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Review

Common-Ground Photovoltaic Inverters for Leakage Current Mitigation: Comparative Review

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Abstract: In photovoltaic systems, parasitic capacitance is often formed between PV panels and the ground. Because of the switching nature of PV converters, a high-frequency voltage is usually generated over these parasitic capacitances; this, in turn, can result in a common-mode current known as leakage current. This current can badly reach a high value if a resonance circuit is excited through the PV's parasitic capacitance and the converter's inductive components. Transformers are usually used for leakage current mitigation. However, this decreases the efficiency and increases the cost, size, and weight of the PV systems. Number of strategies have been introduced to mitigate the leakage current in transformer-less converters. Among these strategies, using common-ground converters is considered the most effective solution as it offers a solid connection between the negative terminal of PV modules and the neutral of the grid side; thus, complete mitigation of the leakage current is achieved. Number of common-ground inverters have been recently presented. These inverters are different in their size, cost, boosting capability, the possibility of producing DC currents, and their capability to offer multilevel shaping of output voltage. This work introduces a comprehensive review and classification for various common-ground PV inverters. Therefore, a clear picture of the advantages and disadvantages of these inverters is clarified. This provides a useful indication for a trade-off between gaining some of the advantages and losing others in PV systems. In addition, the potentials for optimization based on different performance indicators are identified.

Keywords: photovoltaic; transformer-less; leakage current; common-ground; grid

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1. Introduction

Among various renewable energy sources, photovoltaic (PV) is currently one of the most extensively used in the world. This is because of its abundance, easy availability, and pollution-free operation. In addition, with the rapid advancements in the material of manufacturing techniques, the cost of PV systems is continuously decreased. Therefore, it is expected to be the cheapest energy source for massive deployment in the future [1–3]. This will further increase the adoption and integration of PV systems into the utility grid. Single-phase connections are usually adopted for distribution grid connections where the power rating of PV systems is up to 10 kw [3–6].

A typical PV single-phase grid-connected inverter is illustrated in Figure 1, where Q is the negative terminal of the PV panel and represents a common reference point for the output inverter voltages, v_g is the grid voltage at the point of common coupling (PCC), C_{QG} is the parasitic capacitance of the PV panel, and L_1 and L_2 are the lumped inductances from the output inverter terminals to PCC; the value of these impedances include the harmonic filter impedance, the equivalent grid impedance and impedances of other stray elements. The parasitic capacitance of the PV panel (C_{QG}) is mainly measured between the PV terminals and the metal frame where PV panels are mounted, and its value depends on many factors such as the manufacturing methods of PV panels and cells, the mounting structure, weather conditions, and dust covering the PV panel. Thus, with varying atmospheric conditions, this parasitic capacitance could reach a high value [6,7].

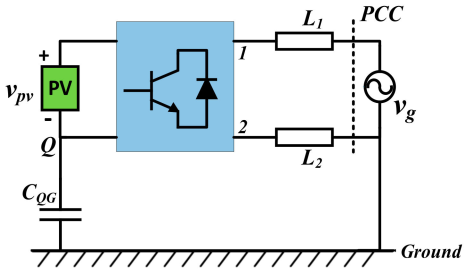


Figure 1. Typical single-phase grid-connected PV converter.

Due to the switching nature of PV converters, a high-frequency voltage component (known as common-mode voltage) may be produced over the parasitic capacitance of the PV panel. According to the used PV converter along with the adopted switching mechanism, the frequency of this voltage component can be identified. For instance, using of H-bridge converter with unipolar switching mechanism will produce common-mode voltage with a frequency equal to the switching frequency [1,6]. This, in turn, can generate common-mode current (known as leakage current), which can badly reach a high value if resonance is excited through the circuit formed by the PV stray capacitance and the circuit inductances. With equal line inductances (L_1 = L_2 = $L/2$) of the above-shown single-phase PV converter; this resonance frequency can be determined as follow [1]:

$$f_{res} = \frac{1}{2\pi\sqrt{LC_{QG}}} \tag{1}$$

With the increased penetration of PV systems into the utility grid, the common-mode voltage (CMV) and the resultant ground leakage current are becoming matters of great concern for both electric utility companies and PV systems owners; this is because of the following problems, which can be arisen due to these issues [8–11]:

- Undesirable tripping of residual current protection system;
- Deterioration of electromagnetic compatibility (EMC);
- Decreasing of PV modules lifetime;
- Harmonic distortion of the current injected into the grid;
- An electric shock for persons touching the PV module.

Galvanic isolation, by using of bulky line frequency (LF) transformer in the AC grid side or compact high-frequency transformer in power electronics interface, is usually adopted to deal with these safety issues. This galvanic isolation can also offer two other advantages for PV systems:

- It can eliminate the injection of DC current into the grid. Such DC current might result in saturation of the distribution transformers and electric motors along over the grid [12,13]. In addition, it can degrade power cables over time and affect normal load operation [14,15]. DC current injection may result due to several factors, such as asymmetric operation during positive and negative half-cycles, delays in gate drive circuits, and offset drift in the current sensing [14,15];
- Transformers can offer high boosting gain; thus, there is no need for series connection of PV modules for grid integration. This is highly desirable feature as it facilitates full use of PV modules during partial shading conditions [16–18].

However, using of transformers degrades of the power density, increases the cost, and decreases the efficiency of PV systems [3,8,13,16,17]. To overcome these problems, research efforts have been carried out to develop transformer-less PV converters with minimized leakage current and DC current components. To ensure their fulfillment of these safety requirements, specific standards must be complied with by PV grid-connected transformer-less converters. Among these standards, the Germany standard VDE-0126-1-1 stipulates the disconnection of PV systems from the grid in case of exceeding certain limits of leakage current; Table 1 lists the RMS values of these limits and the corresponding disconnection times [19]. On the other hand, according to IEC 61727 standard, generated DC currents from grid-connected systems should be limited to 1% of the rated current [20].

Table 1. Leakage current limits and their corresponding disconnection times according to VDE 0126-1-1 standard [19].

Leakage Current Value (mA)	Disconnection Time (msec)
30	300
60	150
100	40

- Generation mechanism of leakage current

The generation mechanism of leakage current can be explained by representing the above-mentioned single-phase PV system as shown in Figure 2a, where v_{1Q} and v_{2Q} are the voltages of the inverter terminals to the reference point Q. Two voltage components, differential-mode (DM) and common-mode (CM) can be identified in terms of v_{1Q} and v_{2Q} as follow:

$$v_{dm} = v_{1Q} - v_{2Q} \text{ and } v_{cm} = (v_{1Q} + v_{2Q})/2 \tag{2}$$

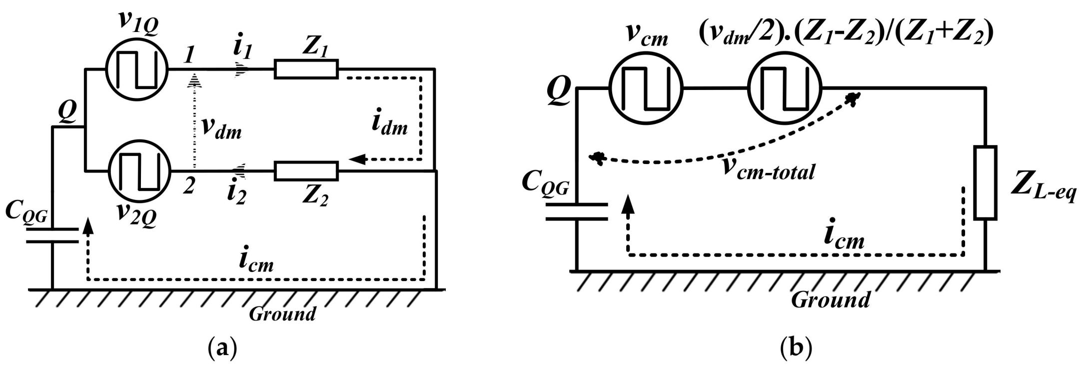


Figure 2. (**a**) Common-mode equivalent circuit of single-phase grid-connected converter, (**b**) simplified equivalent circuit for the total common-mode voltage.

The currents of the output inverter terminals, i_1 and i_2, can be expressed as follow:

$$i_1 = i_{dm} + i_{cm}/2 \text{ and } i_2 = i_{dm} - i_{cm}/2 \tag{3}$$

According to (1) and (2), a simple model for the total common-mode voltage ($v_{cm\text{-}total}$) is shown in Figure 2b, where $Z_{L\text{-}eq}$ is the parallel combination of two lines impedances ($Z_{L-eq} = \left(\frac{Z_1 Z_2}{Z_1+Z_2}\right)$). Thus, the total CMV component ($v_{cm\text{-}total}$) can be expressed as:

$$v_{cm-total} = v_{cm} + \frac{v_{dm}}{2}\left(\frac{Z_1 - Z_2}{Z_1 + Z_2}\right) \tag{4}$$

Accordingly, the unsymmetrical of the line impedances (Z_1 and Z_2) can produce another source for leakage current.

- Mitigation methods of leakage current

According to the above analysis, there are mainly three directions that can be adopted to eliminate or minimize leakage currents in single-phase PV connections:

- Using of common-mode (CM) chokes: this represents an effective solution to mitigate the leakage current in grid-connected systems [21]. These filters can be connected on either the DC side or the AC side of the inverter. To reduce the required size and weight, a number of configurations have been proposed for magnetic integration of the differential-mode (DM) and common-mode (CM) filters [22]. In these configurations, two types of coils use a common core; according to the DM and CM current directions, some coils attenuate the DM current component, and the other coils attenuate the CM current components. However, these filters introduce a significant increase in cost, size, and weight. In addition, the losses of these coils reduce the overall efficiency. Furthermore, core saturation at high leakage current values worse the overall system performance. Thus, large cores might be needed to avoid such scenario;
- Keeping constant CMV: Accordingly, no leakage current can be generated. According to the expression in (3), two conditions must be realized for this purpose:
    (1) Equal line impedances (Z_1 and Z_2). This requires two filter inductors with independent iron cores, which can result in increased size and cost.
    (2) Achieving constant value for CM component expressed in (1). Some effort has been reported in the literature to achieve constant CM component; two main directions are followed:
        a. Modulation-based method [1,3,4,6,8]. A simple way to realize the constant CM component is to use the full-bridge inverter with the bipolar sinusoidal PWM; this offers a constant CM at half of the DC bus voltage. However, compared to unipolar sinusoidal PWM, such modulation strategy results in high switching losses and high harmonic contents, which need a large filter size.
        b. Converter-based methods (modified full-bridge converters). To keep constant CM when the unipolar modulation is used, a number of topologies have been developed based on the full-bridge inverter, such as the H5 inverter and the HERIC inverter. The main idea of these topologies is the disconnection of PV from the grid during freewheeling mode. This is achieved through inserting extra switches into the full-bridge inverter either on the dc or ac side [9,23–25]. However, this will need extra switches, which increases the cost. In addition, perfect disconnection cannot be realized because of the switch parasitic capacitance [26].
- Bypassing the parasitic capacitance of PV through using common-ground converters. This represents the most effective solution as it offers complete mitigation of the leakage current by providing a solid connection between the negative terminal photovoltaic modules and the neutral of the grid side. In addition, the grounding of a PV system can minimize the effects of lighting and other surges [27].

Table 2 summarizes the above-mentioned solutions to mitigate the leakage current.

Table 2. Leakage current mitigation methods.

Mitigation Method		Advantages	Disadvantages
Using transformer-based converters		• Almost complete mitigation of the leakage current. • It can eliminate the injection of DC current into the grid. • Transformers can offer high boosting gain	• Transformers degrade of the power density, increase the cost, and decrease the efficiency of PV systems
Mitigation methods in transformer-less converters	Using common-mode (CM) chokes	• Compared to high-frequency transformers, it offers significant reduction in weight and size. Further reduction can be acquired using magnetic integration design.	• It causes increase in cost. • The losses of these coils reduce the overall efficiency. • Core saturation at high leakage current values can worsen the overall system performance. Thus, large cores might be needed to avoid such a scenario.
	Keeping constant CMV	• Modulation-based methods do not cause any increase in cost nor size.	• This requires two filter inductors with independent iron cores, which can increase size and cost. • Keeping constant CMV through bipolar modulation algorithms causes high switching losses and high harmonic contents, which need a large filter size. • Keeping constant CMV through using modified full-bridge converters will need extra switches, which increases the cost. In addition, perfect disconnection cannot be realized because of the switch parasitic capacitance.
	Using common-ground converters	• Compared to other techniques, it offers complete mitigation of the leakage current. • Grounding of PV systems can minimize the effects of lighting and other surges • Other features such as boosting capability, reduced DC current injections, and multilevel operation can be acquired through using certain common-ground converters.	• Careful design is needed to ensure the cost-effective and efficient operation of PV systems.

There are some survey articles that have been presented about leakage current mitigation methods in PV systems, e.g., the work of [1,3,8,10,28–30]. In this literature, a common-ground configuration has been presented as an effective solution for the leakage current problem; a few examples of common-ground inverters have been discussed in these papers. However, a large number of common-ground converters have already been presented in the literature. Up to our best knowledge, there is no reported work exploring the common-ground inverters and showing their advantages and disadvantages in terms of the other features required in PV systems; these features can include size, cost, boosting capability, possibility of block DC currents, and their capability to offer multilevel shaping of output voltage. Accordingly, this paper introduces comprehensive review and classification for various common-ground PV inverters. Thus, a clear picture of the advantages and disadvantages of these inverters is clarified. This provides a useful indication for a trade-off between gaining some advantages and losing others in PV systems. In addition, the potentials for optimization based on different performance indicators are identified. According to this study, some recommendations for future research topics are presented. Following this introduction, the common-ground converters are classified into current-source and voltage-source converters; the last category is further classified into bucking, boosting, and buck-boost converters. Then, a number of characteristics are identified. In terms of these characteristics, a detailed discussion for the different common-ground converters is introduced, and the advantages and disadvantages of the different common-ground converters are determined. Accordingly, general discussion is introduced to identify the best candidate converters for the cost-effective and efficient operation of PV systems. Finally, some research topics are suggested for future work, and a conclusion for the overall results is introduced.

2. Classification of Common-Ground Converters

Several CG converters have been reported in the literature. These converters can be classified into two categories:

- Current-source CG converters (CSCG);
- Voltage-source CG converters (VSCG); this category can be further classified as follow:
    (a) Bucking VSCG;
    (b) Boosting VSCG;
    (c) Buck/boost VSCG.

Table 3 lists the converters that belong to each of these categories and illustrates the following characteristics for each converter:

- Number of semiconductors (switches and diodes) and number of passive components (capacitors and inductors) along with their values adopted in the reported experimental results of each converter: this can imply the size, cost, complexity, and efficiency of these converters;
- Its capability to offer continuous input current is an important feature for the proper and efficient operation of maximum power point tracking (MPPT) in PV systems [31,32];
- Input/output voltage gain (for VSCS converters): high boosting gain is an important feature in PV converters. This can significantly reduce the capacitance required for power decoupling; in addition, this reduces the required number of series-connected PV modules for grid-tied systems;
- Number of available voltage levels (for VSCS converters): this can help to determine the required filter size; a higher number of voltage levels implies reduced filter size [33–35];
- Number of semiconductors conducted during positive and negative half-cycles of output inverter voltage. Asymmetric inverter operation through using an inequal number of semiconductors in the current path during positive and negative half-cycles can produce DC current components [14,15];
- The reported efficiency for each converter: this implies the total losses for each converter; these losses can be varied according to the converters' structure and switching mechanism.

In the following sections, the features and limitations of the converters belonging to each of the above groups are discussed.

Table 3. CG converters.

Topology				Total No. of Components (S: Switches, D: Diodes, C: Capacitors, L: Inductors)				No. of Semiconductors in Current Path		Output Voltage Levels	Voltage Gain	Is Input Current Continous?	Reported Efficiency
Type		Refs. No.		S	D	C (Capacitance)	L (Inductance)	+Half Cycle	-Half Cycle				
Current-source CG inverters		[36,37]		4	0	2 (3 and 2200 uF)	2 (0.25 and 0.5 mH)	2	2	-	$\frac{M}{1-M}$	Yes	95.7% @300 W
		[38]		5	0	1 (220 uF)	1 (0.3 mH)	2	2	-	NR	No	92.5% @200 W
		[39]		5	3	1 (NR)	1 (320 uH)	4	3	-	NR	No	NR
		[40] *		4	0	2 (NR)	1 + 1 (coupled) (NR)	2	2	-	$\frac{1-2M}{M(1-M)}$	Yes	NR
		[41]		3	0	2 (2 × 18.8 uF)	3 (675 uH and 2 × 1 mH)	2	2	-	$\frac{(1-2(1-D_1)(1+D_1))(2D_2-1)}{1-D_1}$	Yes	≈92.2% @200 W
Voltage-source CG inverters	Buck	[42–44]	I	4	1	2 (NR and 470 uF)	0	2	2	3	M	No	99.2 @1 kW
			II	4	1	2 (NR and 470 uF)	0	1	2	3		No	99.25 @1 kW
			III	4	0	2 (NR and 650 uF)	0	1	1	3		No	97.8 @1 kW
		[45]		4	0	2 (NR and 45 uF)	1 (230 uH)	2	2	2	M	No	96.1% @3 kW
		[46]		4	2	3 (470 and 330 and 220 uF)	0	2	2	3	M	No	97.4% @500 W
		[47]		5	0	2 (470 and 940 uF)	0	3	2	3	M	No	≈97% @500 W
		[48]		4	0	2 (NR and 1.1 mF)	0	2	2	3	M ($\leq$0.637)	No	97.04% @1 kW
		[49]		5	0	2 (100 and 400 uF)	0	3	3	3	M	No	≈97% @1 kW
		[50]		2	0	2 (250 and 110 uF)	1 (2 mH)	1	1	2	**NR**	Yes	≈96% @200 W
		[51]		8	0	3 (3 × 1 mF)	0	2/2	3/2	5	M	No	≈97.1% @800 W
		[52]		6	1	3 (2 × 0.5 mF and 2 mF)	0	3/2	3/3	5	M	No	≈95% @1.2 kW
		[53]		7	0	3 (1 and 2 × 2 mF)	0	2/3	3/3	5	M ($\leq$0.637)	No	≈97.5% @500 W

Table 3. *Cont.*

Topology		Total No. of Components (S: Switches, D: Diodes, C: Capacitors, L: Inductors)				No. of Semiconductors in Current Path		Output Voltage Levels	Voltage Gain	Is Input Current Continous?	Reported Efficiency
Type	Refs. No.	S	D	C (Capacitance)	L (Inductance)	+Half Cycle	-Half Cycle				
Boost	[54]	7	3	5 (4 × 4.7 and 32 uF)	4 (3 × 180 uH and 205 uH)	2	2	3	$\frac{3\,M}{1-D}$	Yes	≈94.43% @300 W
	[55] *	6	2	3	2	2	2	3	$M\left(\frac{1+M}{1-M}\right)$	yes	NR
	[56] *	6	5	3	1 (coupled)	3	3	3	$(1+n(2-M))\left(\frac{M}{1-M}\right)$	Yes	NR
	[57]	4	1	2 (2 × 1 m F)	1 (1 mH)	2	2	3	$\frac{1}{2}\left(\frac{M}{1-D}\right)$	Yes	NR
	[58,59]	5	0	1 (47 uF)	1 (0.2 mH)	3	2	3	$\left(\frac{M}{1-D}\right)$	Yes	≈95.5% @440 W
	[60]	3	5	6 (100 and 20 and 2 × 10 and2 × 120 uF)	1 + 1 (coupled)(600 and 220 uH)	1	1	2	$\left(\frac{1+n}{1-2D}\right)$	Yes	≈92.5% @200 W
	[61]	3	0	3 (3 × 100 uF)	1 + 1 (coupled)(240 and 60 uH)	1	1	2	$\left(\frac{(2n+3)(2D-1)+1}{2D}\right)$	Yes	≈90.5% @280 W
	[62]	6	2	3 (NR and 120 and 680 uF)	0	2/3	3/2	5	1+M	Yes	≈98.1% @900 W
	[63]	10	0	2 (0.94 and 0.47 mF)	1 (100 uH)	3/2	3/2	5	$\left(\frac{2}{1-M}\right)$	Yes	≈98.2% @1 kW

Table 3. *Cont.*

Topology		Total No. of Components (S: Switches, D: Diodes, C: Capacitors, L: Inductors)				No. of Semiconductors in Current Path		Output Voltage Levels	Voltage Gain	Is Input Current Continous?	Reported Efficiency
Type	Refs. No.	S	D	C (Capacitance)	L (Inductance)	+Half Cycle	-Half Cycle				
Buck/boost	[64] *	5	0	2 (NR and 47 uF)	1 (110 uH)	3	3	3	$\left(\frac{M}{1-M}\right)$	Yes	NR
	[65]	7	1	3 (3 × 10 uF)	0	2	1	3	$2M$	Yes	≈98.1% @500 W
	[66]	2	0	1 (1 uF)	2 (2 × 1.3 mH)	1	1	2	$\left(\frac{1-2M}{1-M}\right)$	Yes	≈93.5% @200 W
	[67,68]	6	2	2 (0.47 and 1 mF)	0	3/3	3/2	5	$2M$	Yes	≈98.1% @600 W
	[69]	6	0	1 (47 uF)	1 (110 uH)	2	3	3	NR	Yes	NR@250 W
	[70,71]	5	0	2 (11 uF and2.2 mF)	1 (52 uH)	2	3	3	$\left(\frac{M}{1-M}\right)$	Yes	≈93.5% @300 W
	[72]	5	2	2 (NR and 46 uF)	1 (110 uH)	3	4	3	$\left(\frac{M}{1-M}\right)$	Yes	NR
	[73]	5	1	2 (NR and 50 uF)	1 (110 uH)	2	2	3	$\left(\frac{M^2}{1-M}\right)$	No	NR @300 W
	[74]	6	0	2 (NR and 47 uF)	1 (110 uH)	2	3	3	NR	Yes	NR
	[75]	5	4	2 (2 × 1.36 mF)	1 (3 mH)	4	2	3	$\left(\frac{1}{1-3M}\right)$	yes	NR @500 W
	[76–78]	9	0	2 (2 × 1.64 mF)	0	3/4	3/4	5	$2M$	No	≈98.5% @1 kVA
	[79]	9	2	3 (2 × 0.47 and 1 mF)	0	2/2	2/2	5	$2M$	No	≈96.5% @600 W
	[80]	7	0	2 (2 × 1 mF)	1 (3 mH)	3/3	3/4	5	$\frac{M}{2(1-M)}$	Yes	NR
	[81]	8	0	3 (NR)	0	3/3	3/3	4	$(3/2)\,M$	Yes	NR
	[82]	4	0	1 (100 uF)	1 (3 mH)	2	2	3	$\left(\frac{M}{1-M}\right)$	Yes	≈96.5% @2 kW
	[83]	5	4	2 (NR and 2 × 6.8 uF)	3 (1 mH and 2 × 30 uH)	2	3	3	$\left(\frac{M}{1-M}\right)$	Yes	≈96.5% @400 W

NR: Not reported. * Experimental validation is not presented. M is modulation index of inverter; it is often ≤1; otherwise, else is stated. D is duty cycle. n is turns ration in case of using coupled inductors.

2.1. Current-Source CG Converters (CSCG)

Figure 3 shows the converters that belong to this group, and Table 4 summarizes the features and limitations of each converter.

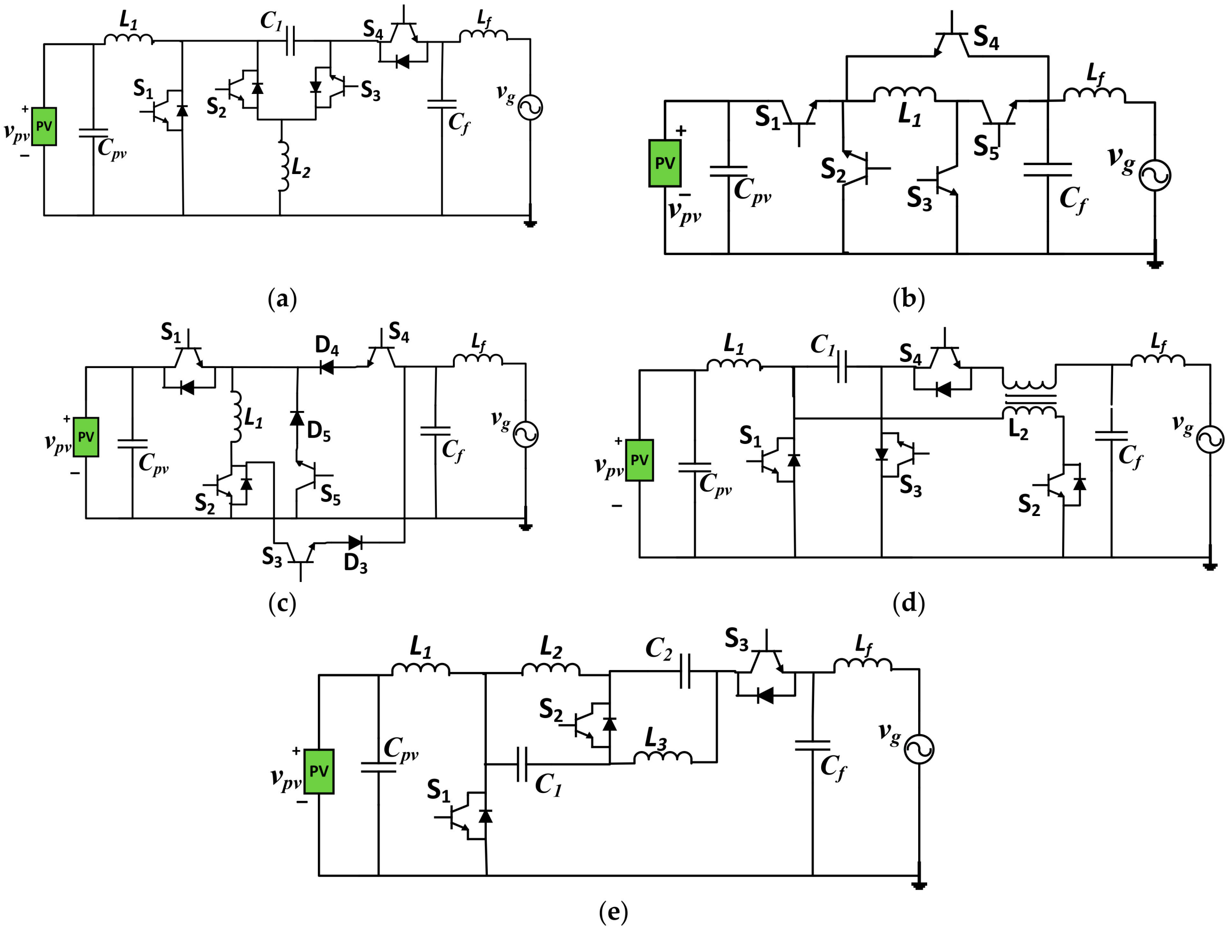


Figure 3. Current-source common-grounded (CSCG) converters. (**a**) Converter presented in the work of [36,37], (**b**) converter presented in the work of [38], (**c**) converter presented in the work of [39], (**d**) converter presented in the work of [40], (**e**) converter presented in the work of [41].

The following remarks can be reported about these converters:

- Current-source inverters usually use high inductance; this can increase the size, weight and decreases efficiency. Compared to other converters in this category, the converters introduced in [40,41] need a high number of magnetic components with relatively high inductances;
- Compared to other converters in this category, the converters introduced in [38,39] cannot offer continuous input current; thus, inefficient MPPT operation is highly expected. For the converter in [39], it also needs the highest number of semiconductors among all CSCG converters; this results in decreased efficiency and cost increase. Furthermore, this converter does not offer a symmetrical current path during positive and negative half-cycles; therefore, it may produce DC current component;
- Except for the converter presented in [38], the other converters of this category support bidirectional power flow. Therefore, they can be operated over a wide range of power factors;
- The CSCG converters introduced in [38–40] offer buck-boost operation. On the other hand, the CSCG converter introduced in [41] offers only boosting operation.

Table 4. Features and limitations of current-source CG converters.

Converter	Features	Limitations
Refs. [36,37]	• The input current is continuous. • Low number of switches is needed.	• High input capacitance is required for power decoupling. • High number of passive components are required • For practical implementation where there is a value for the element's resistance, the gain in the positive half-cycle is different from it in the negative half-cycle. Thus, DC current injection is expected.
Ref. [38]	• Low number of passive components is needed. • All the switches are unidirectional; thus, lower cost and high efficiency can be acquired.	• Its gain is varied according to the values of load power, switching frequency, and used inductance; Thus, for PV systems where the output power is varied with the environmental conditions, the gain is not constant. DC/DC boost converter may be needed for constant voltage gain, especially for grid integration. • All the switches are unidirectional; thus, they can only be used at unity power factor. • The developed MPPT algorithm is complicated as it is highly dependent on the system parameters, which can be varied with time. • The input current is not continuous. This adds more complexity to MPPT operation.
Ref. [39]	• Low number of passive components is needed.	• It needs a high number of semiconductors; therefore, the efficiency will be low, and the cost increases. • The input current is discontinuous • High input capacitance should be used for power decoupling • DC current generation is expected as an unequal number of switches is conducting during positive and negative half-cycles.
Ref. [40]	• The input current is continuous. • Low number of switches is needed.	• Using 2 magnetic components (one inductor and one coupled inductor) increases the cost and size and decreases the efficiency • High capacitance value may be needed for power decoupling.
Ref. [41]	• It uses the lowest number of switches; thus, low complexity can be acquired • The input current is continuous.	• Special attention should be taken when dealing with the dead-time between the switch's operations to avoid high stresses on the switches. • High number of passive components is needed; this increases the cost and decreases the efficiency • High input inductance value should be used.

2.2. Voltage-Source CG Converters (VSCG)

2.2.1. Bucking VSCG

Figure 4 shows the converters that belong to this group. Table 5 summarizes the features and limitations of each converter.

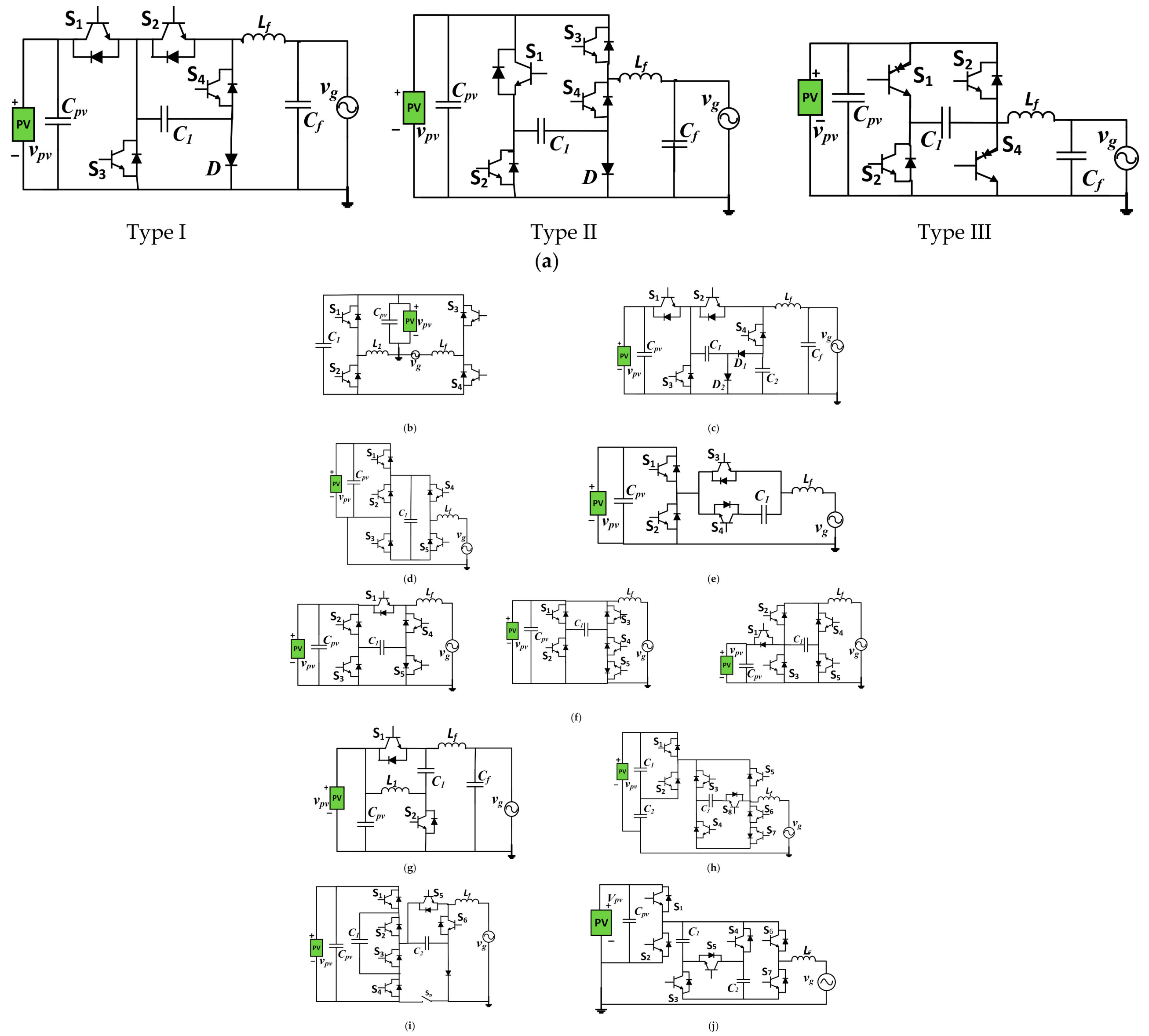


Figure 4. Voltage-source common-grounded (CSCG) converters (bucking type). (**a**) Converter presented in the work of [42–44], (**b**) converter presented in the work of [45], (**c**) converter presented in the work of [46], (**d**) converter presented in the work of [47], (**e**) converter presented in the work of [48], (**f**) converter presented in the work of [49], (**g**) converter presented in the work of [50], (**h**) converter presented in the work of [51], (**i**) converter presented in the work of [52], (**j**) converter presented in the work of [53].

Table 5. Features and limitations of voltage-source CG converters (bucking type).

Converter	Features	Limitations
Refs. [42–44]	• Low number of semiconductors is used. • No need for magnetic components; thus, reduced costs can be acquired.	• The input current is discontinuous. • In addition to the high input capacitance, one extra capacitor with a high capacitance value is needed to act as a flying capacitor to interchange the connection from the positive and negative half-cycles; this increases the failure rate and threatens the overall reliability. • Type 3 of these proposed topologies needs special reverse blocking IGBT (RB-IGBT) switches; this limits the switching frequency (<20 kHz). • Possibility of DC current generation in type 2 as an unequal number of switches is conducted during positive and negative half-cycles.
Ref. [45]	• It uses a low number of switches. • Low capacitance value is needed for power decoupling purposes.	• The input current is discontinuous. • It can only offer two voltage levels; a large filter should be used. • Asymmetrical inverter output voltage may be produced. The output inverter voltage is equal to the input voltage in the positive half-cycle and equal to the difference between the DC-link and the input voltage during the negative half-cycle. • The converter operation can result in the following drawbacks: ○ Very high DC-link voltage should be adopted; thus, more safety concerns should be considered. ○ Large number of PV modules should be connected in series as it should be higher than the peak grid voltage; thus, inefficient MPPT operation is highly expected, especially during shading conditions.
Ref. [46]	• No magnetic components are needed.	• The input current is discontinuous. • High number of semiconductors and passive components are needed • Inrush current may reach a high value during the charging of capacitors.
Ref. [47]	• No magnetic components are needed.	• Two capacitors with high capacitance values are needed • The input current is discontinuous. • Asymmetrical operation during positive and negative half-cycles as an unequal number of switches is conducted during positive and negative half-cycles. This can result in DC current injection. • The switches should be over-rated to withstand the current during the parallel connection of capacitors.

Table 5. *Cont.*

Converter	Features	Limitations
Ref. [48]	• It has a modular structure where higher voltage levels can be realized using a higher number of switches. • No magnetic components are needed.	• In addition to the input capacitor, another one with a high capacitance value is required • The input current is discontinuous. • Its modulation index is limited up to 0.637 at the unity power factor. This increases the required voltage input needed for grid integration. • Although its multilevel operation, the required high input voltage increases the required filter size; an 8 mH filter is used in the experimental work at a switching frequency of 15 kHz and power of 1 kW. This is a very large size. • Pre-charging of one of the capacitors is required, which makes its adequality for practical use requires pre-charging techniques. Autotransformer has been adopted in the experimental validation for this work.
Ref. [49]	• No magnetic components are needed.	• It needs a high number of switches and capacitors • The input current is discontinuous.
Ref. [50]	• It needs a low number of switches (2 switches only) • The input current is continuous.	• In addition to the input capacitor, another flying capacitor with a high capacitance value is required • High inductance value should be adopted to regulate the charging/discharging of the flaying capacitor and ensure continuous input current. • It can only offer two voltage levels; a large filter should be used. • Asymmetrical operation is expected as the flying capacitor is connecting to the output only during the negative half-cycle; thus, voltage variation on this capacitor may cause asymmetrical operation during positive and negative half-cycles.
Ref. [51]	• It can offer 5 output voltage levels; thus, a small filter size can be adopted.	• It needs a high number of switches; thus, more complexity arises. • Three capacitors with large capacitance values are needed. • The input current is discontinuous.
Ref. [52]	• It can offer 5 output voltage levels with a relatively lower number of semiconductors.	• The input current is discontinuous. • Three capacitors with large capacitance values are needed. • Pre-charging is needed for the flying capacitor. • Voltage balancing of DC-link capacitors adds more control complexity.
Ref. [53]	• No magnetic components are needed • It can offer 5 output voltage levels with a relatively lower number of semiconductors.	• Three capacitors with high capacitance values are needed • The input current is discontinuous. • Its modulation index is limited up to 0.637 at the unity power factor. This increases the required voltage input needed for grid integration.

The following remarks can be reported about these converters:

- Due to the bucking operation of these converters, a series connection of several PV modules must be used for grid integration. In addition, high capacitance must be adopted for power decoupling purposes;

- Except for the topology introduced in [50], all other converters in this category do not offer continuous input current. Therefore, improper MPPT operation is expected;
- To overcome the above issues, a front-end DC-DC converter is usually used with bucking VSCG converters. However, this results in increased cost and size;
- Among these topologies, the converters introduced in [51–53] can offer five voltage levels at the output. Thus, a reduced filter size is needed. On the other hand, the inverters introduced in [45,50] can only offer two voltage levels. Therefore, large filter size is needed. Such high filtering requirements can significantly diminish other features related to the use of a low number of components. All other inverters belonging to this category can offer three voltage levels;
- Among the inverters offering five voltage levels, the inverter in [52] uses a fewer number of switches than the other inverters introduced in [51,53]. However, extra electrolytic capacitors are needed for these converters (2 capacitors are needed for the converter in [52], three capacitors for the one in [51,53]). In addition, these converters need a pre-charging circuit to charge the voltages on their capacitors;
- The inverter introduced in [50] uses the lowest number of switches; it uses only two switches. Thus, its operation is not complex. On the other hand, the converter introduced in [51] uses eight switches, which implies complex operation;
- The bucking VSCG inverters introduced in [42–44,47,49,51,52] are suffering from using an inequal number of semiconductors in the current path during positive and negative half-cycles. Therefore, DC current component can be generated.

2.2.2. Boosting VSCG

Figure 5 shows the converters that belong to this group. Table 6 summarizes the features and limitations of each converter.

The following remarks can be reported about these converters:

- The boosting capability offered by these converters facilitates a reduction in the required decoupling capacitance. This can significantly improve reliability. In addition, all these converters offer continuous input current; this can significantly improve MPPT operation;
- The converters introduced in [56,60,61] uses coupled inductors to acquire high boosting capability. However, this results in increased cost and size also. On the other hand, the converters presented in [55,57,62] offer low boosting gain. Finally, the boosting gain offered by other boost converters is high; thus, no series connection of PV modules is needed for grid integration;
- Among these topologies, the converters introduced in [62,63] offer five levels at the output voltage. In addition, these converters do not need a pre-charging circuit to charge the voltages on their capacitors. However, high electrolytic capacitors may be needed for voltage balancing over these capacitors. On the other hand, the converters introduced in [60,61] can offer only two voltage levels. Thus, a large filter size is needed. All other inverters belonging to this category can offer three voltage levels;
- Among these converters, the converters introduced in [54–56,60] use a high number of semiconductors. This can significantly increase the cost and reduce efficiency.

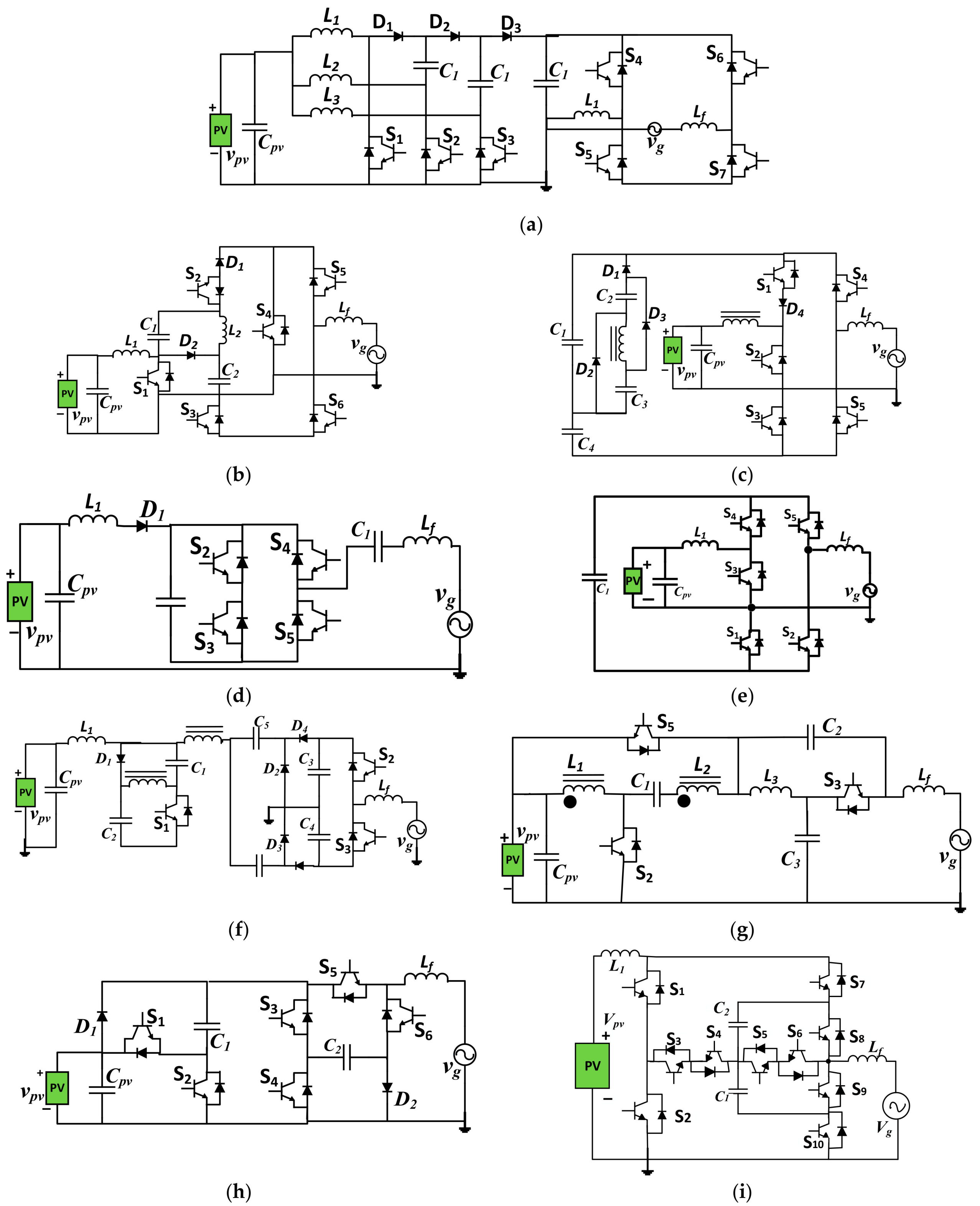


Figure 5. Voltage-source common-grounded (CSCG) converters (boosting type). (**a**) Converter presented in the work of [54], (**b**) converter presented in the work of [55], (**c**) converter presented in the work of [56], (**d**) converter presented in the work of [57], (**e**) converter presented in the work of [58], the work of [59], (**f**) converter presented in the work of [60], (**g**) converter presented in the work of [61], (**h**) converter presented in the work of [62], (**i**) converter presented in the work of [63].

Table 6. Features and limitations of voltage-source CG converters (boosting type).

Converter	Features	Limitations
Ref. [54]	• Although it uses a high number of passive elements, their values are low. Thus, film capacitors and small size magnetic components can be used. • It can offer high boosting gain; thus, it is very acceptable for grid integration. • The input current is continuous.	• High number of semiconductors are needed; this increases the complexity and reduces the reliability. • High voltage stresses on the inverter switches.
Ref. [55]	• The input current is continuous.	• High number of semiconductors is needed; thus, high complexity at a high cost is expected. • Its boosting gain is relatively low compared to other inverters belonging to this category. • High number of passive components is needed; thus, a large size is needed.
Ref. [56]	• High boosting gain can be acquired by controlling the turns ratio of the coupled inductor. • The input current is continuous.	• It needs a high number of semiconductors and passive components; thus, high complexity and large size, and high cost are highly expected. • Using the coupled inductor increases the size and reduces the efficiency.
Ref. [57]	• It needs a low number of switches. • The input current is continuous.	• Its boosting gain is relatively low compared to other inverters belonging to this category. • Two capacitors with high capacitance values are needed. In addition, high inductance should be used.
Refs. [58,59]	• The input current is continuous. • It offers high boosting gain.	• Asymmetrical operation during positive and negative half-cycles. This can result in DC current injection.
Ref. [60]	• It needs a low number of switches. • The input current is continuous. • High boosting gain can be acquired by controlling the turns ratio of the coupled inductor.	• It can offer only two voltage levels. Thus, a large filter size should be used. • It needs a high number of passive components. • It uses a high number of diodes. This increases the losses and decreases the efficiency • Using coupled inductors increases the size and decreases the efficiency.
Ref. [61]	• It uses a low number of switches; thus, low complexity can be acquired. • High boosting gain can be acquired by controlling the turns ratio of the coupled inductor. • The input current is continuous.	• It can offer only two voltage levels. Thus, a large filter size should be used. • It needs a high number of passive components; this increases the size. • It needs coupled inductor; thus, more size and reduced efficiency are expected.
Ref. [62]	• It can offer 5 voltage levels. Thus, small filter size is needed. • The input current is continuous.	• Asymmetric operation during positive and negative half-cycles. This can induce DC current component. • High capacitances are needed. • Its boosting gain low.
Ref. [63]	• The input current is continuous. • It can offer 5 voltage levels. Thus, small filter size is needed. • It offers high boosting gain.	• It needs a high number of switches. • High capacitances are required.

2.2.3. Buck/Boost VSCG

Figure 6 shows the converters that belong to this group. Table 7 summarizes the features and limitations of each converter.

The following remarks can be reported about these converters:

- The buck-boost feature offered by these converters makes it applicable for a wide range of power ratings. It can be used with module-integrated PV applications as well as with multi-series-connected PV modules;
- Among these converters, those introduced in [76–79] can offer five voltage levels on their outputs. This can significantly reduce the required filter size. On the other hand, the converter introduced in [66] can offer only two voltage levels. Thus, a large filter size is needed. All other converters belonging to this category can offer three voltage levels;
- The converters presented in [73,76–79] cannot offer continuous input current. This can result in the improper operation of MPPT;
- Among these converters, those introduced in [75,83] use a high number of diodes. This reduces efficiency. On the other hand, the converter introduced in [65] uses a high number of switches. This can significantly increase the cost and complexity of operation. These converters need this high number of semiconductors while offering only three voltage levels;
- Except for the converter presented in [64], all of these converters support bidirectional power flow; thus, they can be operated at different power factors;
- The converters introduced in [69–72,74–78] are suffering from asymmetric conducting paths during positive and negative half-cycles. Therefore, DC current component may be generated;
- The boosting gain offered by the converters presented in [65,67,68,73,76–81] is relatively low compared to the other converters belonging to this category.

3. General Discussion

With the continuous increase in PV systems integrated into the power grid, the leakage current problem is becoming of great concern as it can cause both safety and operational issues. Compared to other mitigation techniques, CG inverters becomes an interesting solution as it offers complete mitigation for the leakage current. It is highly recommended for CG inverters to combine the following features:

- Multilevel shaping of output voltage to reduce the filter size;
- Continuous input current for efficient operation of MPPT;
- Using the minimum number of semiconductors and passive components to reduce the overall cost, increase the efficiency and decrease the operation complexity;
- Low DC current generation to follow the related standards;
- Voltage boosting capability to reduce the required number of series-connected PV modules for grid integration. In addition, this can reduce the capacitance value needed for power decoupling purposes.

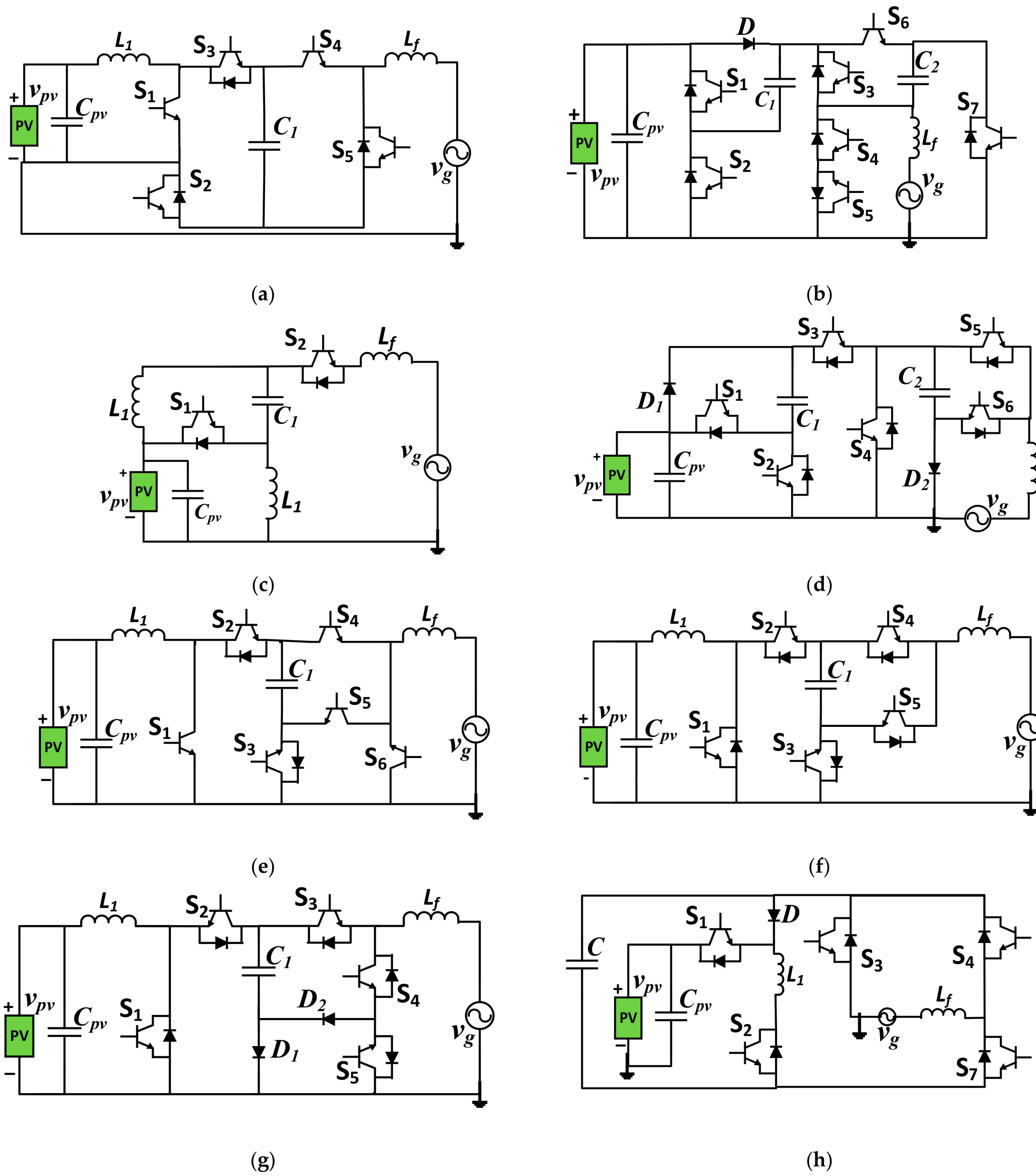
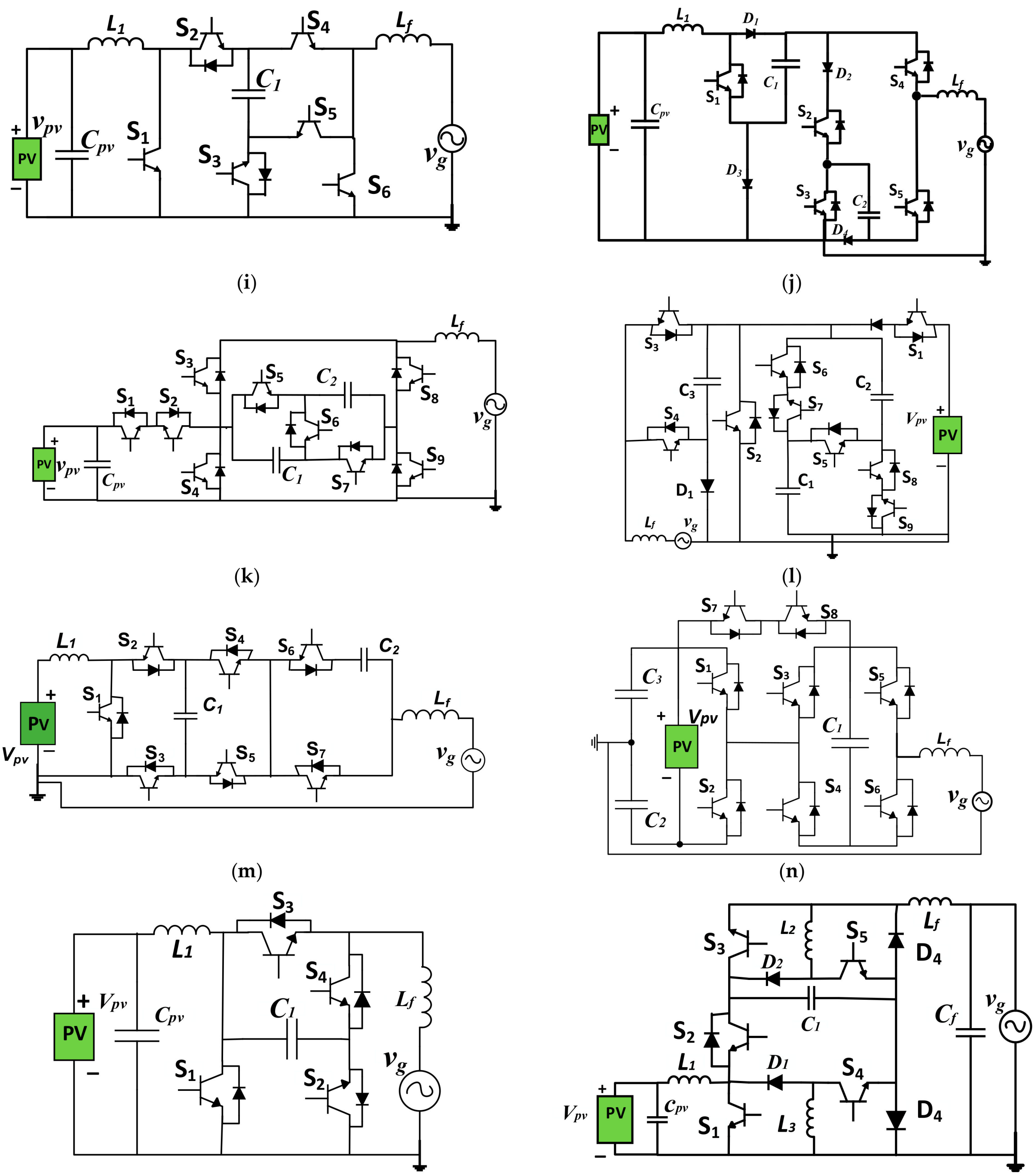


Figure 6. *Cont.*



(i) (j) (k) (l) (m) (n) (o) (p)

Figure 6. Voltage-source common-ground (CSCG) converters (buck/boost type). (**a**) Converter presented in the work of [64], (**b**) converter presented in the work of [65], (**c**) converter presented in the work of [66], (**d**) converter presented in the work of [67,68], (**e**) converter presented in the work of [69], (**f**) converter presented in the work of [70,71], (**g**) converter presented in the work of [72], (**h**) converter presented in the work of [73], (**i**) converter presented in the work of [74], (**j**) converter presented in the work of [75], (**k**) converter presented in the work of [76–78], (**l**) converter presented in the work of [79], (**m**) converter presented in the work of [80], (**n**) converter presented in the work of [81], (**o**) converter presented in the work of [82], (**p**) converter presented in the work of [83].

Table 7. Features and limitations of voltage-source CG converters (buck/boost type).

Converter	Features	Limitations
Ref. [64]	• The input current is continuous.	• High capacitance values may be needed. • It does not support bidirectional power flow.
Ref. [65]	• The input current is continuous. • It needs low values of capacitance.	• Its boosting gain is low. • Asymmetric operation during positive and negative half-cycles. This can induce DC current component. • It needs a high number of switches; thus, more complexity arises.
Ref. [66]	• It uses a low number of switches; thus, low complexity can be acquired. • Low capacitance value is needed. • The input current is continuous.	• It needs 2 inductors with a high inductance value; this increases the size. • It can offer only two voltage levels. Thus, a large filter size should be used.
Refs. [67,68]	• It can offer 5 voltage levels. Thus, small filter size is needed. • The input current is continuous. • No magnetic components are needed.	• It needed high capacitance values. • Its boosting gain is low. • The switches should be over-rated to withstand the currents during capacitors connecting/disconnecting.
Ref. [69]	• The input current is continuous.	• High number of switching is required. • Its boosting gain is not reported. • Asymmetric operation during positive and negative half-cycles. This can induce DC current component.
Refs. [70,71]	• The input current is continuous.	• Also, considering the internal losses of the components, the voltage gain during positive and negative half-cycles is significantly unequal. This can result in large values of DC currents. • High capacitance values are needed.
Ref. [72]	• The input current is continuous.	• High number of semiconductors is needed. • Large input capacitance is needed for power decoupling • It cannot support bidirectional power flow. • Asymmetric operation during positive and negative half-cycles. This can induce DC current component.
Ref. [73]		• The input current is discontinuous. • The boosting gain is low. • High capacitance value is needed.
Ref. [74]	• The input current is continuous.	• Asymmetric operation during positive and negative half-cycles. This can induce DC current component. • High input capacitance is required.
Ref. [75]	• The input current is continuous. • High boosting gain can be acquired.	• Asymmetric operation during positive and negative half-cycles. This can induce DC current component. • High number of semiconductors. • Large capacitance values are needed. • Large magnetic components are needed.

Table 7. *Cont.*

Converter	Features	Limitations
Refs. [76–78]	• It offers 5 voltage levels. • No magnetic components are needed.	• The input current is discontinuous. • Large number of switches is needed. Thus, more complexity and low reliability are expected. • High capacitances are required for boost operation • The switches should be over-rated to withstand the capacitors currents during connection and disconnection • The boosting gain is low.
Ref. [79]	• It offers 5 level operation. • No magnetic components are needed.	• Discontinuous input current • 3 capacitors with large capacitances are needed. • High number of components increases the cost and size. • The switches should be over-rated to withstand the capacitors currents during connection and disconnection • The boosting gain is low.
Ref. [80]	• It can offer 5 voltage levels. Thus, a small filter size is needed. • The input current is continuous.	• Two capacitors with high capacitance values are needed • High magnetic inductance is required • Its boosting gain is relatively low.
Ref. [81]	• It can offer 4 voltage levels. • No magnetic elements are needed.	• It cannot offer a zero-voltage state; thus, a larger filter size is required compared to five level topologies • It needs a high number of capacitors, and the high capacitance value is expected to balance the capacitors voltages • Its boosting gain is low.
Ref. [82]	• The input current is continuous. • Low number of switches.	• Large inductance value is needed.
Ref. [83]	• The input current is continuous.	• It needs a high number of semiconductors. • High input capacitance is needed.

In view of these required features for PV systems, along with the associated advantages and disadvantages of the different CG converters, the following converters can represent suitable candidates for PV systems.

- The buck/boost CG inverter is presented in [82] and shown in Figure 6o. This inverter needs only four switches while it can offer continuous input current along with high boosting gain. In addition, it does not need a high capacitance value for power decoupling; only one capacitor with 100 uF has been adopted for the 2 kW prototype. This inverter does not use any diodes. The reported efficiency is about 96.5% for a 2 kW prototype. This inverter can offer only three voltage levels; thus, compared to other inverters with more voltage levels, a larger filter size is needed;
- The boost CG inverter is presented in [58,59] and shown in Figure 5e. This inverter can offer continuous input current along with high boosting gain. In addition, it does not need a high capacitance value for power decoupling; only one capacitor with 47 uF has been adopted for the 440 W prototype. This inverter needs five switches and does not use any diodes. The reported efficiency is about 95.5% for the 440 W prototype. This inverter can offer only three voltage levels. DC current component can be generated due to using an inequal number of switches during positive and negative half-cycles;
- The current-source CG inverter is presented in [36,37] and shown in Figure 3a. This inverter needs only four switches while it can offer continuous input current along

with high boosting gain. This inverter does not use any diodes. The reported efficiency is about 95.7% for the 300 W prototype. However, it needs a high capacitance value for power decoupling; one capacitor with 2.2 mF has been used for the 300 W prototype. In addition, it needs two inductors (0.25 and 0.5 mH); this can increase the size and cost;

- The boost CG inverter is presented in [54] and shown in Figure 5a. This inverter can offer high boosting gain along with continuous input current. In addition, low capacitance and inductance values are needed. However, this inverter needs seven switches and three diodes; this increases its cost and decreases efficiency. This inverter can offer only three voltage levels. The reported efficiency is about 94.4% for the 300 W prototype;
- The boost CG inverter is presented in [63] and shown in Figure 5i. This inverter can offer five voltage levels, high boosting gain, and continuous input current. The reported efficiency is about 98.2% for a 1 kW prototype. However, this inverter needs 10 switches; this increases its cost along with operational complexity. In addition, it uses high capacitances; two capacitors with 0.94 and 0.47 mF are adopted for the 1 kW prototype;
- The buck/boost CG inverter is presented in [67,68] and shown in Figure 6d. This inverter can offer five voltage levels along with continuous input current. The reported efficiency is about 98.1% for the 600 W prototype. This inverter needs six switches and two diodes. In addition, it uses high capacitances. Its boosting gain is relatively low (2M).

4. Recommendations for Future Work

In view of the above-mentioned features required for PV converters, along with the associated advantages and disadvantages of the different common-ground inverters presented above, the following topics can be highlighted for future research:

- Quantitative evaluation for the different common-ground converters to reflect their differences in terms of specific features;
- This could help multi-input CG converters: such converters can use a reduced number of switches to process the power from several PV sources without the need for a series connection. This can significantly reduce the cost and increase the power density;
- Modular multilevel CG converters: such inverters can offer a high number of voltage levels; thus, reduced filter size can be used;
- Developing high boosting gain CG converters applicable for module-integrated PV applications.

5. Conclusions

This paper introduces a comprehensive review of the common-ground converters reported in the literature to eliminate leakage current produced due to the stray capacitances in PV systems. The generation mechanism of leakage current in the PV system is illustrated. Accordingly, it was illustrated the effectiveness of such topologies compared to other methods to mitigate the leakage current. The common-ground topologies are classified into current-source and voltage-source topologies, which are further divided into buck, boost, and buck-boost converters. The following characteristics are determined for each converter to define its advantages and disadvantages to be used in PV systems: (1) number of components (semiconductors and passive components), (2) number of produced voltage levels, (3) the capability to offer continuous input current, (4) symmetry of the current path during positive and negative half-cycles, and (5) the reported efficiency for each converter. Accordingly, the advantages and disadvantages are identified for each converter. In view of the required features for PV systems along with the associated advantages and disadvantages of the different CG converters, six CG converters shown in Figure 3a, Figure 5a,e,i, and Figure 6d,o are selected as suitable candidates for cost-effective and efficient operation of PV systems. Finally, some research topics have been highlighted for future development.

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