd}^p & u_{gq}^p \end{bmatrix} \begin{bmatrix} i_{gd}^p \\ i_{gq}^p \\ 0 \\ 0 \end{bmatrix} \quad (32)$$

By transforming and solving equation (32), the command current is found to comply with equation (33)

$$\begin{bmatrix} i_{gd}^p \\ i_{gq}^p \end{bmatrix}^* = \frac{2}{3} \begin{bmatrix} u_{gd}^p & u_{gq}^p \\ u_{gq}^p & -u_{gd}^p \end{bmatrix}^T \begin{bmatrix} p_0 \\ q_0 \end{bmatrix}^* \quad (33)$$

By solving equation (33), the expression for the command current when controlling the negative sequence current to zero is obtained as equation (34).

$$\begin{bmatrix} i_{gd}^p \\ i_{gq}^p \\ i_{gd}^n \\ i_{gq}^n \end{bmatrix}^* = \frac{2p_0^*}{3((u_{gd}^p)^2 + (u_{gq}^p)^2)} \begin{bmatrix} u_{gd}^p \\ u_{gq}^p \\ 0 \\ 0 \end{bmatrix} + \frac{2q_0^*}{3((u_{gd}^p)^2 + (u_{gq}^p)^2)} \begin{bmatrix} u_{gq}^p \\ -u_{gd}^p \\ 0 \\ 0 \end{bmatrix} \quad (34)$$

Analyzing the command current expression in equation (34), it is noticeable that the absence of cross-product terms between the positive and negative sequence components of voltage means that harmonic currents at twice the fundamental frequency are not directly introduced into the command current, which might lead to distortions in the grid-connected current. However, when the results of equation (34) are substituted into equation (32) for

calculation, it is observed that due to this characteristic of the command current values, both the active and reactive power outputs of the inverter exhibit second harmonic fluctuations, as illustrated in equation (35).

$$\begin{bmatrix} p_c \\ p_s \\ q_c \\ q_s \end{bmatrix} = \frac{3p_0^*}{2((u_d^p)^2 + (u_q^p)^2)} \begin{bmatrix} u_{gd}^n u_{gd}^p + u_{gq}^n u_{gq}^p \\ u_{gq}^n u_{gd}^p - u_{gd}^n u_{gq}^p \\ u_{gq}^n u_{gd}^p - u_{gd}^n u_{gq}^p \\ -u_{gd}^n u_{gd}^p - u_{gq}^n u_{gq}^p \end{bmatrix} + \frac{3q_0^*}{2((u_d^p)^2 + (u_q^p)^2)} \begin{bmatrix} u_{gd}^n u_{gq}^p - u_{gq}^n u_{gd}^p \\ u_{gq}^n u_{gd}^p - u_{gd}^n u_{gq}^p \\ u_{gd}^n u_{gd}^p + u_{gq}^n u_{gq}^p \\ u_{gq}^n u_{gd}^p - u_{gd}^n u_{gq}^p \end{bmatrix} \quad (35)$$

The analysis above reveals potential conflicts among the three discussed control strategies. Suppressing the negative sequence current to achieve balanced grid-connected current outputs may lead to significant second harmonic fluctuations in active and reactive power outputs. Such fluctuations in active power could trigger instability in the DC side voltage, which, in extreme cases, might even prevent the inverter from functioning properly. Additionally, significant fluctuations in reactive power injected into the grid could cause voltage fluctuations at point-to-point connections. While adopting a constant active power control strategy may be beneficial for maintaining the stability of the DC bus voltage, thereby ensuring the stable operation of the inverter, the grid-connected currents under this strategy may become unbalanced, and issues with reactive power fluctuations still persist. Moreover, the more stable the active power, the greater the potential imbalance in grid-connected currents, which in severe cases might not meet the basic requirements for grid interconnection; a constant reactive power control strategy faces similar challenges.

Unified Control Scheme

Although the three control strategies may seem contradictory on the surface, they are, in fact, interconnected. To enable flexible transition among these strategies based on varying operational demands, we integrate equations (26), (30), and (34) into a unified expression and introduce a coordination coefficient k , facilitating seamless transitions between different control strategies, as illustrated in equation (36).

$$\begin{bmatrix} i_{gd}^p \\ i_{gq}^p \\ i_{gd}^n \\ i_{gq}^n \end{bmatrix}^* = \frac{2p_0^*}{3D_3} \begin{bmatrix} u_{gd}^p \\ u_{gq}^p \\ -ku_{gd}^n \\ -ku_{gq}^n \end{bmatrix} + \frac{2q_0^*}{3D_4} \begin{bmatrix} u_{gq}^p \\ -u_{gd}^p \\ ku_{gq}^n \\ -ku_{gd}^n \end{bmatrix} \quad (36)$$

Set:

$$\begin{cases} D_3 = (u_{gd}^p)^2 + (u_{gq}^p)^2 - k(u_{gd}^n)^2 + (u_{gq}^n)^2 \\ D_4 = (u_{gd}^p)^2 + (u_{gq}^p)^2 + k(u_{gd}^n)^2 + (u_{gq}^n)^2 \end{cases}$$

In the design of the adjustment strategy, the variation of the coordination coefficient k is crucial for implementing diverse control logic, allowing the system to flexibly switch control modes based on different grid conditions and operational requirements. Specifically, when $k = -1$, the system enters a stable active power mode, where the primary goal is to effectively eliminate or minimize fluctuations in active power by finely tuning the output of the inverter. This is vital for maintaining the stability of the DC side voltage and ensuring stable operation of the entire system under various load conditions. When $k = 0$, the control strategy shifts to negative sequence current elimination mode, focusing on compensating for current asymmetries caused by grid imbalances by adjusting the phase and amplitude of the inverter's output current, thus achieving balanced three-phase current output. This control not only improves power quality but also helps prevent equipment overheating and additional losses due to unbalanced currents. When $k = 1$, the system switches to stable reactive power mode, where the control logic aims to regulate the inverter's output to suppress fluctuations in reactive power, which is especially crucial for maintaining grid voltage stability and meeting the grid's demand for reactive support. In practical applications, by dynamically adjusting the value of k , the system can smoothly transition between the aforementioned control modes, achieving adaptive responses to different grid conditions. This flexibility not only enhances the operational efficiency and stability of grid-connected inverters but also allows the inverters to better serve in complex and variable grid environments, meeting diverse grid service requirements. Moreover, this comprehensive control

strategy can further optimize the operational strategy of inverters based on preset priorities or economic considerations, aiming to maximize energy efficiency and minimize costs.

Under conditions of unbalanced grid voltage, Figure 7 illustrates the power-current coordinated control diagram for grid-connected inverters.

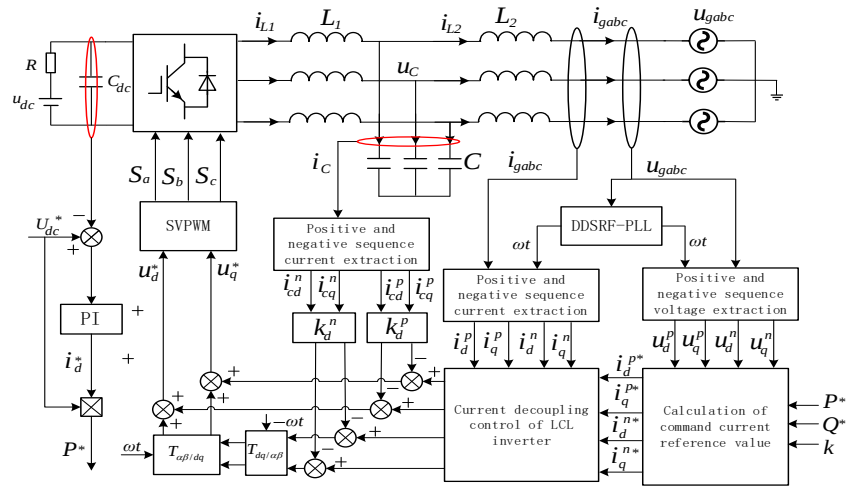


Figure 7. Power-current coordinated control block diagram

SIMULATION OF UNIFIED CONTROL STRATEGY UNDER UNBALANCED ELECTRIC GRID VOLTAGE CONDITIONS

To verify the efficacy of the control strategy introduced in our study, we engineered a model that synergizes power and current management using the MATLAB/Simulink environment, where we executed a series of simulation tests. The configuration of the simulation parameters, detailed in Table 1, was designed to closely replicate the dynamics of actual power systems. These simulations were aimed at assessing the control strategy's capability to preserve current equilibrium, guarantee consistent power generation, and mitigate variations in the electrical grid's voltage, thus providing valuable perspectives for ongoing studies and operational implementations.

Table 1. Main simulation parameters

Parameter	Symbol	Value
DC bus voltage	u_{dc}	400V
Inverter rating	S	5000VA
DC side filtering capacitor	C_{dc}	1000uF
Inverter inductor	L_1	3.56mH
Grid-side inductor	L_2	1.75mH
Filter capacitance	C	15uF
Grid frequency	f	50Hz
Grid voltage	U_g	110V
Switching frequency	f_s	10kHz
Proportional control coefficient	K_p	17.8
Integral control coefficient	K_i	178
Active damping coefficient	K_d	0.12

Grid Synchronization Simulation under Unbalanced Grid Conditions

In this study, to effectively achieve grid synchronization, we implemented the Decoupled Double Synchronous Reference Frame Phase-Locked Loop (DDSRF-PLL) technique. The cornerstone of this technique lies in its unique capability to precisely extract the positive sequence voltage components from unbalanced grid conditions and maintain stable phase tracking of these components. This process is critical as it ensures that inverters can remain synchronized with the grid voltage, even amidst fluctuations and imbalances in complex grid environments. To rigorously evaluate the performance of the DDSRF-PLL technique, we constructed a corresponding simulation

model in the MATLAB/Simulink environment and conducted a series of simulation experiments. These experiments were designed to mimic the synchronization process under unbalanced grid states, with a particular focus on how the DDSRF-PLL effectively identifies both positive and negative sequence voltage components and accurately tracks the positive components.

The simulation results, presented in Figure 8, vividly demonstrate the exceptional performance of the DDSRF-PLL technique in ensuring inverter-grid synchronization. It is evident from the figure that the DDSRF-PLL technique can accurately identify and separate the positive and negative sequence components of grid voltage, maintaining stable phase locking and exhibiting robust dynamic response, even in the face of grid voltage imbalances. These findings highlight the efficiency and reliability of the DDSRF-PLL technique in addressing grid imbalances, ensuring stable inverter operation under various grid conditions, and enhancing the overall system performance and power quality.

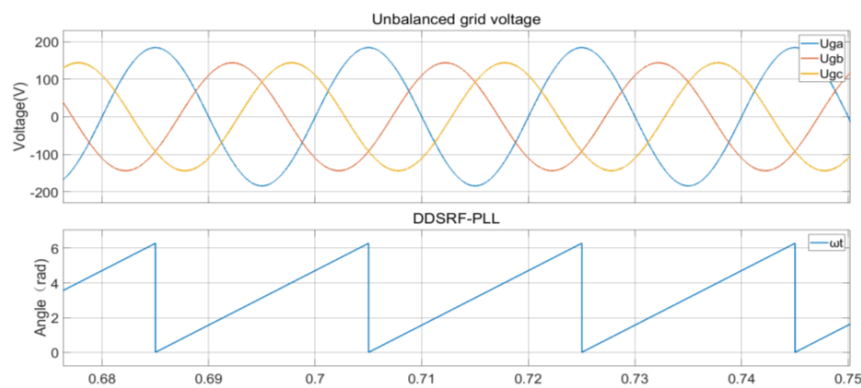


Figure 8. DDSRF-PLL

Simulation of Positive and Negative Sequence Separation of Voltage and Current

This simulation experiment was segmented into four distinct phases, commencing with the inverter's integration into the three-phase grid at $t=0.01$ seconds, accompanied by the simulation of a negative sequence voltage disturbance with a 20V RMS value. Subsequently, the experiment explored the system's performance under varying control objectives by adjusting the coordinated control coefficient k to 1, 0, and -1 during the time intervals of 0.1 to 0.4 seconds, 0.4 to 0.7 seconds, and 0.8 to 1 second, respectively. Figure 9 illustrates the efficacy of extracting positive and negative sequence components of grid current.

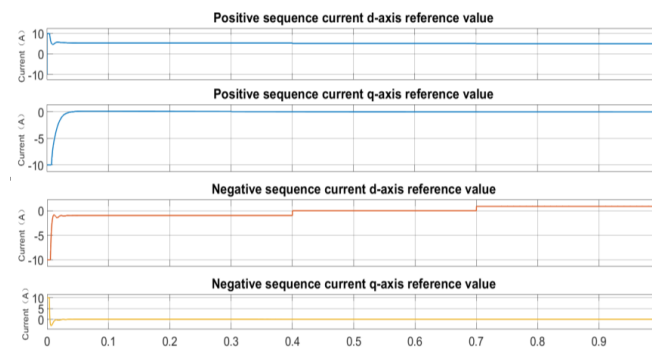


Figure 9. Extracting positive and negative sequence components of grid current

Simulation of Power-Current Collaborative Control under Different Modes

Each phase of the experiment was dedicated to assessing the specific impact of control objectives on system performance. In the initial phase of the simulation (0.1 to 0.4 seconds), the control coefficient k was set to 1, focusing on mitigating fluctuations in active power to ensure a stable supply of electricity, thereby significantly enhancing the system's stability against grid imbalances. In the subsequent phase (0.4 to 0.7 seconds), by adjusting k to 0, the emphasis shifted towards maintaining the three-phase balance of the inverter output current, primarily by reducing the negative sequence current component, demonstrating the control strategy's high adaptability to grid variations. In the final phase (0.8 to 1 second), k was set to -1 to stabilize the reactive power output and

alleviate the fluctuations in reactive power caused by grid imbalances, highlighting the importance of enhancing power quality while maintaining stable system operation.

The simulation results, as illustrated in Figures 10 and 11, clearly validate the effectiveness of the proposed control strategy in addressing grid imbalances under different control parameter configurations, showcasing its remarkable adaptability and practicality. These findings not only theoretically substantiate the accuracy of the control method but also provide a solid experimental foundation for applying these strategies in real-world power systems.

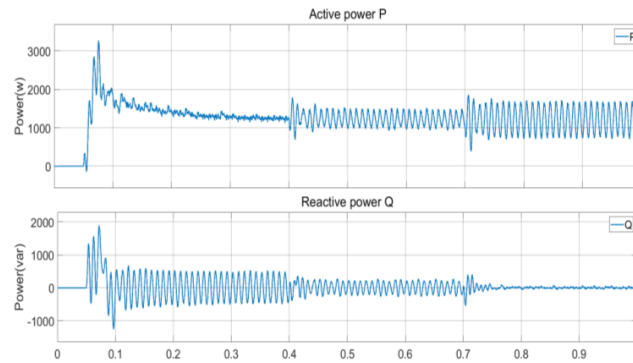


Figure 10. Inverter output power waveforms under different modes

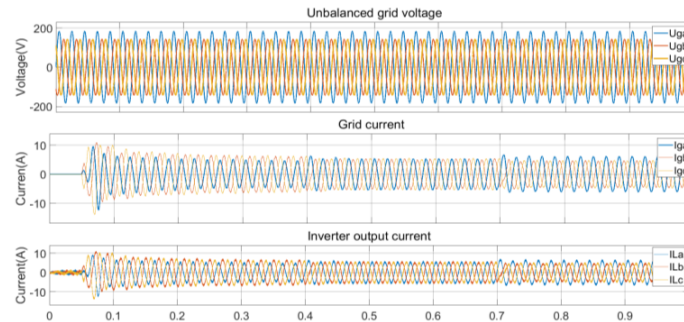


Figure 11. Output current waveforms under different modes

CONCLUSION

In conclusion, this paper introduces a novel coordinated control strategy designed to enhance the resilience of grid-connected inverters to voltage imbalances. Distinguished by its utilization of the d-q rotating reference frame, this approach sets itself apart from conventional methods by dynamically synchronizing with grid fluctuations, thereby achieving precise regulation of both active and reactive power of inverters, ensuring rapid and stable response to grid disturbances. By integrating active and reactive power management with adaptive tuning coefficients, the strategy achieves efficient coordinated control and incorporates a current limiting feature to prevent peak currents from exceeding predefined thresholds, significantly enhancing system reliability. Experimental validation confirms the effectiveness of this strategy in improving the fault ride-through capabilities of inverters under voltage imbalance conditions, showcasing its potential in bolstering the stability of grid-connected inverters. The findings of this study make a valuable contribution to the fields of power electronics and grid management, highlighting the significant potential of this strategy in improving the stability and reliability of grid-connected inverters.

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