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A Review on the State of the Art of the Transformerless Converters for PV Systems

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Abstract

Transformerless converters for PV systems have been a field of interest for researchers for decades. The transformers make the system bulky, costly, and inefficient. With the advancement of photovoltaic and power electronic technology, it was hoped to eliminate the transformer. Constraints were posed in the form of ratings for semiconductor devices, PV source voltage requirements, efficiency, filter size, THD, and, most importantly, the leakage current problem in a grid-connected PV system. The smart grid aimed to incorporate distributed energy resources, which led to grid-connected PV systems. So, new topologies were proposed, and isolated converters evolved over time. Transformerless inverter topologies aim to address leakage current issues without using isolation transformers. The objective of this paper is to present a review and comparison of existing transformerless converters, with a focus on inverter topologies for leakage current reduction, based on major technical parameters, in a way that is helpful for seekers to readily find information. Most recent developments have been incorporated.

Keywords: Grid-connected PV System; Transformerless converter; Inverter topologies; Leakage current; Common-mode voltage.

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1. Introduction

Renewable energy sources, especially solar and wind, are rapidly replacing conventional sources due to their depletion and other issues. With a current installed capacity of 48.56 GW [1] in India and growing, solar energy offers the most promising alternative for future energy demands.

Solar energy can be converted into electrical energy by two methods: (i) Photovoltaic (PV) System and (ii) Concentrated Solar-thermal Power System. Due to its simple structure, versatility, and lower initial and running costs, the PV system is more common.

The photovoltaic system consists of a PV module, which is fundamentally a series-parallel combination of PV cells in order to generate the required voltage and current. The module generates a DC voltage proportional to the solar radiation. Even a series-parallel combination of multiple PV modules can meet the supply requirement. The combination of series-connected modules is called a string. For AC applications, the module's DC output must be converted to AC using an inverter. If the voltage level of the generated power is not as desired, a DC-DC converter on the DC side of the inverter or a transformer on the AC side would be required.

The power converters in a PV system perform several jobs, viz., islanding detection and protection, reactive power control, grid code compliance, synchronization, power transfer, DC/AC conversion, and Maximum Power Point Tracking (MPPT) [3].

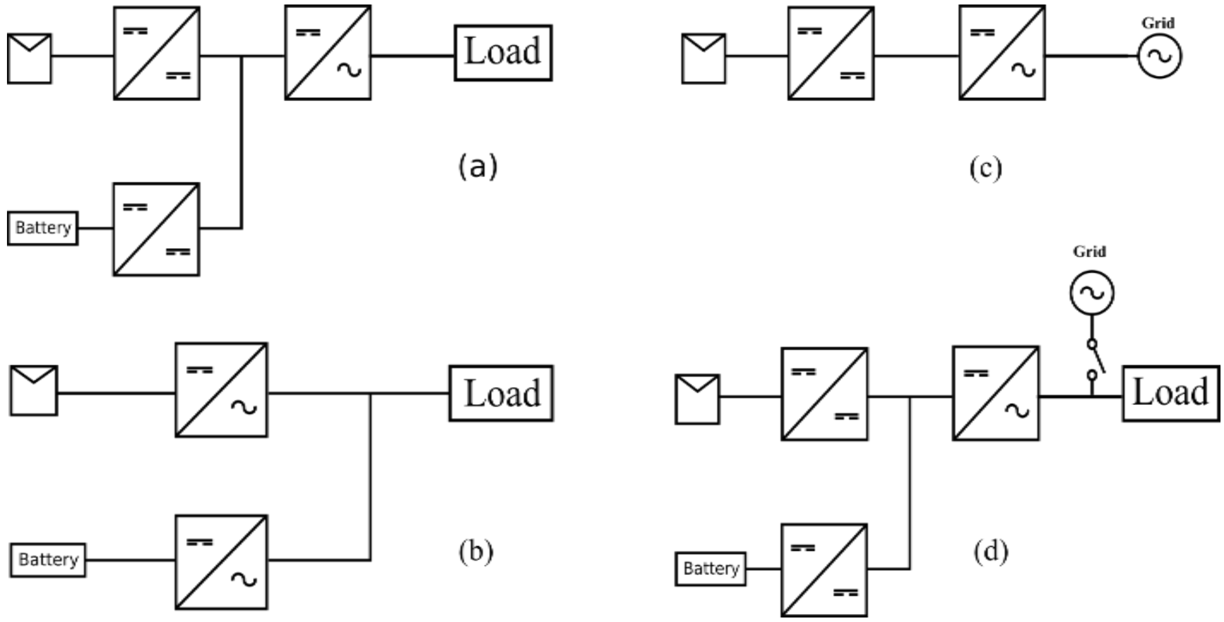


Fig.1. Various Topologies for PV System

2. Classification of PV Systems

The PV system may be used as a standalone system or a grid-connected system. A battery for power storage may or may not be required. The two sources, namely the PV module and the battery, may be coupled on the DC or AC side. The type of converter, i.e., DC/DC or DC/AC, to be used is also variable according to needs. The permutation and combination of the above-mentioned variations make possible several topologies, each of them having their advantages, drawbacks, and applications.

Fig.1 shows some of the systems formed using the above combinations. Fig. 1(a) shows a standalone system with a battery coupled to the PV module. Both sources have been coupled through a boost DC-DC converter. DC coupling allows a flexible voltage range for the PV module and the battery. Fig. 1(b) shows a standalone, AC-coupled system using inverters. The AC coupling offers better power flexibility. Fig. 1(c) shows a grid-connected system with a DC-DC converter and an inverter. Fig. 1(d) is a hybrid system that allows for both standalone and grid-connected operation. The PV source shown is usually a combination of several modules.

The converters and MPPT units may be installed individually for every PV module, or there may be a central unit for the whole system, and there may be a trade-off as well by treating a string of modules as one source. The individual MPPTs more effectively deal with the partial shading issue [4]

3. DC-DC Converters for PV Systems

The DC-DC converter stage is required in a PV system only when the voltage generated by the photovoltaic stage is less than the peak voltage of the grid (i.e., 325V for a 230V grid), otherwise, the inverter stage is sufficient to perform the above-mentioned jobs of the power converters in a PV system (refer to section 1).

The PV sources are usually designed to generate low voltage. Thus, a high-gain DC-DC converter is needed. There exist conventional boost converters (CBC) and quadratic boost converters (QBC). The latter have a much higher gain and less stress upon switches. [5] proposes a high-gain converter that achieves a quadratic boost through minimum components. The DC-DC converters may be classified as isolated and non-isolated converters, unidirectional and bidirectional converters, voltage-fed and current-fed converters, hard-switched and soft-switched converters, and single-level and multilevel converters.

While the research continues to explore the possibilities of using different techniques, some have proved to be more preferable than others. The non-isolated converter is preferred because it eliminates the need for a transformer, making it simple and inexpensive. The output side may be grounded or floated only if it is permissible. But for use in high-power applications, magnetic coupling is necessary. Isolated converters may use transformer or inductor coupling. [6]
Unidirectional converters are adequate when no energy storage is needed, otherwise, a bidirectional DC-DC converter is inevitable. The current source-fed converters have the advantage of lower input ripple due to the input

inductors. Soft switching in power converters improves efficiency and reduces the switch rating requirements. [7]

The PV source consists of multiple modules. Using a multilevel converter instead of a single-level one offers better MPPT, reliability, cost effectiveness, and safety. [8]

The DC-DC converter topologies used in PV systems, in the case of isolated converters, are simple boost, Zeta, Cuk, and SEPIC. The flyback, forward, push-pull, half-bridge, and full-bridge converters are all common, especially in the case of non-isolated converters.

4. Inverters for PV Systems

Apart from DC/AC conversion, the inverters are capable of performing the job of DC link voltage control and, hence, the control of the flow of active and reactive power. They also perform maximum power point tracking. Thus, the inverters are sufficient if the voltage generated by the PV source is equal to or greater than the peak value of the sinusoidal voltage on the output side. In another case, a voltage step-up device is inevitable. [9]

A grid-connected PV system suffers from the issue of leakage current due to the parasitic capacitance of the PV module. When the connecting wires of the PV cells have an electric potential, a capacitance called parasitic capacitance exists between the wires and the grounded metallic frame. The parasitic capacitance has a small value that depends on the PV module's power rating, the size of the metallic frame, and atmospheric conditions. It causes a small amount of current to flow along the path- PV panel, ground impedance, grounding at the substation, output filter, power converter, and back to the PV panel. This has been illustrated in Fig. 2.

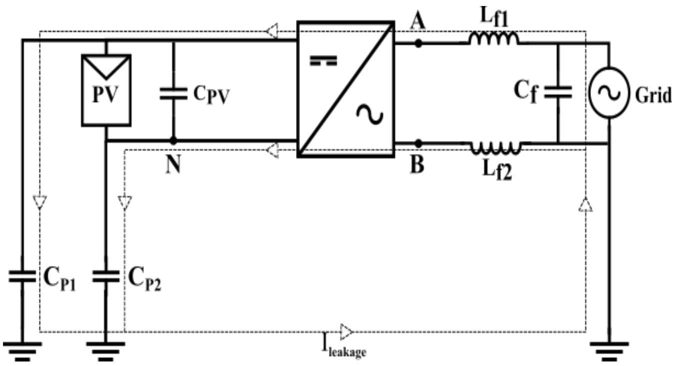


Fig. 2. The flow of leakage current

In the figure, the parasitic capacitances associated with the PV conductors of positive polarity and negative polarity have been represented by C_{P1} & C_{P2}, respectively. As depicted by the arrows, since the direction of the leakage current is the same in both the positive- and negative-polarity conductors, it is also called common-mode current (CMC). Moreover, it is also known as residual current and ground current.

The leakage current is necessarily a high-frequency current owing to it being a capacitive current of small value. The parasitic capacitance is of the order of 50-150nF/kW for crystalline silicon solar panels and 1μF/kW for thin film solar panels. Thus, the leakage current is of the order of milliamperes as explained by the equation:

$$i_{CM} = C_P \frac{dv_{CM}}{dt} \tag{1}$$

where, i_{CM} is the common mode (leakage) current
v_{CM} is the common mode voltage
C_P is the total parasitic capacitance of the panel
The common mode voltage is given by:

$$v_{CM} = \frac{V_{AN}+V_{BN}}{2} + (V_{AN} - V_{BN})\frac{L_{f2}-L_{f1}}{2(L_{f2}+L_{f1})} \tag{2}$$

where, V_{AN} & V_{BN} are the potentials of points A & B, respectively, with respect to point N marked in fig.2.
L_{f1} & L_{f2} are filter inductors in the two arms, as shown. Clearly, if the two inductances are equal, the second term of the equation can be neglected. [10]

Moreover, the DC side may be grounded, causing a more severe leakage. The leakage current, being small in magnitude, does not cause any power loss, but it injects harmonics into the grid, degrading power quality and causing electromagnetic interference (EMI). It may also cause deterioration of thin-film based solar panels. But most importantly, it hampers the elements of the protection system that are based on the phenomenon of residual current. Thus, grid compliance includes ensuring that leakage current remains below the value specified in the grid code.

To mitigate leakage current, isolation transformers can be employed, which are specifically designed to reduce inter-winding capacitance. This sort of technique is called galvanic isolation. However, the transformers are costly and voluminous. The high-frequency transformers are better candidates, but still not an optimum solution. The best possible solution to the problem is to modify the existing inverter circuits such that the leakage current is minimized [11]. In what follows, the same has been explored. Moreover, by excluding the transformer and physically attaching the inverter circuit to the PV module, the PV module may be thought of as an AC source.

5. Transformerless Inverter Topologies for Grid-Connected PV Systems

Transformerless inverter topologies for grid-connected PV systems have been researched and developed over the past few years. Some canonical topologies and their modifications, both patented and non-patented, are available in the literature. Most of the topologies developed and available are based upon the classical half-bridge or full-bridge topologies.

Fundamentally, leakage current can be suppressed by maintaining the common-mode voltage (CMV) constant, as suggested by equation (1). There are three methods of doing so, i.e.:

a. Isolating the AC and DC sides during the freewheeling period
b. Clamping neutral point of the DC link to ground
c. Connecting the negative PV terminal to the grid neutral.

The first two of the above can be done on either the AC or DC side. This is noticeable in the topologies discussed below. The modulation technique used in DC/AC conversion also affects the amount of leakage current. The bipolar modulation technique has the advantage of low leakage current due to the low-frequency component in the inverter output, but it suffers from poor efficiency (~95%) and higher filter requirements. On the other hand, unipolar modulation has high efficiency (~98%), low filter requirements due to low ripple, and low core losses due to unipolar variation of the voltage, but high leakage current due to a high-frequency component in the output. The unipolar modulation is preferred, which makes suppression of leakage current more challenging [12].

Since the conventional half-bridge and the full bridge form the basis of derived topologies, they are discussed first, followed by the special topologies that incorporate one of the three methods to reduce leakage current. The illustration is for a single-phase system, but the concept can be readily extended to three-phase systems.

5.1. Half-Bridge Inverter

The half-bridge inverter consists of two switches and a voltage divider formed by two dc-link capacitors on the input side. When the switch S1 is ON, the inverter output is $+V_{PV}/2$, and when S2 is ON, the inverter output is $-V_{PV}/2$. The L_f and C_f form the output filter to smoothen the waveform. The figure shows a semiconductor switch replaced by a manual switch, while the actual switching device, as shown to the side, consists of a power transistor in parallel with a diode. It is a bidirectional switch. The direction of the switch's closure indicates the polarity of the semiconductor switch.

The topology and the common-mode behaviour are shown in Fig. 3(a) to 3(c). The leakage current is inherently low in this topology, but the input voltage requirement is twice, and hence the stress on the switches. Also, due to voltage jumping from $+V_{PV}/2$ to $-V_{PV}/2$, the ripple content is high. The switching frequency is also required to be double the grid frequency. Furthermore, it is difficult to attain MPPT. Thus, the topology is not suitable for versatile use.

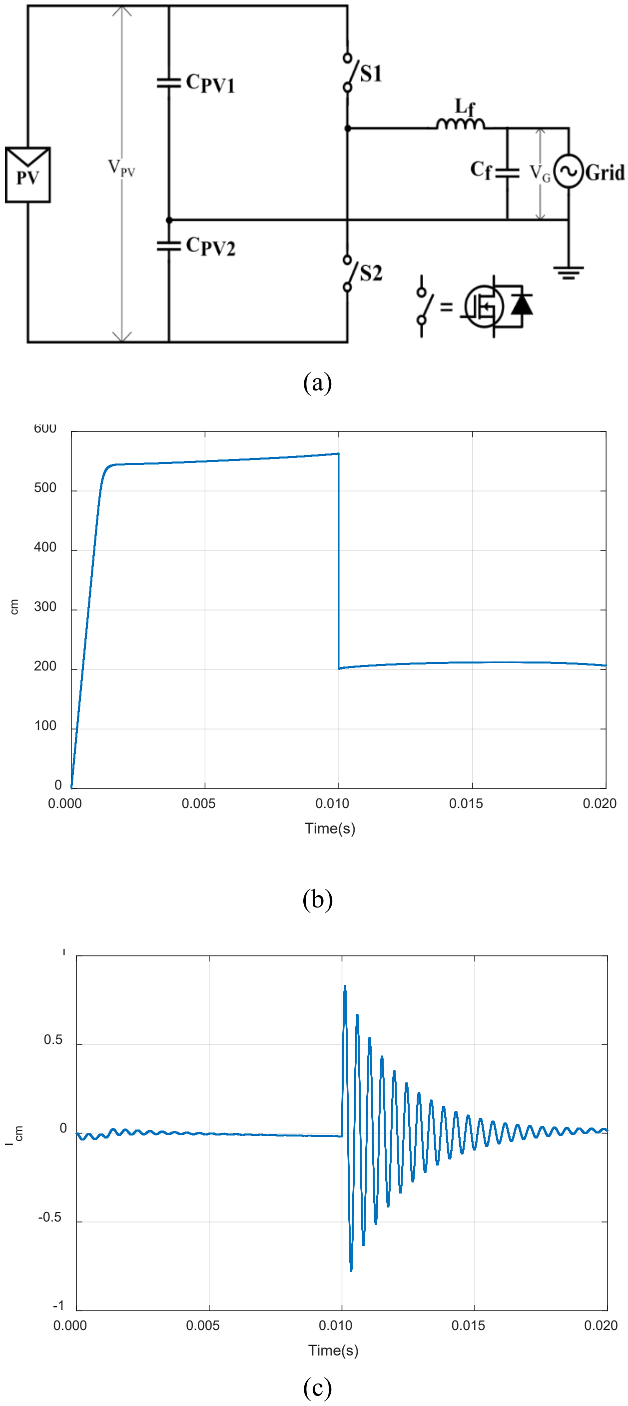
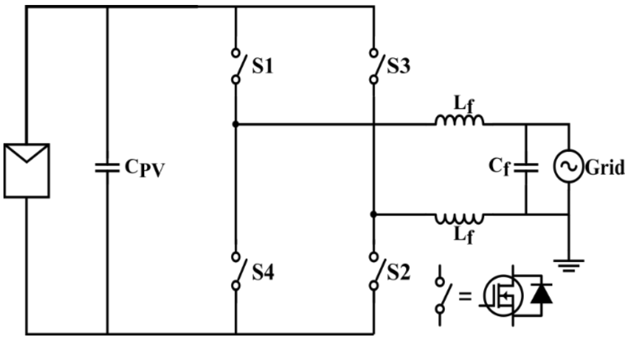


Fig.3. Half-Bridge Inverter: (a) Topology, (b) Common Mode Voltage, (c) Common Mode Current

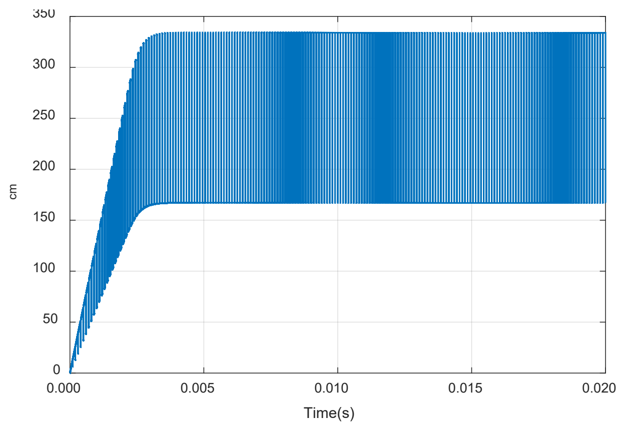
5.2. Full-Bridge Inverter

It is based on the classical H-bridge. For the positive state, switches S1 and S2 are ON, and for the negative state, switches S3 and S4 are ON. This is in the case of bipolar modulation. In the case of unipolar modulation, a zero voltage state is needed in both positive and negative half cycles, while the current should always be non-zero. For the zero state during the positive half cycle, S1 and the diode of S3 conduct, and for that in the negative half cycle, S4 and the diode of S2 conduct for current to freewheel.

The topology and the common mode behaviour have been shown in Fig. 4(a) to 4(c). The issue of the voltage requirement being twice is not there in the full bridge, which also implies less stress on switches. But the leakage current in this inverter is prohibitively high. So, only bipolar modulation is feasible, but that implies large filter requirements and lower efficiency. Therefore, other methods need to be considered.



(a)



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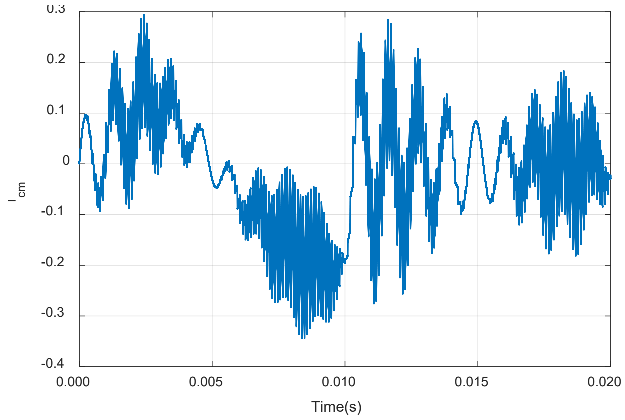
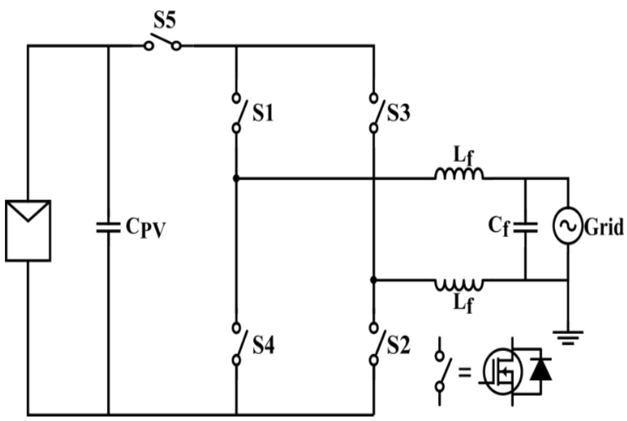


(c)

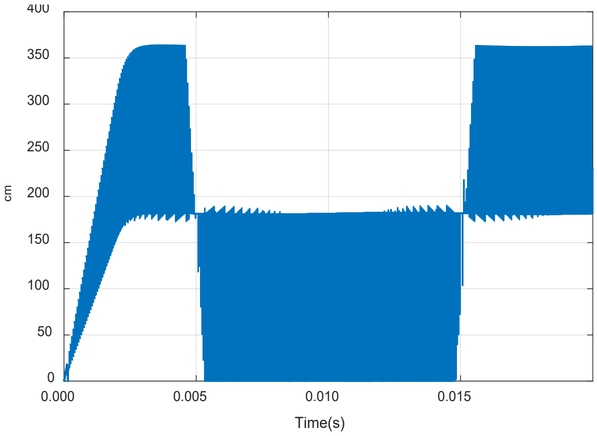
Fig.4. Full Bridge Inverter: (a) Topology, (b) Common Mode Voltage, (c) Common Mode Current

5.3. H5 Inverter

The H5 inverter represented in Fig.5(a) consists of one additional switch apart from the regular H-bridge. Since unipolar modulation is employed, the switches S1 and S2 are ON for the positive state, and during the freewheeling period in the positive state, S2 is switched OFF, and the current freewheels through S1 and the diode of S3. For the negative state, S3 and S4 are ON, and for the freewheeling period in the negative state, S4 is switched OFF, and the current freewheels through S3 and the diode of S1. The switch S5 remains OFF in the freewheeling period of both positive and negative states and ON otherwise, so that the AC and DC sides are isolated during the zero state. It implements DC-side decoupling between the AC and DC sides during freewheeling. The common mode voltage is not altered except for a small advancement in the grid voltage during this period. Thus, the leakage current is suppressed.



(a)



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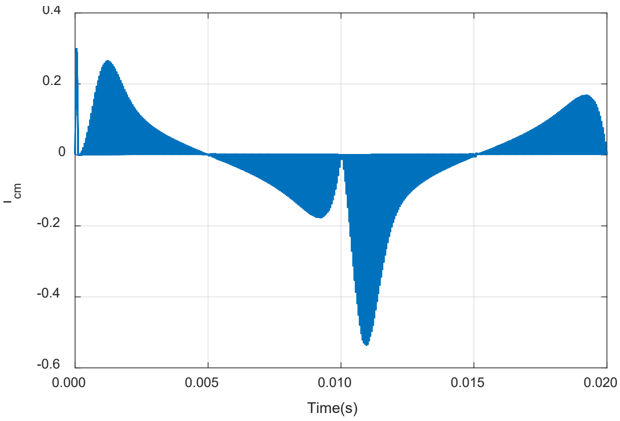


(c)

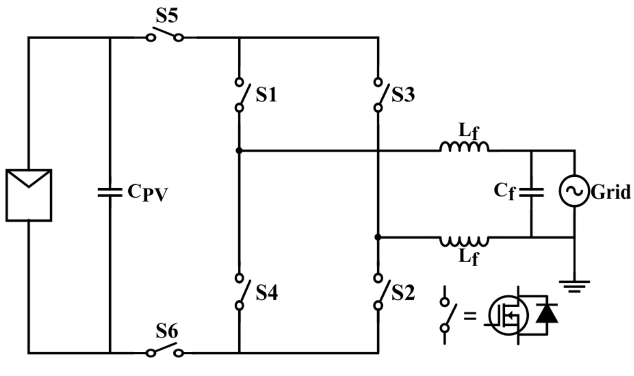
Fig.5. H5 Inverter: (a) Topology, (b) Common Mode Voltage, (c) Common Mode Current

The switches S1 and S3 need to operate at grid frequency, and S2 and S4 at high frequency. The common-mode behaviour is shown in Fig. 5(b) and 5(c). The advantage of this topology is that it uses only one extra switch to achieve a constant common mode voltage. The main drawback of this topology is three simultaneously ON switches, causing more conduction losses [13].

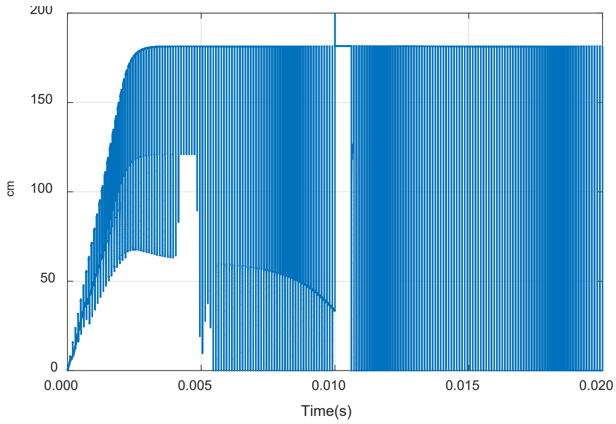
5.4. H6 Inverter

The H6 inverter has been shown in Fig. 6(a). It contains two extra switches compared to the H-bridge. In the positive state, S1, S2, S5, and S6 are ON, and in its freewheeling period, S1 and the diode of S3 are ON. In the negative state, S4, S5, and S6 are ON, and in its freewheeling period, S4 and the diode of S2 conduct.

The common-mode behaviour is shown in Fig. 6(b) and 6(c). Again, due to the disconnection between the grid and PV during the freewheeling period, the common-mode voltage remains nearly constant, and leakage current is suppressed. The addition of two switches and their simultaneous conduction causes still more losses, but a better balance is achieved between the two terminals.



(a)



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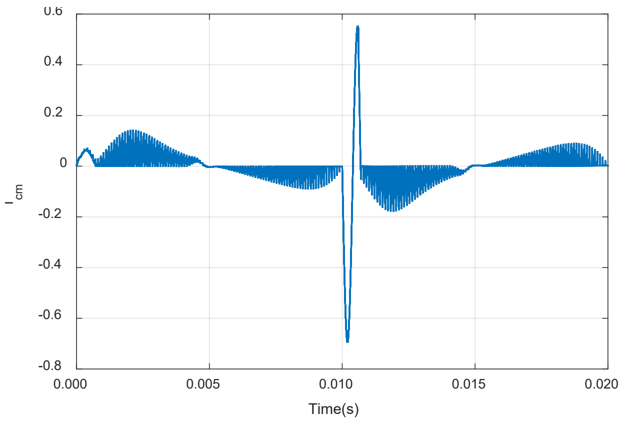


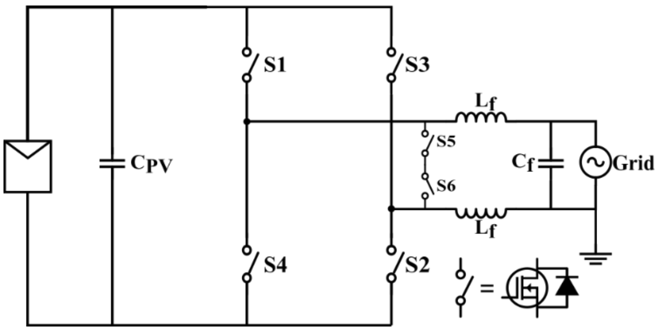
(c)

Fig.6. H6 Inverter: (a) Topology, (b) Common Mode Voltage, (c) Common Mode Current

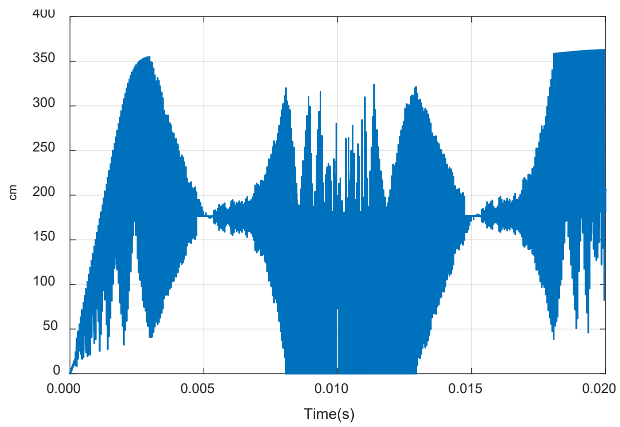
5.5. Highly Efficient and Reliable Inverter Concept (HERIC) Inverter

As shown in Fig. 7(a), it consists of six switches: four to form an H-bridge and two back-to-back switches on the AC side. In the positive state, S1 and S2 are ON and in their freewheeling period, S5, along with the diode of S6 conduct. In the negative state, S3 and S4 are ON, and during its freewheeling period, S6, along with the diode of S5, conducts. The switches S1, S2, S3, and S4 operate at high frequency, while S5 and S6 operate at grid frequency. It implements AC side decoupling.

There is no exchange of reactive power between the filter capacitor and inductor during the freewheeling period. Efficiency is improved due to low-frequency switching [2]. The common-mode behaviour is shown in Fig. 7(b) and 7(c). The low-frequency components also mean lower leakage currents. Also, it has only two switches at most, conducting at a time, reducing losses. The disadvantage is that it has two extra switches [14].



(a)



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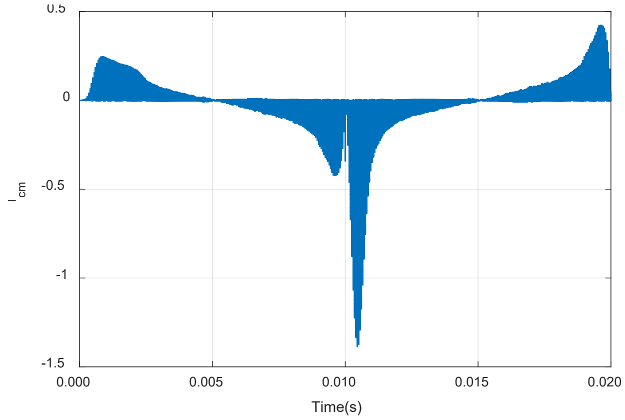


(c)

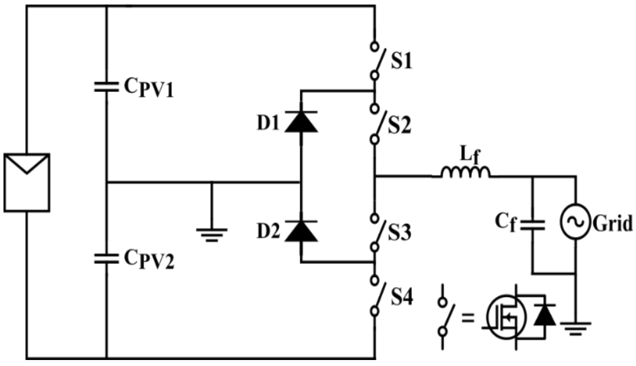
Fig.7. HERIC Inverter: (a) Topology, (b) Common Mode Voltage, (c) Common Mode Current

5.6. Neutral Point Clamped (NPC) Inverter

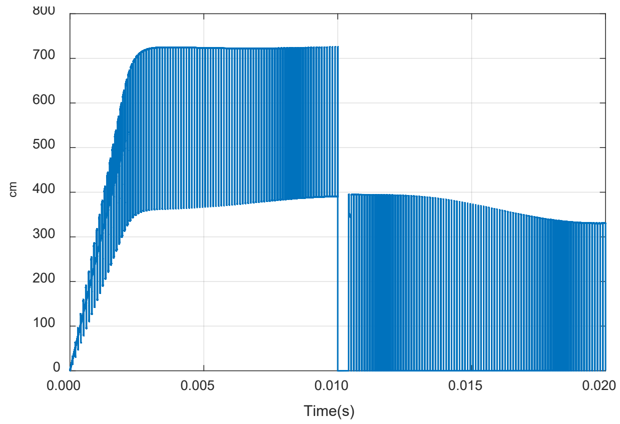
It is a modification of the half-bridge topology and consists of four switches and two diodes for freewheeling. The mid-point of the DC-link capacitor is connected to the grounded terminal of the grid. For the positive half cycle, S1 and S2 operate while the zero state current flows through S2 and D1. For the negative half cycle, S3 and S4 operate while a zero state is obtained with current flowing through S3 and D2. Since the middle DC-link is connected to ground, the common mode voltage remains constant, and leakage current is thus suppressed by a large amount.

The common mode behaviour has been shown in Fig. 8(b) and 8(c). The fluctuation of common mode voltage is reduced due to clamping of the neutral point of the DC link; therefore, suppression of leakage currents is quite effectively met through this topology. The rating of the switches required is lower because the dV/dt stress upon the switches is low, i.e., $V_{PV}/4$. The efficiency is higher because there is no reactive power exchange between the filter capacitor and the inductor during the freewheeling period.

However, the PV voltage requirement is twice that of an H-bridge inverter. The middle two switches experience more transients as they do not have DC link capacitors across them, and they have more switching losses than the outer ones.



(a)



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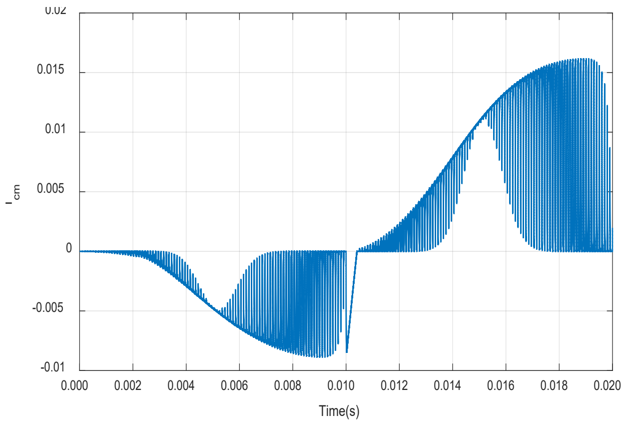

(c)

Fig.8. Neutral Point Clamped (NPC) Inverter: (a) Topology, (b) Common Mode Voltage, (c) Common Mode Current

5.7. Karschny Inverter

As shown in Fig.9, it is a modification of a buck-boost converter with extra switches, diodes, and an inductor to store energy. It is also called a flying inductor topology. The switches S1 and S2 are operated at high frequency, while S3 and S4 operate at grid frequency. A low-frequency input current is required from the PV source. The negative PV terminal is connected directly to the grid neutral, which removes the voltage oscillations.

The leakage current is highly suppressed. Depending upon the input PV voltage, both buck and boost modes are possible. But the large flying inductor to store energy causes losses. There are at least two and at most three switches conducting simultaneously, thus causing more losses. Thus, efficiency is reduced. The presence of several devices makes the control very complicated. The input capacitor must be large enough to meet the low ripple requirement of the PV output.

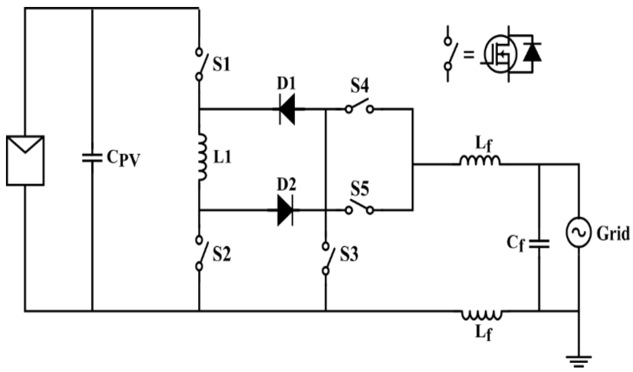

Fig.9. Karschny Inverter

5.8. Other Topologies

Apart from the above well-established topologies, the literature has several other modifications. [17] describes a full bridge zero voltage (FB-ZVR) inverter derived from HERIC topology. Instead of two switches on the output side, it uses a diode bridge and a switch that is clamped to the mid-point of the DC voltage, as in the NPC inverter. [18] describes a full bridge DC bypass (FB-DCBP) topology, which is the modification of the full bridge as in H6, but with two diodes clamped to the mid-point of the DC link capacitors. The flying capacitor topology of [19] consists of a large capacitor installed between the switches that charges and discharges depending upon the modulation technique, and the negative PV terminal is directly connected to the grid neutral.

The active NPC topology mentioned in [20] utilises bidirectional switches in place of diodes for clamping and shows a modification of the NPC topology patented by Coenergy, in which the DC link midpoint is clamped to grid-neutral through two back-to-back switches instead of diodes. It also mentions a topology based on a full bridge and, with the parallel-connected two switches, shows a variation of NPC called Positive Negative Neutral Point Clamping (PN-NPC), which is nothing but a combination of both positive and negative point clamping and uses eight switches for that purpose. H6 also has two modified forms called H6 with diodes-1, having six switches with diodes, and its modification called H6-1, where diodes have been removed, and corresponding points shorted. [15] proposes a modified form of H6, i.e., an H7 inverter, which consists of an extra 7th switch used for clamping common-mode voltages. The existing topologies need to be studied to do away with their drawbacks. [21] proposes a novel topology that makes use of both isolation and clamping methods and gives superior results.

6. Comparison between the Transformerless Inverter Topologies

The technical features and parameters to be considered in analysis of a topology are the following: common mode voltage variation and hence the amount of leakage current, losses which are of two types - firstly conduction losses which further may be loss in active state or in freewheeling state and secondly switching losses - and hence the overall efficiency, source voltage requirement, number of switches, diodes, and passive elements used, stress upon the switches, output voltage levels, total harmonic distortion (THD), and cost of implementation [22-23].

By theoretical analysis and through inspection of the result data pertaining to various topologies, some general conclusions can be drawn, which are as follows:

i. The topologies having PV negative connected to the grid neutral are better than those based on voltage clamping, and the latter are better than those based on isolating the DC and AC sides in terms of fixing common mode voltage and hence suppressing the leakage current.

ii. More number of switches implies more conduction and switching losses, but the number of simultaneously conducting switches during active and freewheeling periods also needs to be considered. Thus, the AC decoupling methods have lower losses than the DC decoupling methods, clearly due to fewer switches in the conduction path during the freewheeling period.

iii. The topologies based on a half bridge need double the DC link voltage needed by full bridge-based topologies.

iv. The double dc link voltage requirement also doubles the stress upon each switching leg, but the presence of more number of switches in a leg causes distribution of the stress.

v. The implementation cost for a topology is chiefly a function of the number of switches employed in it.

Table 1 illustrates the comparison between the various topologies.

Table 1: Comparison between various transformerless inverter topologies [3,8,9,11,12,14,15]

Topology	Semiconductor Devices		Passive Elements		Common Mode Parameters		Efficiency	Source Voltage Requirement	Switch Voltage Stress	Total Harmonic Distortion	Cost
	Switches	Diodes	Capacitors	Inductors	Voltage Variation	Leakage Current					
Half Bridge	2	0	3	1	Constant	L	L	$2V_{PV}$	V_{PV}	-	L
Full Bridge	4	0	2	2	H	H	L	V_{PV}	$V_{PV}/2$	-	M
H5	5	0	2	2	M	M	H	V_{PV}	$V_{PV}/2$	1.67%	H
H6	6	0	2	2	M	M	M	V_{PV}	$V_{PV}/2$	1.84%	H
HERIC	6	0	2	2	M	M	H	V_{PV}	$V_{PV}/2$	1.59%	H
NPC	4	2	3	1	Constant	L	M	$2V_{PV}$	$V_{PV}/2$	-	M
Karschny	5	2	2	3	Constant	L	M	V_{PV}	$V_{PV}/2$	-	H
FB-ZVR	5	4	3	2	M	M	L	V_{PV}	$V_{PV}/2$	-	H
FB-DCBP	6	2	3	2	M	M	M	V_{PV}	$V_{PV}/2$	-	H
Flying Capacitor	4	1	3	1	Constant	L	M	V_{PV}	$V_{PV}/2$	-	M
Active NPC	6	0	3	1	Constant	L	M	$2V_{PV}$	$V_{PV}/2$	-	H
PN-NPC	8	0	3	2	M	L	L	V_{PV}	$2V_{PV}/3$	-	H
Coenergy NPC	4	0	3	1	Constant	L	M	$2V_{PV}$	$V_{PV}/2$	-	M
H6 with Diodes	6	2	2	2	M	M	M	V_{PV}	$V_{PV}/3$	-	H
H6-1	6	0	2	2	M	M	M	V_{PV}	$V_{PV}/3$		H
H7	7	1	3	2	M	M	H	V_{PV}	$V_{PV}/2$	1.75%	H

All results are for unipolar modulation. •For leakage current- L means <30mA, M means <250mA, H means >250mA. •For efficiency- L means <95%, M means <98%, H means >98%. •For CMV- M means<200mV, H>200m

7. Conclusion

The grid-connected PV system has a demand for converters that comply with the grid code, especially in terms of leakage current and THD, along with being energy and cost-efficient and having low requirements for component rating. The paper reviews, explains, and analyzes various transformerless inverter topologies reported in the literature, focusing on pertinent aspects. The result of the comparison has been discussed in the last section and summarized in the table. This should help information seekers for varying purposes.

Conclusively, the half bridge topology uses the fewest components, Karschny has the lowest leakage current, HERIC stands among those having the highest efficiency, all full bridge-based topologies have the advantage of requiring half the source voltage and half the switch rating required by the half bridge-based ones, and the half bridge has the least implementation cost. The problem presently lies in finding an optimal topology that is as close as possible to the benchmark set by the best topology concerning an individual parameter.

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