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Introduction

A paradigm shift from large power plants to small distributed generation (DG) systems located at the point of consumption is an emerging trend in the field of electricity. In recent years, DG systems have been powered by photovoltaic (PV) cells, wind turbines, wave generators, fuel cells, small hydro-powered, and gas-powered combined heat and power stations [1–5]. As reported by the Global Renewable Energy Policy Multi-Stakeholder Network REN21, solar PV cells and wind are currently the mainstream options in the power sector with an increasing number of countries generating more than 20% of their electricity. As shown in Figure 1.1, the installed renewable power capacity increased beyond 200 GW in 2019 (mostly with solar PV cells), which is the largest increase ever. During the same year, 57% of renewable power capacity additions were using solar PV cells (direct current) followed by wind power (approximately 60 GW for 30%) and hydropower (approximately 16 GW for 8%). The remaining 5% of additions were from bio-power, geothermal power, and concentrating solar thermal power. For the fifth year in a row, net additions of renewable power generation capacity clearly outpaced the net installations of fossil fuel and nuclear power capacity combined as shown in Figure 1.2. Globally, 32 countries had at least 10 GW of renewable power capacity in 2019; a decade earlier, it was only 19 countries. In most countries, producing electricity from wind and solar PV cells is cost-effective than generating electricity from new coal-fired power plants.

1.1 Architecture of DG Grid-Connected Converter

Regardless of the type of renewable energy source, a DG grid-connected converter is essential for converting the energy produced by the source to the grid [2, 3]. Considering their high degree of modularity, scalability, adaptability, maintainability,

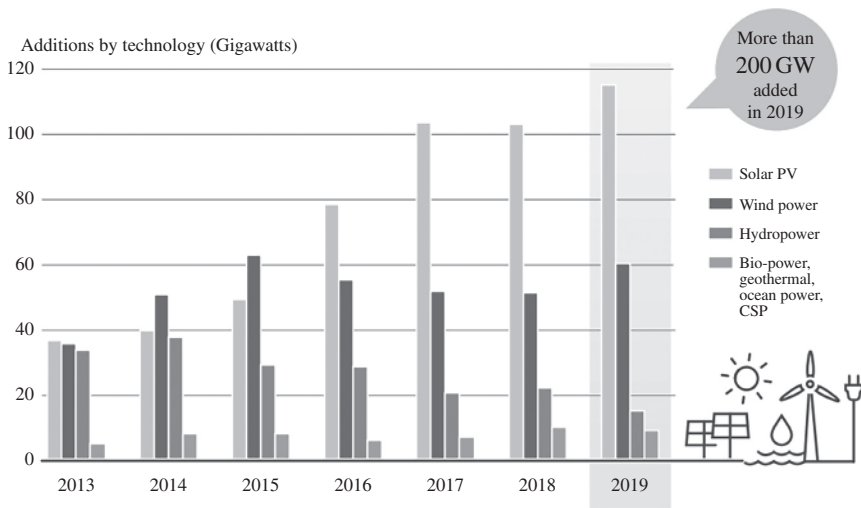


Figure 1.1 Estimated renewable share of total final energy consumption, 2018.
Source: [1]/REN21.

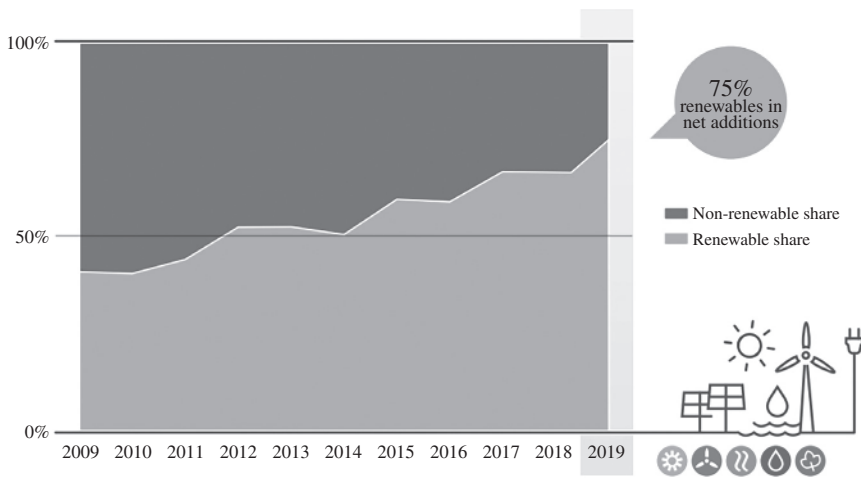


Figure 1.2 Renewable and non-renewable shares of net annual additions in power generation capacity, 2009–2019. Source: [1]/REN21.

and autonomic behavior, DG grid-connected converters have been widely employed in many commercial, industrial, and domestic applications.

The basic structure of a modern DG grid-connected converter is similar to that of power electronics systems. It consists of a power conversion stage (PCS) and a

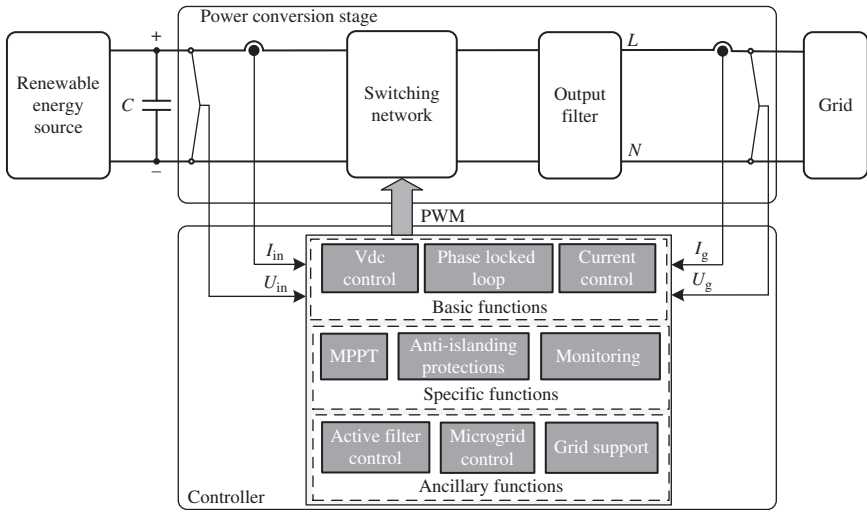


Figure 1.3 Architecture of DG grid-connected converter.

controller. Its architecture is shown in Figure 1.3. The controller includes basic functions, specific functions, and ancillary functions [4]. The basic functions are necessary to ensure normal operation of the system and specific functions are used to meet the industrial requirements. The ancillary functions are optional depending on specific applications such as microgrid applications [5]. The basic functions of the controller are typically composed of grid synchronization or phase-locked loop (PLL), DC-link voltage regulation, and output current regulation.

1.1.1 Power Conversion Stage

The PCS of DG grid-connected converter consists of a switching network and an output filter as shown in Figure 1.3. The switching network converts incoming DC power into high-frequency AC power. The output filter allows the line-frequency component to pass and attenuate, thus switching harmonics to the grid to meet statutory requirements, such as IEEE519-2014 [6] and IEC61727-2004 [7].

1.1.1.1 Switching Network

Based on input source types, the switching network of DG grid-connected converters can be classified into two basic types as shown in Figure 1.4 [8]. Figure 1.4a, b depict a two-level bridge for the current source converter and voltage source converter (VSC), respectively. The number n varies with the system configuration.

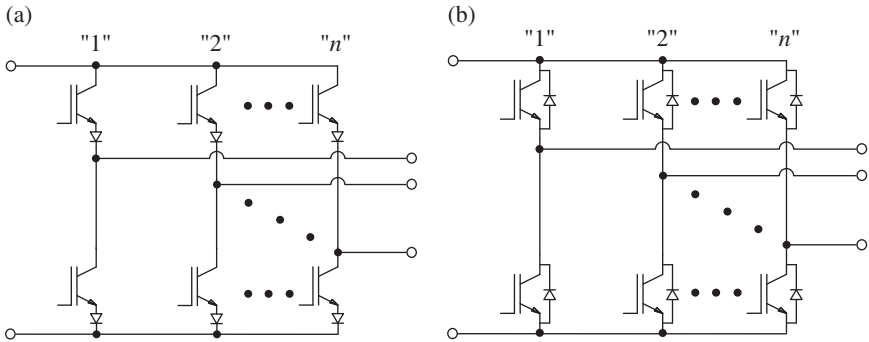


Figure 1.4 Configurations of switching networks. (a) Current source converter; (b) voltage source converter.

Considering that a VSC with bidirectional power feature plays a major role in distributed renewable generation systems, switching networks with $n = 1, 2$, and 3 for single- and three-phase voltage-source inverters (VSIs) are extensively studied.

1.1.1.2 Output Filter

The power grid is an infinite bus bar; hence, the grid interfacing circuit at the point-of-common-coupling (PCC) must be inductive. The simplest form of output filter for VSI is an inductor (L). The lower limit of the filter inductance is determined by the harmonic requirement of the grid-injected current according to IEEE 519-1992, where the percentage relative to the nominal grid-side fundamental current is specified in Table 1.1. The harmonic currents at different harmonic frequencies can be calculated from the ratio of corresponding harmonic voltage amplitudes to the filter impedance characteristics. The first-order L-type filter has a simple structure and is easy to install; however, it has relatively poor attenuation of switching harmonics, resulting in a very large size.

Thus, as shown in Figure 1.5, the industry prefers to use higher-order filters, such as a third-order inductor-capacitor-inductor (LCL) filter or a third-order

Table 1.1 Maximum permitted harmonic current distortion in percentage of current I_g according to IEEE 519-1992.

Individual harmonic order h	$h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 < h$	THD
Percentage (%)	4.0	2.0	1.5	0.6	0.3	5.0

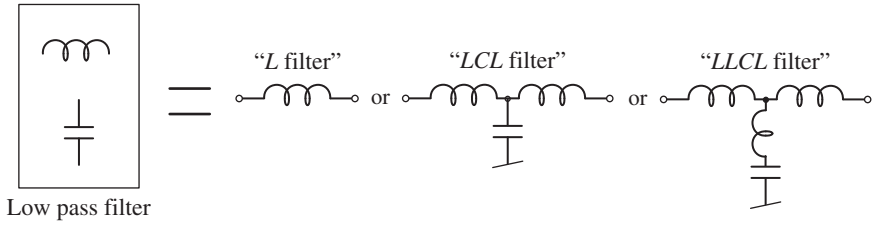


Figure 1.5 Filter configurations.

LCL filter with a parallel notch circuit (*LLCL* filter) [9] to achieve better switching harmonic attenuation with small reactive elements.

1.1.2 Control Stage

Depending on their operation, DG grid-connected converters can be classified into grid-feeding, grid-supporting, and grid-forming power converters [10, 11].

The grid-forming converters can be represented as an ideal AC voltage source with a low-output impedance by setting the voltage amplitude E^* and frequency ω^* of the local grid using a proper control loop as illustrated in Figure 1.6a.

Correspondingly, grid-feeding power converters are designed to deliver power to an energized grid. They can be represented as an ideal current source connected to the grid in parallel with high impedance. The simplified scheme of the grid-feeding power converter is depicted in Figure 1.6b where P^* and Q^* represent the active and reactive powers to be delivered, respectively. In this application, it is important to note that the current source should be perfectly synchronized with the AC voltage at the connection point to accurately regulate the active and reactive power exchanged with the grid. Currently, the grid-feeding power converter is still the mainstream of grid-connected converters, and it is also the focus of the following study.

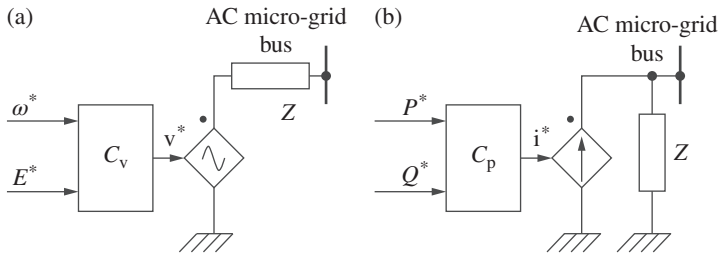


Figure 1.6 Simplified representation of grid-connected power converters.

(a) Grid-forming; (b) grid-feeding.

1.2 Challenges for Controlling DG Grid-Connected VSCs with High-Order Power Filter

Modern DG grid-connected VSC must remain stable for different grid conditions, especially when higher-order output filters such as *LCL* or *LLCL* filters are used to minimize the size of reactive components. Additionally, they are necessary to address many intrinsic and extrinsic challenges in current regulation, such as oscillation due to filter resonance, filter parametric sensitivities, digital delay, uncertainty of the grid condition, and disturbances at the PCC.

1.2.1 Intrinsic Challenges

- Filter resonance

To reduce the size and weight of the filter, the most commonly applied solution is to use a high-order *LCL* or *LLCL* filter instead of a first-order *L* filter. However, the presence of multiple reactive elements, such as inductive and capacitive components, results in resonant frequencies. Thus, the output resonates when the inverter with *LCL* or *LLCL* filter is subject to disturbances [9]. In particular, filter resonance results in system instability [12, 13].

Depending on the output current detection positions as shown in Figure 1.7a, there are two methods for regulating the output current of the system: (i) by directly controlling the grid current or (ii) by controlling the converter-side current. The transfer function characteristics in the frequency domain are plotted in Figure 1.7b where the resonant poles are formed by the parallel converter grid-side inductors and filter capacitor, and the complex-conjugate zeros are formed by the grid-side inductor(s) and filter capacitor. If single-loop converter-side current regulation is chosen, the conjugate zeros aim to reduce the effect of resonant poles and improve system stability [14]. Hence, this type of regulation is commonly used in many practical applications owing to its inherent damping capability and overcurrent protection purposes [15, 16]. However, it is challenging to design a controller by considering both the variable resonant poles and conjugate zeros under variable grid conditions. Moreover, the converter-side current regulation does not directly offer harmonic rejection capability of grid current against grid harmonic voltage. If single-loop grid-side current regulation is chosen, the phase angle around the resonant poles decreases sharply and the resonant peak excites the potential oscillation around the filter resonant frequency, thus affecting the system stability. In digital control implementation, the sampling-and-computational delay time would be favorable in regulating the grid-side current owing to its inherent damping properties, which was reported in previous

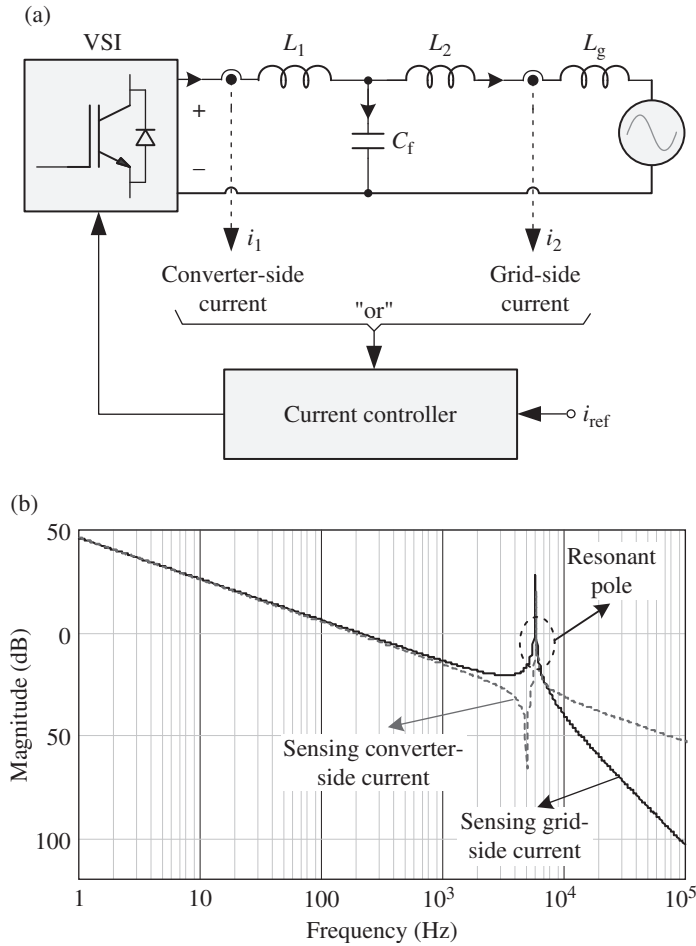


Figure 1.7 Different current regulation schemes and their characteristics. (a) Two main current regulation configurations; (b) comparison of open-loop transfer characteristics.

studies [17]. However, the filter resonant frequency must be higher than the critical frequency and one-sixth of the sampling frequency.

1.2.1.1 Filter Parametric Sensitivities

It is essential to design a system that is stable for specific filter parameters. However, the significant tolerance of filter parameters for example, $\pm 20\%$ variation of inductance and $\pm 10\%$ variation of capacitance still challenges the system stability. Thus, parametric sensitivities should be examined in the controller design.

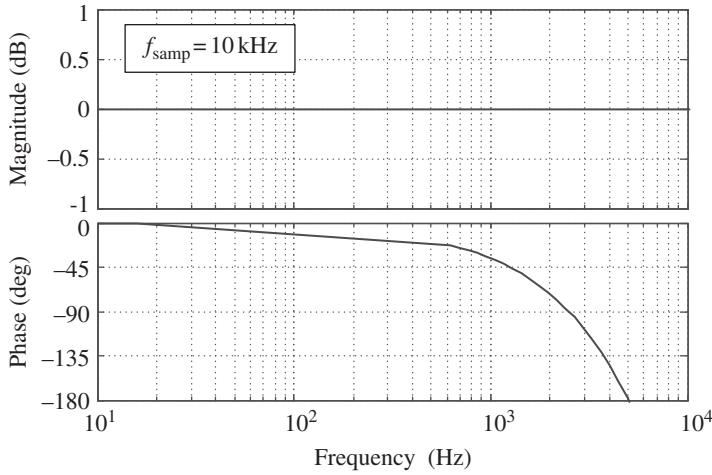


Figure 1.8 Significant phase delay with sampling delay.

1.2.1.2 Digital Delay

Digital delays, such as sampling and computational delays, are inherently present in digital control systems. This results in a significant phase delay as the frequency increases as shown in Figure 1.8. This adversely affects the system robustness and control bandwidth.

1.2.2 Extrinsic Challenges

1.2.2.1 Grid Impedance Variation

Owing to the growing integration of decentralized DG systems with long transmission cables and transformers, the non-negligible grid impedance poses challenges to circuit designers in developing an effective control scheme that can ensure the operational stability of inverters both in stiff and weak-grid conditions [18, 19]. This is because the filter resonant frequency varies with grid impedance as shown in Figure 1.9. Thus, impedance levels must be considered when installing inverters in large power plants or remote areas. For simplicity, the grid impedance level is usually denoted as a percentage of the base impedance value of the inverter or short-circuit ratio at the PCC between the short-circuit power of the AC power system and maximum apparent power of the shunted inverter [3].

1.2.2.2 Disturbances at the PCC

A pure sinusoidal grid voltage is produced by an ideal AC generator built with finely distributed stator and field windings that operate in a uniform magnetic field. However, nonlinear electronic loads in shunted grids cause the current to

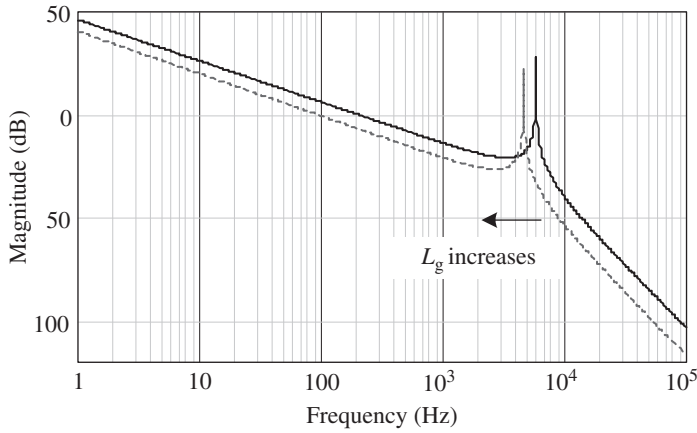


Figure 1.9 Transfer characteristics with grid impedance variation.

vary disproportionately with the grid voltage during each cyclic period. When there is significant impedance in the path from the power source to a nonlinear load as shown in Figure 1.10, these current distortions will also produce distortions or harmonics in the voltage waveform at the load [20, 21]. Thus, disturbances at the PCC caused by the source or nonlinear loads can sometimes affect the normal operation of the inverter. Conversely, inverters with slow dynamics or poor harmonic suppression deteriorate the voltage distortion at the PCC [22].

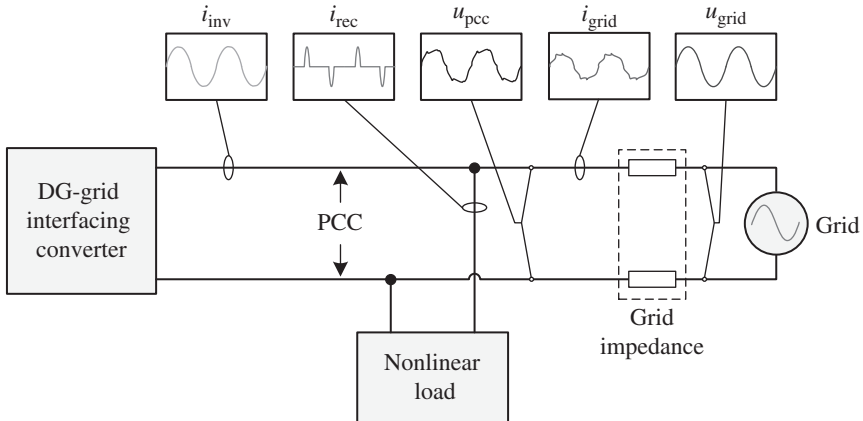


Figure 1.10 Disturbances caused by nonlinear loads at the PCC.

1.3 Methods for Controlling DG Grid-Connected VSCs with High-Order Power Filter

1.3.1 Methodologies to Assess the Stability of DG Grid-Connected VSCs

To address the abovementioned challenges, it is essential to develop effective modeling and analysis of the harmonic stability problem of DG grid-connected VSCs.

1.3.1.1 Eigenvalue-Based Analysis

Eigenvalue-based analysis is widely used to assess the small-signal stability of AC power systems [23, 24]. This analysis is usually based on the study of eigenvalues of a system state space model matrix and requires adequate information of the elements in the system, including the physical characteristics and control parameters [25]. However, the control parameters of grid-tied inverters are generally unavailable especially when analyzing the stability of a large-scale power-converter-based AC distributed power generation system (DPGS).

1.3.1.2 Impedance-Based Stability Analysis

Impedance-based stability analysis is based on generalized Nyquist stability criterion proposed by Middlebrook to assess the stability of the DC system [26]. It is used to analyze the stability of AC DPGS [22, 25–29].

A detailed description of impedance-based stability method for current-controlled grid-tied inverters that are widely used in DPGSs is given in [22]. As shown in Figure 1.11, a current-controlled inverter has a current source I_c in parallel with the output impedance Z_o under zero grid impedance condition, and the grid is represented by a voltage source V_g in series with the equivalent grid impedance Z_g . The grid impedance consists of line impedance and transformer output impedance; however, Z_g for a local current-controlled inverter still depends on the number of grid-tied inverters connected to the PCC [30].

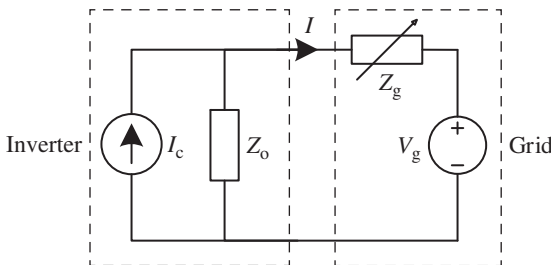


Figure 1.11 Equivalent circuit of a current-control-based grid-tied inverter.

Based on Thevenin and Norton equivalent circuits, if the grid voltage is assumed to be stable without the inverter and the inverter is assumed to be stable when the grid impedance is zero, the injected current from the grid-tied inverter is defined as follows:

$$I(s) = \left[I_c(s) - \frac{V_g(s)}{Z_o(s)} \right] \cdot \frac{1}{1 + Z_g(s)/Z_o(s)} \quad (1.1)$$

For the current-controlled grid-tied inverter system to be stable, the minor-loop gain $Z_g(s)/Z_o(s)$ must satisfy the generalized Nyquist stability criterion.

1.3.1.3 Application Issue Related to Impedance-Based Stability Analysis

The principle of impedance-based stability analysis is widely accepted by academic and industrial communities. However, many scholars are still divided in their opinion on the application of impedance-based stability analysis to the design of grid-tied power converters in AC DPGS.

Impedance-based stability analysis is a type of small-signal analysis method, and AC DPGS has no time-invariant operating point. Hence, researchers performed the analysis in a rotating (dq) reference frame. As a result, the minor-loop-gain matrix has four items: Z_{dd} , Z_{qq} , Z_{dq} , and Z_{qd} . In addition, different stability criteria were induced; however, a more convincing mathematical analysis and derivation of these stability criteria need further exploration. Moreover, an effective stability criterion in the dq frame has not been investigated for a three-phase unbalanced AC DPGS [31].

In addition to the dq frame, impedance-based stability analysis was performed in a stationary frame [22, 31]. From an engineering point of view, it can be noted that, as long as the switching frequency of the inverters is higher than the line frequency of 50/60 Hz, small-signal analysis can be simplified.

In fact, for a linear-control-based grid-tied inverter, system stability assessed by impedance-based stability analysis is approximately equal to that of the Bode diagram analysis. Impedance-based stability analysis focuses on the interaction between Z_g and Z_o of the local grid-tied inverter while Bode diagram analysis focuses on the stability of the entire system including Z_g . Unlike Bode diagram analysis, the impedance of the grid can be tested or estimated online using impedance-based stability analysis. However, universal quantitative stability indices for the AC system, such as phase margin and gain margin in Bode diagram analysis, have not been defined for impedance-based stability analysis.

Theoretically, impedance-based stability analysis should sample grid impedance information online. However, the measured grid impedance may not be reliable because of the possible harmonic voltages at the PCC. Currently, it is difficult to use impedance-based stability analysis to derive guidelines for designing the

controller for converters quantitatively. Nevertheless, it is still a useful tool for qualitatively analyzing the enhancement of the stability of an AC DPGS. For example, as shown in Figure 1.2, Z_o , Z_g , or both Z_o and Z_g can be reshaped to ensure the stability of the local *LCL*-filter-based current-controlled grid-tied inverter thereby enhancing the stability of the AC DPGS.

1.3.2 Methods to Mitigate Filter Resonance

To mitigate the resonance caused by the high-order filter and improve the stability margin of the system, proper damping is mandatory. Damping can be achieved by either passive or active methods, such as online grid impedance estimation, inherent damping, passive damping, active damping, and hybrid damping.

1.3.2.1 Online Grid Impedance Estimation

Theoretically, as long as Z_g can be estimated accurately and periodically, the control parameters can be adjusted online to modify Z_o and thereby ensure system stability under any grid condition [18, 32]. To estimate the variation in grid parameters, many online estimation methods were proposed [31, 33–50]. Based on the mode of realization, these methods can be classified into active, passive, and quasi-passive methods.

Active estimation methods, including noncharacteristic harmonic injection [33], broadband signal injection [34], *LCL* resonance excitation [35], and reactive power variation method [36, 37] deliberately disturb the grid and extract feedback information to estimate the grid impedance.

Passive estimation methods [31, 38–46] are based on direct measurement and evaluation of grid information using least-squares estimation algorithm [40], successive approximation estimation [38], inherent switching feature application [39], and plant time constant identification algorithm [40].

Quasi-passive estimation methods [47, 48] combine the nonintrusive advantage of a passive estimation method and accuracy of an active estimation method. In this method, passive estimation is first selected to estimate the grid impedance. When the value exceeds a selected evaluation index, the quasi-passive method switches to active estimation online.

The accuracy of grid impedance estimation method is inevitably affected by the harmonics generated by other grid-tied inverters at the same PCC. However, the accuracy, detection speed, and anti-interference ability of the online grid impedance estimation method must be improved. Currently, the grid impedance estimation method cannot be independently applied to grid-tied inverters, but it can be adopted as an additional method for enhancing their stability [49, 50].

1.3.2.2 Inherent Damping

The digital time delay induces inherent damping (ID) effect in the current control loop [14, 17, 51–54]. ID effect depends on the location of sensing of current and set time delay. Yin et al. [17] studied the damping characteristic of time delay in a grid-current-feedback-based single-loop control system, and many other studies [51–53] discussed the ID region of a grid-tied inverter. Wang et al. [54] summarized the previous research and derived the time delay range using different current feedback methods to improve the stability of a single-loop control system. As presented in [54], when inverter-side-inductor current feedback is used, the related time delay should satisfy the following condition:

$$\begin{cases} T_d < \frac{1}{4f_r} (k = 0) \\ \frac{4k-1}{4f_r} < T_d < \frac{4k+1}{4f_r} (k = 1, 2, \dots) \end{cases} \quad (1.2)$$

where T_d is the total time delay and $f_r = [(L_1 + L_2 + L_g)/(L_1(L_2 + L_g)C)]^{1/2}/2\pi$ is the filter resonance frequency (L_1 is the inverter-side inductor, L_2 is the grid-side inductor, L_g is the grid inductor, and C is the filter capacitor).

When the grid-side-inductor current feedback is used, the related time delay should satisfy the following condition:

$$\frac{4k+1}{4f_r} < T_d < \frac{4k+3}{4f_r} (k = 0, 1, 2, \dots), \quad (1.3)$$

Based on the ongoing research, two key points must be considered when using the ID technique:

- 1) When Z_g changes, f_r cannot shift across the critical frequency, which is defined as:

$$f_{\text{crit}} = 1/4\tau T_s \quad (1.4)$$

where τT_s is the total delay, including the computational delay and pulse-width modulation (PWM) delay.

- 2) If the cable is long enough, the system may have multi-resonance peaks where gains are greater than 0 dB owing to the distributed capacitances [55, 56]. Therefore, Eqs. (1.2) and (1.3) should be satisfied at every resonant frequency.

In addition, it is difficult to apply the ID technique to a current-controlled inverter independently when Z_g varies and multiple resonance peaks exist.

1.3.2.3 Passive Damping

Passive damping (PD) is easy to implement and widely used in industrial applications [57–61]. The parameter design of PD is based on the physical characteristics

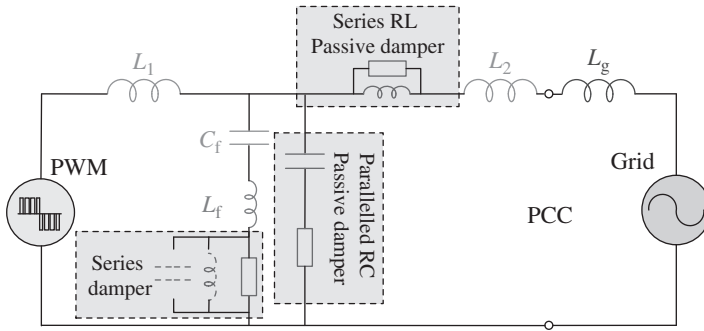


Figure 1.12 Possible passive damping methods for a grid-tied inverter.

of the system, such as resistive region [58] and Q-factor [59]. Figure 1.10 illustrates the different types of PD where L_f is the trap inductor for the $LLCL$ filter. As shown in Figure 1.12, the insertion of a resistor(s) to damp the possible resonance results in extra power losses.

Figure 1.13 shows the open-loop Bode diagram of $i_g(s)/i_{gref}(s)$ for a grid-tied inverter with only RC passive damping [32, 59]. It can be observed that a single

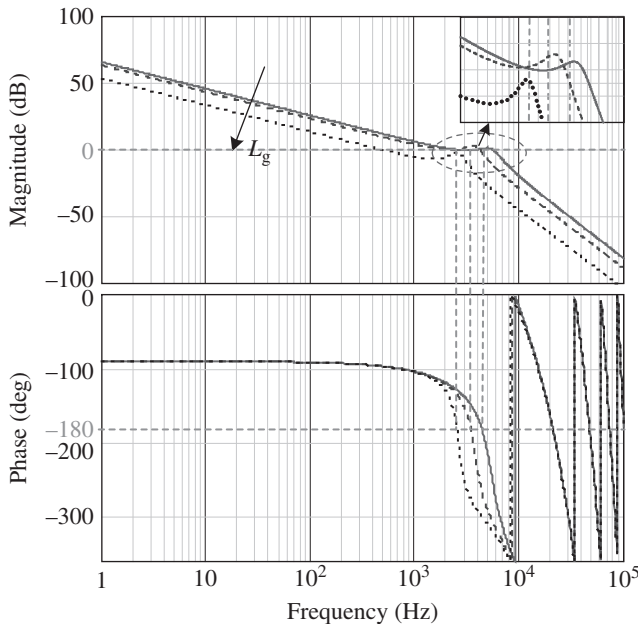


Figure 1.13 Open-loop gain $i_g(s)/i_{gref}(s)$ of the LCL -filter-based grid-tied inverter with RC damper.

PD-based system cannot achieve high bandwidth in a weak grid. However, a composite PD method can handle the variation in Z_g at the cost of additional materials and increased damping power losses [60].

1.3.2.4 Active Damping

Active damping (AD) is a unique method in state feedback-based control. In contrast to PD, AD [51, 62–80] has received more attention over the years because of its flexibility and decreased damping power losses; however, it increases the control complexity and cost of the sensors [63]. There are two main types of AD: single loop and multiloop. Figure 1.14 shows the control block of an *LCL*-filter-based grid-tied inverter with a digital filter and AD with capacitor current feedback where $G_h(s)$ is the zero-order-hold delay, $G_d(s)$ is the computational delay, $1/T_s$ is the sampler, T_s is the sampling period, G_{inv} is the inverter gain, K_{ic} and K_{ig} are the feedback constants of the capacitor current and grid current, respectively, $G_c(s)$ is the proportional controller, and $H_{dig}(s)$ is the digital filter.

As shown in Figure 1.14, when $K_{ic} = 0$, a single-loop control AD is obtained. The digital filter $H_{dig}(s)$ used in single-loop control consists of a notch filter, lead-lag network, and bi-quad filter [64]. Alzola et al. [65] proposed a self-commissioning notch filter to deal with the variation in Z_g . However, this method still relies on the accuracy of the real-time resonance frequency estimation, which is inevitably affected by harmonics at the PCC. Yao et al. [66] suggested a digital notch-filter-based AD technique in which the notch filter frequency is different from the nominal resonant frequency of the *LCL* filter. Nevertheless, if multi-resonance peaks appear, this damping method may become ineffective.

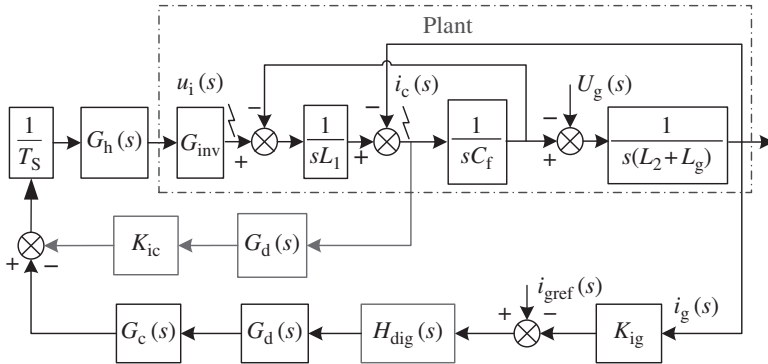


Figure 1.14 Control diagram of *LCL*-filter-based grid-tied inverter using a digital filter and AD method with capacitor current feedback.

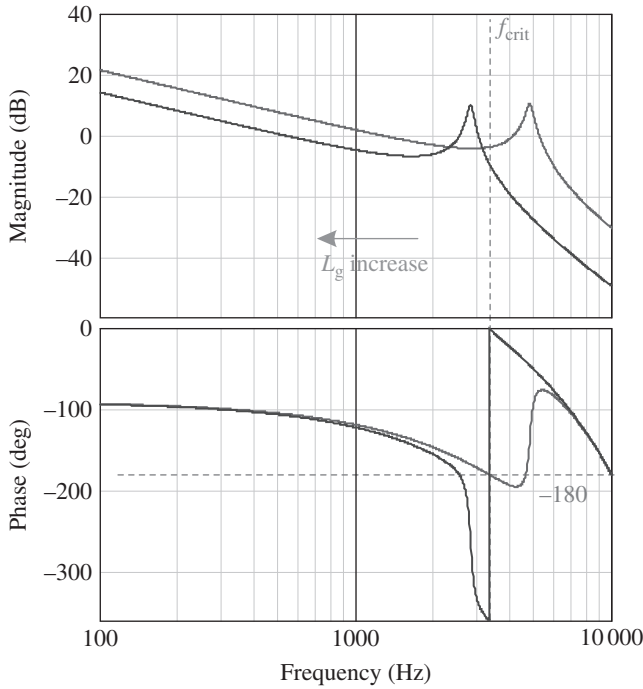


Figure 1.15 Open-loop gain $i_g(s)/i_{gref}(s)$ of system using capacitor current feedback damping method.

Multiloop AD methods include a virtual resistor [67–69], capacitor current feedback [70–75], capacitor voltage feedback [76–79], and LC -trap voltage feedback [80].

Figure 1.15 depicts the open-loop gain $i_g(s)/i_{gref}(s)$ of a current-controlled inverter using capacitor current feedback damping method only. When the characteristic frequency of the system is greater than f_{crit} , the system exhibits a non-minimum-phase response as a result of the appearance of right-half-plane poles, thus complicating the controller design.

Many different methods have been proposed for modifying the capacitor current feedback AD. Yang et al. [72] proposed a real-time computational method to reduce the computational delay, which can simplify the closed-loop design and improve the system performance effectively. However, when the grid voltage has many harmonics or many other factors exist that result in a sharp variation of duty cycle of the grid-tied inverter, this method will not work efficiently. Wang et al. [67] and Li et al. [74] aimed to increase f_{crit} from $1/6T_s$ to $1/4T_s$ or $1/3T_s$ by modifying the feedback loop where the damping region can be widened. However,

the high-pass filter inserted into the capacitor current feedback inner loop [67] increases the high-frequency noise interference and the proposed optimal damping coefficient in [74] cannot be derived precisely.

To ensure the stability of the system when f_r changes across f_{crit} , Pan et al. [70] modified the capacitor current feedback AD by inserting a phase-lag component in the control loop. With a digital delay of $0.75T_s$, this method can maintain system stability when Z_g varies widely. However, the phase margin of the system is not sufficiently large when the characteristic frequency is close to f_{crit} . To ensure a sufficient phase margin, Bao et al. [73] proposed the forbidden frequency region of $[(1 - \xi)f_{crit}, (1 + \xi)f_{crit}]$, where ξ is the coefficient of the forbidden region. Nevertheless, when ω_{res} is strictly less than $(1 - \xi)f_{crit}$, it is difficult to maintain high bandwidth of the system in a weak grid. Additionally, when f_r is strictly within the range of $[(1 + \xi)f_{crit}, 1/2T_s]$, it is difficult to maintain a good phase margin in the parametric design of *LCL* filter when Z_g varies significantly.

Similar to the capacitor current feedback AD method, the derivative feedback of capacitor voltage can also induce effective AD [76–78]. Using an *LLCL* filter, Huang et al. [80] compared the capacitor current feedback AD with the *LC*-trap voltage feedback AD and found that the latter had a wider damping region. However, as the grid voltage experiences a sudden and large change, it is difficult to choose a suitable feedback coefficient to ensure a satisfactory damping effect under different grid voltage conditions.

Furthermore, similar to the ID method, if multi-resonance peaks appear owing to the distributed capacitance of the cable, AD method (single-loop or multiloop) may not be effective especially when Z_g varies over a wide range and the grid background harmonics are abundant.

1.3.2.5 Hybrid Damping

Hybrid damping (HD) techniques have been discussed in previous research works [32, 81, 82]. These techniques result in a trade-off between the power losses and damping robustness of the system. Lei et al. [81] proposed a hybrid damper that uses a resistor in series with a filter capacitor along with capacitor current feedback control where the extra damping losses may be high. The *RC* damper is preferred in HD because the extra power losses are negligible [32, 61, 82].

Liu et al. [32] combined an *RC* damper with a digital notch filter to dampen the resonance caused by an *LLCL* filter. The control diagram is shown in Figure 1.16.

$$Z_c(s) = \frac{(R_d C_d s + 1)(L_f C_f s^2 + 1)}{L_f C_f C_d s^3 + R_d C_d C_f s^2 + (C_d + C_f)s}, \quad (1.5)$$

where R_d and C_d are the parallel PD resistor and capacitor, respectively. A high control bandwidth can be achieved when Z_g varies widely. Therefore, a

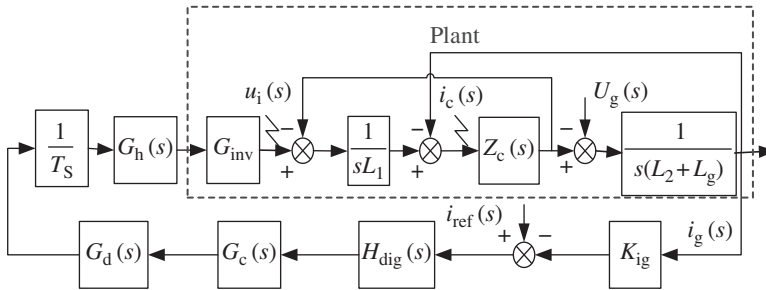


Figure 1.16 Control diagram of the hybrid damper composed of PD of RC and AD of the digital filter. *Source:* [32]/IEEE.

proportional plus resonant controller can be used to attenuate the low-frequency grid background harmonics.

1.3.3 Harmonic distortion Mitigation Methods

To mitigate the disturbances at the PCC caused by the source or nonlinear loads, there are three basic ways to suppress the effect of background harmonic voltage (BHV):

- 1) First is the grid-voltage feed-forward method, which is widely used to suppress the low-order harmonics of the grid-injected current [83–85]. For example, [9] adopted an adaptive feed-forward grid voltage method to obtain an appropriate phase margin or high control bandwidth while the equivalent grid impedance changes. However, the reliability of this method still relies on the accuracy of detection of the feed-forward grid voltage and estimated grid impedance; however, it is difficult to maintain reliability in a real grid full of high-order BHVs.
- 2) Second is to insert a proportional resonant regulator with a harmonic compensator (PR + HC regulator) for a grid-tied inverter using a low control bandwidth [86] where the lowest frequency of HC is higher than the control bandwidth under any grid condition. The compensated gain at the high-order harmonic frequencies should be large enough to suppress the effect of BHV, thus making the grid-tied inverter susceptible to the frequency drift of the grid.
- 3) Third is to adopt a PR + HC regulator for a grid-tied inverter based on a high-bandwidth control strategy [18, 87, 88] as presented in Figure 1.17a. In Figure 1.17b, the frequency of the highest HC should be within the control bandwidth under any grid condition to ensure the overall stability of the system. In this case, the control bandwidth of the grid-tied inverter is expected to be as high as possible in the weakest grid state.

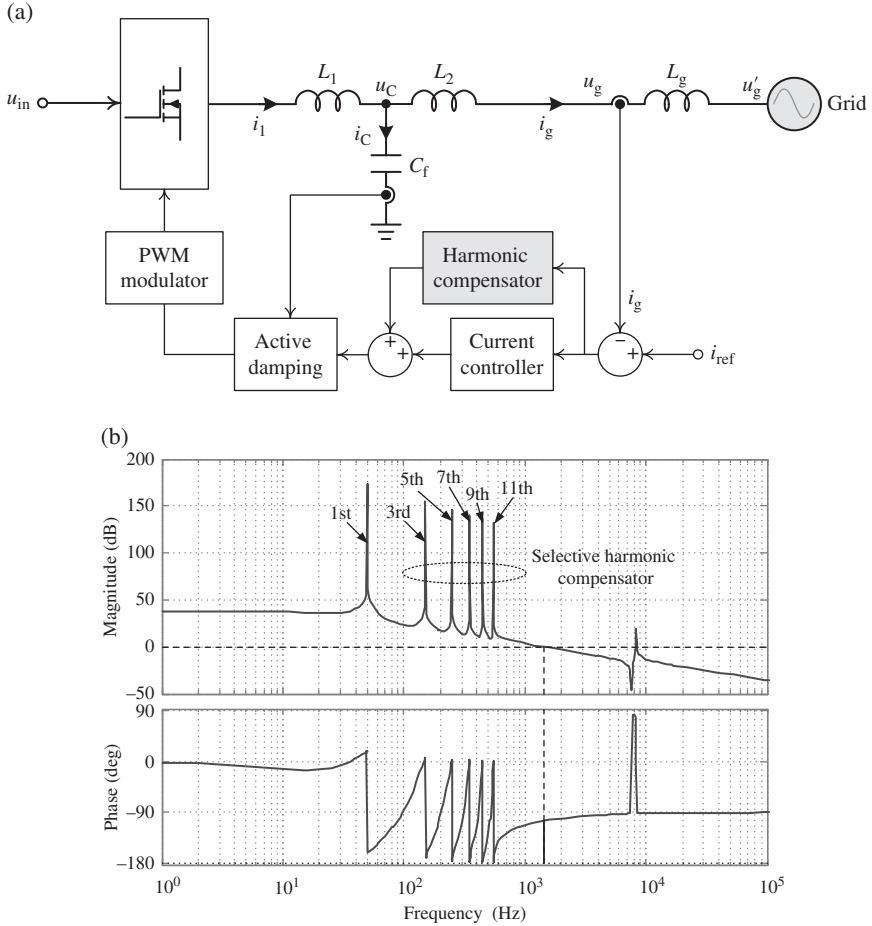


Figure 1.17 Control characteristics with selective harmonic compensator. (a) Control architecture; (b) open-loop gain.

1.4 Supplementary Note

In terms of topology, the *LCL/LLCL* filter design method introduced in this study can be used for single-phase inverters and three-phase four-wire grid-connected inverters. A similar idea of filter design can be used for three-phase three-wire grid-connected inverter circuits. The switching order and double-frequency switching order harmonics in the output voltage spectrum of a three-phase three-wire inverter with PWM modulation are relatively abundant. Therefore,

compared to the *LCL* filter, the advantage of *LLCL* filter in saving inductance is not obvious. Note: In the future, a three-phase three-wire grid-connected inverter system with a new filter topology scheme can be developed.

Additionally, the performance of the controller improves when the control of the grid-connected inverter gradually shifts from classic linear control [89] to nonlinear control [90–93] and finally develops into intelligent control. This study introduces the concept of classic linear control methods that are limited to the length and focus of this study. The nonlinear control of grid-connected inverters and intelligent control methods will be introduced in the future.

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