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3 Overview of Single-Phase Grid-Connected Photovoltaic Systems

Yongheng Yang and Frede Blaabjerg

ABSTRACT

A continuous booming installation of solar photovoltaic (PV) systems has been witnessed worldwide. It is mainly driven by the imperative demand of “clean” power generation from renewables. Grid-connected PV systems will thus become an even more active player in the future mixed power systems, which are linked together by a vast of power electronics converters and the power grid. In order to achieve a reliable and efficient power generation from PV systems, more stringent demands have been imposed on the entire PV system. It, in return, advances the development of the power converter technology in PV systems. This chapter thus gives an overview of the advancement of power electronics converters in single-phase grid-connected PV systems, being commonly used in residential applications. Demands to single-phase grid-connected PV systems and the general control strategies are also addressed in this chapter.

3.1 INTRODUCTION

Traditional power generations based on fossil fuel resources are considered to be unsustainable in long-term national strategies. This has been one of the main driving forces for an extensive installation of renewable energies like wind power, solar photovoltaic (PV) power, hydropower, biomass power, geothermal power, and ocean power into public grids in the last decade [1, 2]. Among the major renewables, solar PV power generation has continued to be expanded at a rapid rate over the past several years, and it already plays a substantial role in electricity generation in some countries [3]. As an example, approximately 7.9% of the annual electricity demand was covered by solar PV systems throughout 2014 in Italy [3]. In Germany, the total installed capacity had reached 38.2 GW
by the end of 2014, where most of the PV systems are residential applications [3–5]. Figure 3.1 illustrates the worldwide solar PV capacity evolution in the past 15 years [5], which shows increasing worldwide expectations from energy production by means of solar PV power systems. Therefore, as the typical configuration for residential PV applications, the single-phase grid-connected PV systems have been in focus in this chapter in order to describe the technology catering for a desirable PV integration into the future mixed power grid.

The power electronics technology has been acknowledged to be an enabling technology for more renewable energies into the grid, including solar PV systems [7]. Associated by the advancements of power semiconductor devices [8], the power electronics part of entire PV systems (i.e., power converters) holds the responsibility for a reliable and efficient energy conversion out of the clean, pollution-free, and inexhaustible solar PV energy. As a consequence, a vast array of grid-connected PV power converters have been developed and commercialized widely [9–15].

However, the grid-connected PV systems vary significantly in size and power—from small-scale DC modules (a few hundred watts) to large-scale PV power plants (up to hundreds of megawatts). In general, the PV power converters can simply be categorized into module-level (AC-module inverter and DC-module converter), string, multistring, and central converters [9, 10]. The multistring and central converters are intensively used for solar PV power plants/farms as three-phase systems [16–18]. In contrast, the module and string converters are widely adopted in residential applications as single-phase systems [19, 20]. Although the PV power converters are different in configuration, the major functions of the power converters are the same, including PV power maximization, DC to AC power conversion and power transfer, synchronization, grid code compliance, reactive power control, and islanding detection and protection [7, 21]. It also requires advanced and intelligent controls to perform these PV features and also to meet customized demands, where the monitoring, forecasting, and communication technology can enhance the PV integration [18, 21].

As mentioned previously, PV systems are still dominant in the residential applications and will even be diversely spread out in the future mixed grid. Therefore, state-of-the-art developments of single-phase grid-connected PV systems are selectively reviewed in this chapter. The focus has been
Overview of Single-Phase Grid-Connected Photovoltaic Systems

on power converter advancements in single-phase grid-connected PV systems for residential applications, which will be detailed in Section 3.3. First, demands from grid operators and consumers for single-phase PV systems are introduced in Section 3.2. In order to meet the increasing demand, the general control structures of single-phase grid-connected PV systems are discussed in Section 3.4 before the conclusion.

3.2 DEMANDS FOR GRID-CONNECTED PV SYSTEMS

The grid-connected PV systems are being developed at a very fast rate and will soon play a major role in power electricity generation in some areas [22, 23]. At the same time, demands (requirements) for PV systems as shown Figure 3.2 are increasing more than ever before. Although the power capacity of a PV system currently is still not comparable to that of an individual wind turbine system, similar demands for wind turbine systems are being transitioned to PV systems [18, 21] since the number of large-scale PV systems (power plants) is being continuously increased [24].

Nevertheless, the demands for PV systems can be specified at different levels. At the PV side, the output power of the PV panels/strings should be maximized, where a DC–DC converter is commonly used, being a double-stage PV system. This is also known as maximum power point tracking (MPPT). In this case, the DC voltage (DC-link voltage) should be maintained as a desirable value for the inverter. Moreover, for safety (e.g., fire), panel monitoring and diagnosis have to be enhanced at the PV side [25]. At the grid side, normally a desirable total harmonic distortion (THD) of the output current should be attained (e.g., lower than 5% [26]) for a good power quality. In the case of large-scale PV systems with higher power ratings, PV systems should not violate the grid voltage and the grid frequency by means of providing ancillary services (e.g., frequency regulation). Additionally, PV systems have to ride through grid faults (e.g., voltage sags and frequency variations), when a higher PV penetration level becomes a reality [18, 21, 27–33].

Since the power capacity per generating unit is relatively low but the cost of energy is relatively high, there is always a strong demand for high efficiency in order to reduce the cost of PV energy and also to optimize the energy yield. With respect to efficiency, the power electronics system (including passive components) accounts for most of the power losses in the entire PV system. Thus, possibilities to meet the efficiency demand include using advanced semiconductor devices, intelligent control, and power-lossless PV topologies. Transformerless PV technology is an example, and transformerless PV inverters can achieve a relatively high conversion efficiency when the isolation transformers are removed [11, 26]. However, minimizing the ground current in these transformerless

![Figure 3.2](https://example.com/image.png)

**FIGURE 3.2** Demands (challenges) for a grid-connected PV system based on power electronics converters (DC, direct current; AC, alternating current; $P_{pv}$, PV output power; $P_g$, active power; $Q_g$, reactive power).
3.3 POWER CONVERTER TECHNOLOGY FOR SINGLE-PHASE PV SYSTEMS

According to the state-of-the-art technologies, there are mainly five configuration concepts [2, 9, 37, 38] to organize and transfer the PV power to the grid as is shown in Figure 3.3. Each grid-connected concept consists of a series of paralleled PV panels or strings, and they are configured by a couple of power electronics converters (DC–DC converters and DC–AC inverters) in accordance with the output voltage of the PV panels as well as the power rating.

A central inverter is normally used in a three-phase grid-connected PV plant with the power greater than tens of kWp, as it is shown in Figure 3.4. This technology can achieve a relatively high efficiency with a lower cost, but it requires high-voltage DC cables [9]. Besides, due to its low immunity to hot spots and partial shading on the panels, the power mismatch issue is significant in this concept (i.e., low PV utilization). In contrast, the MPPT control is achieved separately in each string of the string/multistring PV inverters, leading to a better total energy yield. However, there are still mismatches in the PV panels of each string, and the multistring technology requires more power electronics converters, resulting in further investments. Considering the issues mentioned earlier, the module converters (DC-module converters and/or AC-module inverters) are developed, there being a flexible solution for the PV systems of low power ratings and also for module-level monitoring and diagnostics. This module-integrated concept can minimize the effects of partial shading, module mismatch, and different module orientations, etc., since the module converter acts on a single PV panel with an individual MPPT control. However, a low overall efficiency is the main disadvantage in this concept due to the low power.

As it can be seen in Figure 3.3, the module concept, string inverter, and multistring inverters are the most common solutions used in single-phase PV applications, where the galvanic isolation for safety is an important issue of concern. Traditionally, an isolation transformer can be adopted either at the grid side with low frequencies or as a high-frequency transformer in such PV converters as it is shown in Figure 3.5a and b. Both grid-connected PV technologies are available on the market with an overall efficiency of 93%–95% [26], mainly contributed to by the bulky transformers. In order to increase the overall efficiency, a large number of transformerless PV converters have been developed [9, 11, 26], which are selectively reviewed as follows.

3.3.1 TRANSFORMERLESS AC-MODULE INVERTERS (MODULE-INTEGRATED PV CONVERTERS)

In the last years, much more effort has been devoted to reduce the number of power conversion stages in order to increase the overall efficiency, as well as to increase the power density of the single-stage AC-module PV inverters. By doing so, the reliability and thereby the cost may be reduced. Figure 3.6 shows a general block diagram of a single-stage grid-connected AC-module PV topology, where all the desired functionalities, as shown in Figure 3.2, have to be performed. It should be noted that the power decoupling in such single-stage topology is achieved by means of a DC-link capacitor, $C_{DC}$, in parallel with the PV module [9, 11].
Overview of Single-Phase Grid-Connected Photovoltaic Systems

FIGURE 3.3 Grid-connected PV system concepts for: (a) small systems/residential, (b) small systems/residential, (c) residential, (d) commercial/residential, and (e) commercial/utility-scale PV applications.
FIGURE 3.4 Large-scale PV power plant/station based on central inverters for utility applications, where multilevel converters can be adopted as central inverters to manage even higher power of up to tens of megawatts (MW).

FIGURE 3.5 Single-phase grid-connected PV systems, where the AC-module inverters, the string inverters, and the multistring inverters are commonly used: (a) with a low-frequency (LF) transformer, (b) with a high-frequency (HF) transformer, and (c) without transformers. Note that $C_p$ represents the parasitic capacitor between the PV panel and the ground.

FIGURE 3.6 General block diagram of a single-stage single-phase PV topology (AC-module/string inverter system) with an AC filter.
Overview of Single-Phase Grid-Connected Photovoltaic Systems

Since the power of a single PV module is relatively low and is strongly dependent on the ambient conditions (i.e., solar irradiance and ambient temperature), the trend for AC-module inverters is to integrate either a boost or a buck-boost converter into a full-bridge (FB) or half-bridge (HB) inverter in order to achieve an acceptable DC-link voltage [39–45]. As it is presented in [39], a single-stage module-integrated PV converter can operate in a buck, boost, or buck-boost mode with a wide range of PV panel output voltages. This AC-module inverter is shown in Figure 3.7, where an LCL filter is used to achieve a satisfactory THD of the injected current to the grid. A variant of the AC-module inverter has been introduced in [40], which is actually a mix of a boost converter and an FB inverter. The main drawback of the integrated boost AC-module inverter is that it may introduce a zero-crossing current distortion. In order to solve this issue, the buck-boost AC-module inverters are preferable [41–44].

Figure 3.8 shows two examples of the buck-boost AC-module inverter topologies for single-phase grid-connected PV applications. In the AC-module inverter, as it is shown in Figure 3.8a, each of the buck-boost converters generates a DC-biased unipolar sinusoidal voltage, which is 180° out of phase to the other in such a manner as to alleviate the zero-cross current distortions. Similar principles are applied to the buck-boost-integrated FB inverter, which operates for each half-cycle of the grid voltage. However, as it is shown in Figure 3.8b, this AC-module inverter is using a common source.

In addition to the topologies mentioned earlier, which are mainly based on two relatively independent DC–DC converters integrated in an inverter, alternative AC-module inverters are also proposed in the literature. Most of these solutions are developed in accordance with the impedance–admittance conversion theory and an impedance network [46–52]. The Z-source inverter is one example, which is able to boost up the voltage for an FB inverter by adding an LC impedance network, as it is exemplified in Figure 3.9. Notably, the Z-source inverter was mostly used in three-phase applications in the past.

### 3.3.2 Transformerless Single-Stage String Inverters

The AC-module inverters discussed earlier with an integration of a DC–DC boosting converter are suitable for use in low power applications. When it comes to higher power ratings (e.g., 1–5 kWp), the compactness of AC-module inverters is challenged. In such applications, the most commonly used inverter topology is the single-phase FB string inverter due to its simplicity in terms of less power switching devices. Figure 3.10 depicts the hardware schematics of a single-phase FB string inverter with an LCL filter for better power quality. It is also shown in Figure 3.10 that a leakage current will circulate in the transformerless topology, requiring a specifically designed modulation scheme to minimize it. Conventional modulation methods for the single-stage FB string inverter topology include a bipolar modulation, a unipolar modulation, and a
hybrid modulation [26]. Considering the leakage current injection, the bipolar modulation scheme is preferable [26, 53]. Notably, optimizing the modulation patterns is another alternative to eliminate the ground (leakage) currents [54].

Transformerless structures are mostly derived from the FB topology by providing an AC path or a DC path by using additional power switching devices. This will result in isolation between the


**FIGURE 3.9** Single-phase Z-source-based AC-module inverter with an LCL filter.
PV modules and the grid during the zero-voltage states, thus leading to a low leakage current injection. Figure 3.11 shows two examples of single-stage transformerless PV inverters derived from the single-phase FB topology by providing a DC path [55, 56]. Thanks to the extra DC bypass, the PV strings/panels are isolated from the grid at zero-voltage states. Alternatively, the isolation can be achieved at the grid side by means of adding an AC path. As it is exemplified in Figure 3.12a,
the highly efficient and reliable inverter concept string inverter [57] has the same number of power switching devices as that of the H6 inverter, but it provides an AC path to eliminate the leakage current injection. Similarly, the full-bridge zero-voltage rectifier (FB-ZVR) topology is proposed in [58], where the isolation is attained by adding a zero-voltage rectifier at the AC side, as it is shown in Figure 3.12b.

It should be pointed out that there are many other transformerless topologies reported in the literature in addition to the solutions mentioned previously by means of adding an extra current path [26, 54, 59–62]. Taking the Conergy string inverter as an example, which is shown in Figure 3.13, a single-phase transformerless string inverter can be developed based on the multilevel power converter technology [26, 60, 61].

### 3.3.3 DC-Module Converters in Transformerless Double-Stage PV Systems

A major drawback of the single-stage PV topologies is that the output voltage range of the PV panels/strings is limited especially in the low power applications (e.g., AC-module inverters), which thus will affect the overall efficiency. The double-stage PV technology can solve this issue since it consists of a DC–DC converter that is responsible for amplifying the voltage of the PV module to a desirable level for the inverter stage. Figure 3.14 shows the general block diagram of a double-stage single-phase PV topology. The DC–DC converter also performs the MPPT control of the PV panels, and thus, extended operating hours can be achieved in a double-stage PV system. The DC-link capacitor $C_{DC}$ shown in Figure 3.14 is used for power decoupling, while the PV capacitor $C_{pv}$ is used for filtering.
In general, the DC–DC converter can be included between the PV panels and the DC–AC inverters. The inverters can be the string inverters as discussed earlier or a simple half-bridge inverter. The following illustrates the double-stage PV technology consisting of a DC–DC converter and an FB string inverter. Figure 3.15 shows a conventional double-stage single-phase PV system, where the leakage current needs to be minimized as well. However, incorporating a boost converter will decrease the overall conversion efficiency. Thus, variations of the double-stage configuration have been introduced by means of a time-sharing boost converter or a soft-switched boost converter [63, 64]. The time-sharing boost converter shown in Figure 3.16 is a dual-mode converter, where the switching and conduction losses are reduced, leading to a satisfactory efficiency.
An alternative to improve the efficiency can be achieved using a DC–DC converter with parallel inputs and series outputs in order to process the source energy one and a half times instead of twice. This topology has been introduced in [65] and is shown in Figure 3.17. It should be pointed out that the voltage step-up gain of the DC–DC converter is also improved at the same time. In addition, the impedance network–based DC–DC converters (e.g., the Z-source and Y-source networks) might be the other promising solutions for single-phase double-stage PV systems, due to the high step-up voltage gain [66–69], which might be beneficial in some applications.

3.4 CONTROL OF SINGLE-PHASE GRID-CONNECTED PV SYSTEMS

3.4.1 General Control Objectives and Structures

The control objectives of a single-phase grid-connected PV system [70] can be divided into two major parts: (1) PV-side control with the purpose to maximize the power from PV panels and (2) grid-side control performed on the PV inverters with the purpose of fulfilling the demands to the grid.
Overview of Single-Phase Grid-Connected Photovoltaic Systems

Power grid as shown in Figure 3.2. A conventional control structure for such a grid-connected PV system thus consists of a two-cascaded loop in order to fulfill the demands/requirements [32, 70]—

the outer power/voltage control loop generates the current references and the inner control loop is responsible for shaping the current, so the power quality is maintained, and also it might perform various functionalities, as shown in Figure 3.18.

Figure 3.19 shows the general control structure of a single-phase single-stage grid-connected PV system, where the PV inverter has to handle the fluctuating power (i.e., MPPT control) and also to control the injected current according to the specifications shown in Figure 3.18. As it can be observed in Figure 3.19, the control can be implemented in both stationary and rotating reference frames in order to control the reactive power exchange with the grid, where the Park transformation (dq → αβ) or inverse Park transformation (αβ → dq) is inevitable [70]. In terms of simplicity, the control in the stationary reference frame (αβ-reference frame) is preferable, but it requires an orthogonal system to generate a “virtual” system, which is in quadrature to the real grid. In the dq-reference frame, the MPPT control gives the active power reference for the power control loop based on proportional integral (PI) controllers, which then generate the current references as shown in Figure 3.19b. The current controller (CC) in the dq-reference frame can be PI controllers, but current decoupling is required in order to alleviate the interactive impact of the d-axis and q-axis currents in the synchronous rotating reference frame (i.e., the dq-reference frame). In contrast, enabled by the single-phase PQ theory [32, 71], the reference grid current \( i_g^* \) can be calculated using the power references and the in-quadrature voltage system. In that case, the PI controller will give an error in the controlled grid current. The controller (CC) should be designed in the αβ-reference frame. For example, a proportional resonant (PR) controller, a repetitive controller, or a deadbeat controller [70, 72–75] can directly be adopted as the CC as shown in Figure 3.19c.

Notably, since the CC is responsible for the current quality, it should be taken into account in the controller design and the filter design (e.g., using high-order passive filter, LCL filter). By introducing harmonic compensators [26, 32, 70, 72] and adding appropriate damping for the high-order filter [76, 77], an enhancement of the CC tracking performance can be achieved.

Similar control strategies can be applied to the double-stage system, as shown in Figure 3.20. The difference lies in that the MPPT control is implemented on the DC–DC converter, while the other functionalities are performed on the control of the PV inverter. There are other control solutions available for single-phase grid-connected PV systems [78–80]. For example, the instantaneous power is controlled in [79], where the synthesis of the power reference is a challenge; in [80], a one-cycle control method has been applied to single-stage single-phase grid-connected PV inverters for low power applications.

### 3.4.2 Grid Synchronization

It should be noted that the injected grid current is demanded to be synchronized with the grid voltage as required by the standards in this field [70]. As a result, grid synchronization is an essential grid monitoring task that will strongly contribute to the dynamic performance and the stability of the entire control system. The grid synchronization is even challenged in single-phase systems, as there is only one variable (i.e., the grid voltage) that can be used for synchronization. Nevertheless, different methods to extract the grid voltage information have been developed in recent studies [26, 70, 81–84] like the zero-crossing method, the filtering of grid voltage method, and the phase-locked loop (PLL) techniques, which are important solutions.

Figure 3.21 shows the structure of the PLL-based synchronization system. It can be observed that the PLL system contains a phase detector (PD), namely, to detect the phase difference, a PI-based loop filter (PI-LF) to smooth the frequency output, and finally a voltage-controlled oscillator (VCO). Accordingly, the transfer function of the PLL system [26, 84, 85] can be obtained as
FIGURE 3.18 General control blocks (control objectives) of a grid-connected single-phase PV system (PWM, pulse width modulation; MPPT, maximum power point tracking).
FIGURE 3.19 General control structure of a single-phase single-stage FB PV system with an LCL filter and reactive power injection capability (CC, PLL): (a) hardware schematics, (b) control block diagrams in the $dq$-reference frame, and (c) control block diagrams in the $\alpha\beta$-reference frame, where $L_t$ is the total inductance ($L_t = L_1 + L_2$), $V_{gm}$ is the grid voltage amplitude, $Z_g$ is the grid impedance, $P$ and $Q$ are the active and reactive power, and subscripts $d$ and $q$ indicate the corresponding voltage or current in the $dq$-reference frame.
FIGURE 3.20 General control structure of a single-phase double-stage grid-connected PV inverter with an LCL filter and reactive power injection capability (CC, PLL): (a) hardware schematics, (b) inverter control diagrams in the dq-reference frame, and (c) inverter control diagrams in the αβ-reference frame, where $L_t$ is the total inductance ($L_t = L_1 + L_2$), $V_{gm}$ is the grid voltage amplitude, $P$ and $Q$ are the active and reactive power, and subscripts $d$ and $q$ indicate the corresponding voltage or current in the dq-reference frame.
Overview of Single-Phase Grid-Connected Photovoltaic Systems

$$G_{PLL}(s) = \frac{\theta'(s)}{\theta(s)} = \frac{k_p s + k_i}{s^2 + k_p s + k_i}$$

(3.1)

which is a typical second-order system with $k_p$ and $k_i$ being the proportional and integral gain of the PI-LF, respectively. Subsequently, the corresponding damping ratio $\zeta$ and undamped natural frequency $\omega_n$ can be obtained, respectively, as

$$\zeta = \frac{k_p}{2\sqrt{k_i}} \quad \text{and} \quad \omega_n = \sqrt{k_i}$$

(3.2)

which can be used to tune the PI-LF parameters according to the desired settling time and resultant overshoot. More details about single-phase PLL synchronization techniques are directed to [26].

In literature, a vast array of PLL-based synchronization schemes has been reported [26, 70, 79, 81–88], while the major difference among the various PLL systems lies in the configuration of the PD unit. The most straightforward way is to use a sinusoidal multiplier [85], where the output contains a double-line-frequency term that requires more efforts to design a low-pass filter to filter it out. Thus, in prior-art PLL synchronization systems, more advanced PD techniques are adopted. Figure 3.22 exemplifies three possibilities for phase detection, namely,
forming the T/4 Delay PLL [26, 84], the enhanced PLL (EPLL) [87], and the second-order generalized integrator (SOGI)-based PLL system [88]. It can be seen in Figure 3.22 that the phase detection of the T/4 Delay PLL and the SOGI-PLL systems is enabled by the Park transformation ($\alpha\beta \rightarrow dq$), where a virtual voltage component $v_\beta$ in quadrature with the input grid voltage $v_\alpha$ is also generated. In contrast, the EPLL adopts an adaptive filter and a sinusoidal multiplier to detect the phase error $\varepsilon$.

Practically, the grid voltage is not purely sinusoidal, and it may be distorted or it may be sagged due to various severe situations like lightning strikes. This challenges significantly the synchronization of grid-connected systems. Hence, the PLL systems mentioned earlier are benchmarked when the grid suffers from disturbances, and the parameters of the PI-LF are set as $k_p = 0.28$ and $k_i = 13$, which roughly results in a settling time of 100 ms. Comparison results are summarized in Table 3.1. The benchmarking reveals that the SOGI-PLL is a good solution for single-phase applications in terms of high tracking accuracy and fast dynamic, where the grid voltage may experience various disturbances, for example, voltage sags and frequency variations.

In addition to the phase of the grid voltage, other grid condition information is also very important for the control system to perform special functionalities, for example, low-voltage ride through [27, 32], and flexible active power control to regulate the voltage level, where the grid voltage amplitude has to be monitored. Thus, advancing the monitoring technology is another key to a grid-friendly integration of grid-connected PV systems into the future mixed power grid and other energy systems (e.g., with integrated storage systems).

### 3.4.3 Operational Example

As discussed previously and also shown in Figure 3.18, operating a PV inverter system involves the control of different components of the system: at the PV side for power maximization, at the inverter side for proper injection of a high-quality current (power), and at the grid side for ancillary services [7, 26, 70]. In all cases, the PV panels are exposed to varying environmental conditions,
Overview of Single-Phase Grid-Connected Photovoltaic Systems

which are also referred to as mission profiles (i.e., solar irradiance level and ambient temperature). The mission profile should be considered in the design and planning phases of a PV system, since it affects the availability of PV energy. Hereafter, referring to Figure 3.20, the MPPT operation is demonstrated on a 3-kW double-stage single-phase PV system grid, where the grid-side control has been implemented in the \( \alpha\beta \)-reference frame (i.e., Figure 3.20c). A PI controller is adopted as the DC-link controller, and a PR controller is used as the CC with a resonant harmonic compensator (RHC). A SOGI-PLL is employed to generate the in-quadrature voltage system (i.e., for synchronization). The system and control parameters are given in Table 3.2.

For the MPPT control, a perturb and observe (P&O) method [13, 89–91] has been adopted for simplicity, as it is given in Figure 3.23a (see also Chapter 5 for more details). The entire CC is shown in Figure 3.23b. As it can be seen, the P&O MPPT algorithm gives the reference voltage for the PV panels (i.e., the voltage at the maximum power point), which is controlled by a proportional controller \( k_m \). In this chapter, \( k_m \) is designed as 0.00126. Since there might be background distortions in the grid voltage, the current quality should be enhanced by incorporating a harmonic compensator, which is an RHC as mentioned earlier. Actually, the RHC is a summation of multiple resonant controllers, whose central frequencies are placed at the targeted harmonics (e.g., the third, fifth, and seventh harmonics), as shown in Figure 3.23b. The CC and the RHC are designed as \( k_{pr} = 22 \), \( k_{p1} = 2000 \), \( k_{p2} = 1200 \), \( k_{pi} = 800 \), and \( k_{pi} = 200 \). Simulation models have been built up in MATLAB®/Simulink®/Simscape, as shown in Figure 3.24. The simulation results are shown in Figure 3.25, where the solar irradiance has experienced step changes under a constant ambient temperature of 25 °C, and the system was operated at unity power factor according to demands.

The step changes in the solar irradiance are actually to reflect the PV intermittency, which leads to a continuous injection of fluctuating PV power, as it is shown in Figure 3.25. The fluctuation could be even severer during daily operations, for example, cloudy days with passing clouds. Nevertheless, the P&O MPPT algorithm shown in Figure 3.23a can effectively maximize the power production from PV panels. Moreover, the use of a boost converter can extend the operating hours for PV systems, when the solar irradiance is very weak.

Additionally, in order to test the performance of the CC, a grid with background distortions has been considered. This results in a THD of 3.4% for the grid voltage. Hence, the PR controller with

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**TABLE 3.2**

Parameters of the 3 kW Two-Stage Photovoltaic Inverter System

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid voltage (root mean square [RMS])</td>
<td>( V_{gRMS} )</td>
<td>230 V</td>
</tr>
<tr>
<td>Grid frequency</td>
<td>( \omega_g )</td>
<td>314 rad/s</td>
</tr>
<tr>
<td>Grid impedance</td>
<td>( Z_g = (L_g, R_g) )</td>
<td>0.5 mH, 0.2 Ω</td>
</tr>
<tr>
<td>Boost inductor</td>
<td>( L )</td>
<td>2 mH</td>
</tr>
<tr>
<td>DC-link capacitor</td>
<td>( C_{DC} )</td>
<td>2200 μF</td>
</tr>
<tr>
<td>DC-link voltage reference</td>
<td>( V_{DC}^* )</td>
<td>400 V</td>
</tr>
<tr>
<td>LCL filter</td>
<td>( L_1 )</td>
<td>1.8 mH</td>
</tr>
<tr>
<td></td>
<td>( C_f )</td>
<td>2.35 μF</td>
</tr>
<tr>
<td></td>
<td>( L_2 )</td>
<td>1.8 mH</td>
</tr>
<tr>
<td>Boost converter switching frequency</td>
<td>( f_b )</td>
<td>20 kHz</td>
</tr>
<tr>
<td>Inverter switching frequency</td>
<td>( f_{inv} )</td>
<td>10 kHz</td>
</tr>
</tbody>
</table>
the RHC is enabled, which can maintain a high-quality grid current. Specifically, when the RHC is absent, the resultant THD of the grid current is around 3.6% at the nominal operating condition. In contrast, when the harmonic compensator is added in parallel with the PR controller, the harmonics in the grid current have been suppressed, thus leading to a THD of 2.1%. It is suggested using the provided model to identify the difference as an exercise.

3.5 SUMMARY

In this chapter, a review of the recent technology of single-phase PV systems has been conducted. Demands for the single-phase PV systems, including the grid-connected standards, the solar PV panel requirements, the ground current requirements, the efficiency, and the reliability of the single-phase PV converters have been emphasized. Since achieving higher conversion efficiency is always of intense interest, both the transformerless single-stage (with an integrated DC–DC converter) and the transformerless double-stage (with a separate DC–DC converter) PV topologies have been in focus. The review reveals that the AC-module single-stage PV topologies are not very suitable for use in the European grid, since it is difficult to achieve a desirable voltage, and thus, the daily operating time is limited. The AC-module inverter concept is very flexible for small PV units with lower power ratings. In contrast, the string inverters are gaining greater popularity in Europe due to the higher efficiency that they are able to achieve. Especially, when a DC–DC boost stage is included, the MPPT control becomes more convenient, and the operating time of the PV systems is then extended. Finally, the general control structures for both single-stage and double-stage transformerless PV systems are presented, as well as a brief discussion on the synchronization and monitoring technologies. Operational examples are also provided at the end of this chapter.
FIGURE 3.24 MATLAB®/Simulink® model of a double-stage single-phase grid-connected PV system.
REFERENCES


Overview of Single-Phase Grid-Connected Photovoltaic Systems


