Chapter 1

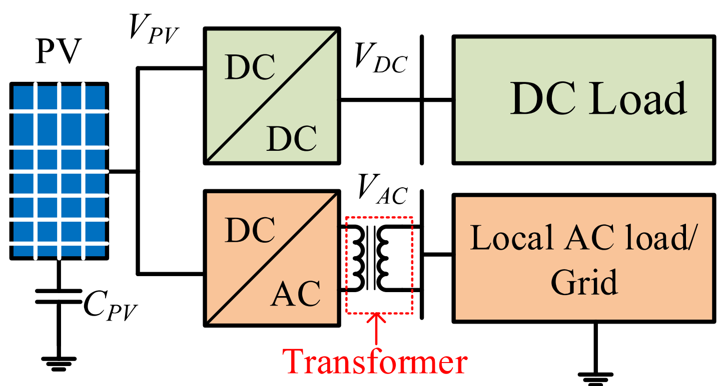
Introduction

1.1 Background and Motivation

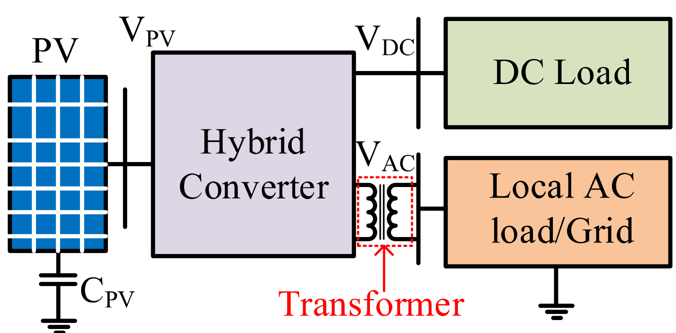
In the last few decades, because of the depletion of fossil fuels (coal, oil and gas) and environmental pollution issues, the significance of renewable energy sources (RESs) has increased manifold [1]. Further, the importance of renewable energy has increased in recent times, as it has not only diversified the energy supply, but also reduced the dependency on imported fuels [2]. The RESs produce energy from natural sources like sunlight, wind, tides and biomass, which are available in abundance in nature. Among all the RESs, wind power generation is a widely used efficient energy source [3]-[4]. However, the wind power plants require more maintenance than the other RESs. Further, they are prone to make lots of noise [4]. Also, they are not applicable for residential installations (roof-top installations of residential/commercial buildings) to meet the localized demands. The solar photovoltaic (PV) systems are better choices for the residential/commercial distribution systems compared wind power plants to due to absence of mechanical moving parts, lower maintenance cost and compactness. Also, the PV sources have no harmful greenhouse gas emissions (like the biomass energy sources) and can be deployed close to the load centers for their uses in large solar plants to small household applications [5]. Among all the RESs, the solar PV source is considered as one of the most reasonable renewable energy sources [6]-[8]. The research carried out in the area of solar PV power generation and its applications are increasing day-by-day through various power electronic converters (PECs). Among all the solar PV power applications, design of hybrid output (simultaneous DC and AC outputs) PECs is one of the predominant areas for PV based residential and microgrid applications.

In recent times, hybrid output concept has become a popular choice for modern photovoltaic (PV) systems due to the gradual increment in DC loads along with the existing AC loads [9]-[11]. Previously, two different PECs were used for different outputs (DC and AC outputs) from a single DC source/solar PV panel; i.e., one DC-DC converter was used for the DC output and one DC-AC inverter was used for the AC output. By using two different PECs, number of switches and passive components increase, which results into increase in weight and size of the overall system resulting into reduction in the overall efficiency [12]. Also, a deadtime circuit is required in the

PECs, which are used in the DC-AC inverter part to prevent the shoot-through issue [13]. In order to take care of this, the concept of hybrid output through a single PEC, namely hybrid converter was used for the PV based residential and microgrid applications. By using hybrid converters, both DC and AC outputs can be obtained simultaneously from a single DC source/solar PV panel using only one PEC. Fig. 1.1 shows the schematic of PV based PEC for residential microgrid applications, where in Fig. 1.1 (a) two different PECs are used and in Fig. 1.1 (b) a single hybrid converter is used.



(a)



(b)

Fig. 1.1 schematic of PV based power electronic converter for residential microgrid applications. **(a)** Two different PECs, **(b)** A single hybrid converter.

The solar PV cells are low voltage energy sources and have variable DC outputs [14]. So, to achieve a high DC gain along with improved quality of AC output voltage through the PV based hybrid converters, either a large number of PV cells are required to be connected in series and parallel or high DC gain hybrid PECs are required. By connecting a large number of PV cells in series and parallel, the size and cost of the PV panels increase [15]. Therefore, the use of high DC gain hybrid converter was realized for giving efficient solutions to PV applications. Keeping this in mind, the boost derived hybrid converters are designed to give high gain DC output along with better quality of AC output voltage. Further in case of the boost derived hybrid converters, as the same controlled switches decide the value of duty ratio (D) and modulation index (M_i), they can operate only in the operating condition $D + M_i \leq 1$ [16]-[20]. So, these converters operate in narrow operating ranges of D and M_i, which leads a trade-off between DC gain and AC output quality. To take care of this issue, either high DC gain at low D converters or the converters which can operate in wide operating ranges of D and M_i (can operate in $D + M_i \geq 1$) are designed. Further in case of boost derived hybrid converters, the non-minimum phase property is predominant due to the presence of right half-plane zeros (RHPZs) in their control-to-output transfer function [21]-[24]. Because of the RHPZs, the bandwidth and phase margin (PM) of these hybrid converters vary inversely [25]. So, the increase in bandwidth results in decrease in PM and vice-versa. Also, due to the presence of RHPZs, hybrid converters show non-linear behaviour during the dynamic conditions [26]. As a result, the dynamic performance of the hybrid converters is not good, which leads to instability of the system. Further, the hybrid converter topologies used in PV systems are of two types: 1) converters with galvanic isolation between the PV panel and the AC output and 2) converters without galvanic isolation (transformerless) between the PV panel and the AC output [27]-[30]. Fig. 1.1 (b) and Fig. 1.2 shows two different types of architectures of the solar PV hybrid converter, where in Fig. 1.1 (b) a low frequency (LF) transformer is used in between the PV panel and the local AC load/grid and in Fig. 1.2 the LF transformer is not used in between the PV panel and the local AC load/grid.

In case of galvanic isolation type hybrid converters, the advantageous features due to presence of transformer are

- It provides isolation between the PV system and the AC ground, so that the ground current that results due the capacitance formation between the PV panel and the ground is limited [31].
- It inhibits injection of DC current to local AC load/grid and thereby avoid saturation problem in the AC side [32].

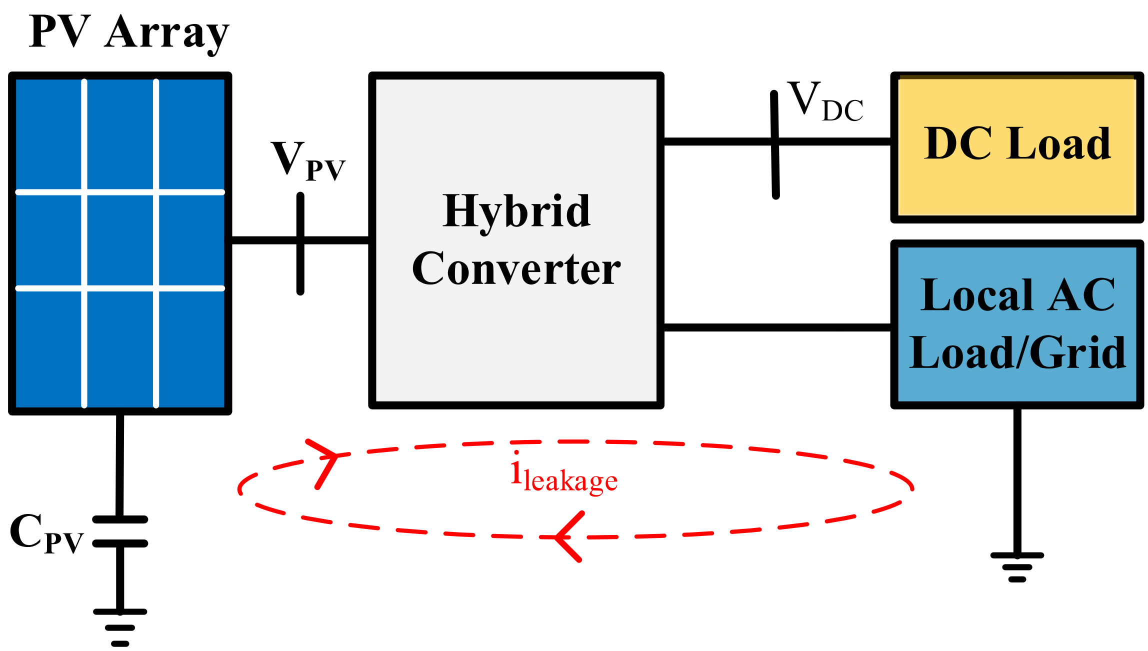


Fig. 1.2 PV based hybrid converter without a LF transformer in between the PV panel and local AC load/grid.

However, due to the presence of LF transformer in galvanic isolation type hybrid converters; the overall cost, losses, weight and volume of the system increases [33]-[36]. Also because of the leakage flux in the LF transformer, the entire primary side energy is not transferred to the secondary side/AC load side and it results in reduction in the overall efficiency of the system [37]. This has encouraged researchers to solve the problems associated with the LF transformer. One alternative approach is to use a high frequency (HF) transformer during the power conversion stage. This reduces the overall size, weight and cost of the PV system and the galvanic isolation is achieved. Suitable control schemes can be used to obtain AC side load current/grid current free from DC quantity. However, due to the inclusion of HF transformer, the power conversion stage becomes complex and no significant improvement is achieved in terms of overall efficiency of the PV system [38]. On the other hand, in case of hybrid converters with no galvanic isolation, due to the absence of LF transformer; the overall cost, losses, weight and volume of the system decrease. Also in this case, the overall efficiency of the system increases due to the absence of transformer in the system [39]-[42]. Therefore, nowadays some of the European countries and some parts of USA allow the grid integration of solar PV systems without LF transformer in between the PV panel and local AC load/grid. But from the Fig. 1.2, it can be concluded that the harmful common mode leakage current flows between the PV panel and ground (for grid tied mode and for the cases where the inverter neutral point of the hybrid converter is grounded) in case of transformerless hybrid converters. Due to the flow of leakage current, the losses in the system and the total harmonic distortion (THD) in the grid current increases and it also increases the chances of electromagnetic interference with the nearby grounded systems [43]-[45]. Further, as per IEEE safety standard (DIN VDE 0126-1-1 standard), for personal safety, a residual current monitoring device (RCMD) is essential in transformerless hybrid converters. If leakage current value is more than 300 mA, the inverter part of the transformerless hybrid converter should be disconnected within 0.3 sec of detection [46]-[48]. Therefore, nowadays different techniques are used to minimize the flow of leakage current. Further, the dynamic behaviour of DC and AC parts of the transformerless hybrid converters exhibit different characteristics while varying the load current, D and M_i. As, the DC and AC outputs are obtained from a common DC source/solar PV panel using power electronic converters, the variation in one/more parameters may affect the dynamic responses of both the DC and AC parts [49]. Also, the effect of change in passive components values leads to instability in the system [50].

To address the above issues, the present thesis investigates hybrid PECs and their usages in PV based residential and microgrid applications.

1.2 Literature Review

This section discusses various PECs which are designed for PV based residential and commercial microgrid applications. Further, a survey of research on the design aspects of transformerless hybrid converters for both off-grid and grid-tied mode operations are presented in the subsequent subsections.

1.2.1 Hybrid Output

The solar PV panels are widely installed at the consumer load premises (i.e., residential and commercial buildings) because of the advancements in power semiconductor devices and cost reduction of PV panels [51]. Further, the DC loads are gradually increasing along with the existing AC loads in the residential buildings. Hence, the conventional power distribution systems are required to be modified as hybrid AC/DC residential distribution system for supplying both DC and AC loads simultaneously [52]-[55]. To meet these requirements, hybrid converters can be used for supplying AC and DC loads using a single power electronic converter. The hybrid converters are operated by a single DC input source with improved reliability [56]. A family of hybrid converter topologies which can supply both DC and AC loads simultaneously from a single DC input are discussed in [57]-[60]. A class of active impedance source inverters, having high boost factor such as current-fed switched inverter (CFSI) is discussed in [57] for DC nano grid applications. In [58], the design and operations of a boost derived hybrid converter (BDHC) is discussed. The reported BDHC is derived from a conventional DC-DC boost converter for simultaneous DC and AC outputs with inherent shoot-through capability. Also, some additional passive components are included in the input side of BDHC to form a single-switch quadratic BDHC (QBDHC) which has higher voltage gain as compared to BDHC. In addition, a three-phase BDHC was studied by incorporating a constant-frequency shoot-through sinusoidal pulse width modulation (SPWM) scheme. In case of the reported three-phase BDHC, a three-phase AC output and a step-up DC output has been obtained simultaneously from a single DC source [61]. A switched boost inverter (SBI) is reported in [62] for supplying both DC and AC loads at the same instant. The SBI is a single-stage power converter derived from the Inverse Watkins Johnson (IWJ) topology [63]. In [64], two types of hybrid converters have been reported, which are derived from a quadratic boost topology by replacing its main switch by n-number of series or parallel connected single-phase voltage source inverters (VSIs). A SBI based three-phase modified Z-source inverter is discussed in [65]. The reported topology has higher boost factor due to the presence of one additional switch along with one diode. Also, it gives high voltage gains at low values of duty ratios. In [66], two-hybrid multioutput quasi-Z-source converters are discussed, which are capable of giving two DC and one AC outputs from a single DC input source. In [66], a transformerless hybrid converter derived from BDHC is presented for the minimization of leakage current along with simultaneous DC and AC outputs.

It can be observed that the aforesaid hybrid converters [56]-[62] are mostly derived from the conventional DC-DC boost converter, and their DC output voltage acts as an input voltage for the H-bridge VSI to obtain AC output voltage. Fig. 1.3 shows a conventional DC-DC boost converter, whereas Fig. 1.4 shows a single-phase VSI. The BDHC and some other hybrid converters are developed by replacing the controlled switch of the conventional boost converter by a single-phase or a three phase VSI. In Fig. 1.3, the controlled switch S_{sw} of the conventional DC-DC boost converter is replaced by a VSI (as shown in Fig. 1.4) to develop the conventional BDHC. The conventional BDHC thus obtained is shown in Fig. 1.5.

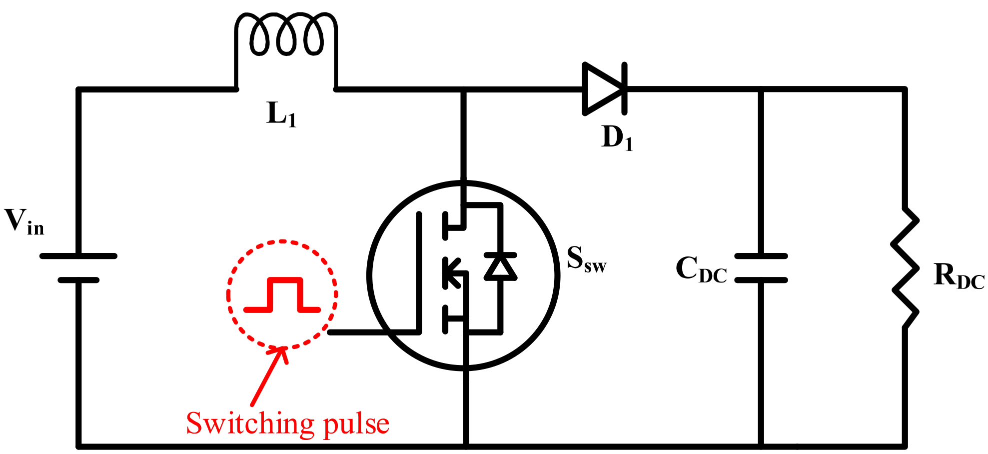


Fig. 1.3 Conventional DC-DC boost converter.

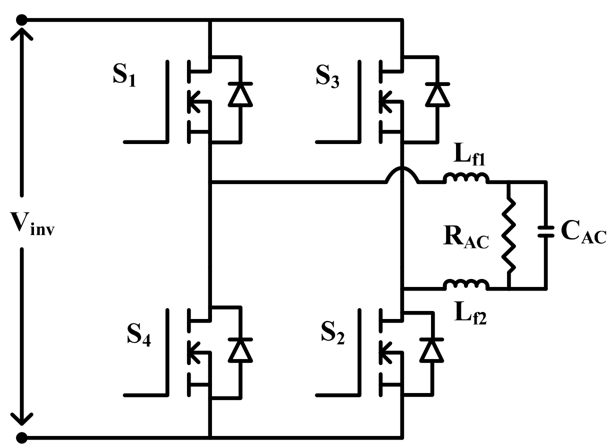


Fig. 1.4 Voltage source inverter.

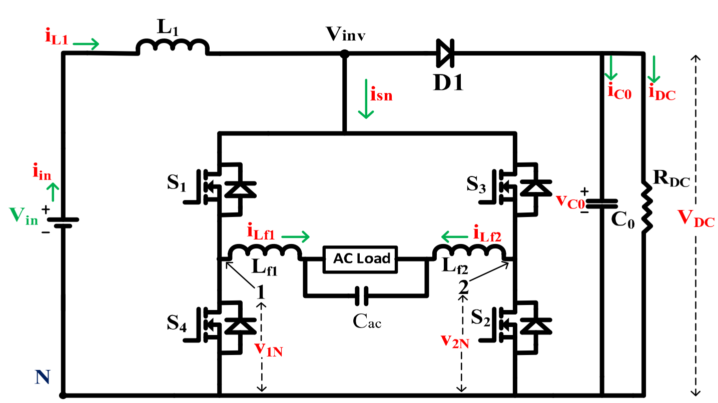


Fig. 1.5 Conventional boost derived hybrid converter.

The BDHC has two controlled parameters (D and M_i). Both the control parameters are decided by the switching pulses of switches ($S_1 - S_4$). Basically, the BDHC operates in two operating states which are shoot-through and non-shoot through states. During the shoot-through state, both the switches of either of the legs are in switch-on positions. So, during this interval/state the BDHC behaves as a switched-on conventional DC-DC boost converter and it decides D of the BDHC. However, the non-shoot through state consists of power and zero intervals. During the non-shoot through state, the BDHC behaves as a switch-off operation of the conventional DC-DC boost converter. Further, during the zero interval all the control switches are in switch-off positions and the entire power of the source is transferred to the DC load. When either of the switches S_1 and S_2 or the switches S_3 and S_4 are in switch-on positions, the power is transferred from the source to the AC load directly. So, this particular duration decides M_i of the BDHC. As the same switches ($S_1 - S_4$) decide the value of D and M_i, the operating constraint of the BDHC is $D + M_i \leq 1$. Since all the aforesaid hybrid converters [56]-[66] are mostly derived from the conventional DC-DC boost converter, the operating constraint $D + M_i \leq 1$ is applicable to all of them. So, for these hybrid converters D and M_i are not varied independently, which leads to a compromise between the DC gain and the AC output voltage quality. To overcome this issue, researchers have developed some high DC gain hybrid converters which can operate at low D. The SBI has a DC gain of ($\frac{1-D}{1-2D}$) [62] and the CFSI [57] has a DC gain of ($\frac{1}{1-2D}$). However, both SBI and CFSI suffer from high voltage and current stresses on the passive components and on the controlled switches. Therefore, the need of a wide operating range hybrid converter was felt, which can operate in the operating condition $D + M_i \geq 1$. An interleaved hybrid converter (IHC) with simultaneous DC and AC outputs is presented in [67]. It was observed that the reported IHC has three different operating modes with $D + M_i \geq 1$. Similarly, in [68] a transformerless interleaved hybrid converter (TLIHC) is reported, where both DC and AC outputs are obtained from a single DC source with wide operating range of D and M_i. Also, the reported TLIHC can minimize the leakage current within the specified limits. Fig. 1.6 shows the schematic of the basic structure of a boost derived interleaved hybrid converter. Here, two conventional DC-DC boost converters are interleaved together in a single topology. For simultaneous DC and AC outputs, the lower rated boost converter switch is replaced by a single-phase/three-phase VSI. As the two different set of switches are responsible for deciding the values of D and M_i, both of them are varied independently. In case of interleaved hybrid converters, the higher rated boost converter switch decides D, whereas the lower rated boost converter switch decides M_i of the hybrid converter.

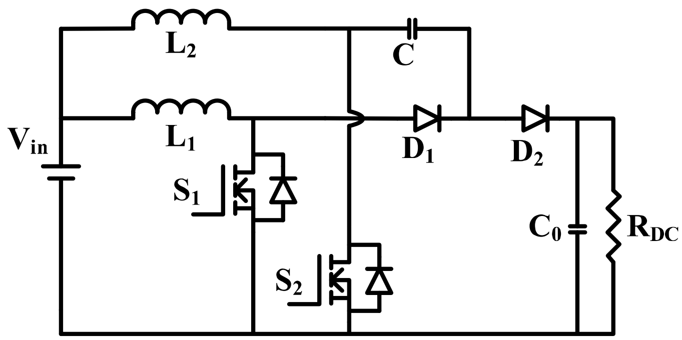


Fig. 1.6 Schematic of basic structure of boost derived interleaved hybrid converter

1.2.2 Minimum Phase Behaviour

The solar PV cell is a low voltage energy source and it gives DC output. In order to improve the voltage level, high gain DC-DC boost converter is used with the solar PV cell. The introduction of a high gain DC-DC boost converter also helps in maximum power point tracking (MPPT) [69]. Further, it can also be noticed that the aforesaid hybrid converters [58]-[63] are mostly derived from the conventional DC-DC boost converters. Because of the presence of RHPZs in the control-to-output transfer function of the boost converter, the non-minimum phase property is predominant in these hybrid converters. However, due to the presence of RHPZs, the hybrid converters show nonlinear behaviour during the dynamic conditions. In such converters, if D is increased suddenly, the DC output voltage first decreases then follows D and vice-versa [70]-[72]. Also, as the DC output voltage of the aforesaid hybrid converters acts as an input voltage to the single-phase/three-phase VSI, the AC output side is also affected during the dynamic operations. Therefore, the dynamic performance of the hybrid converters is deteriorated and this leads to instability [21]. Further, due to the presence of RHPZs, the gain of the system increases, but at the same time phase of the system reduces, which results in reduced phase margin (PM). This results into instability of the overall system [73]. In addition, the non-minimum phase system causes a phase reduction with respect to the increase in frequency, which makes the controller design complicated along with the bandwidth limitations. A series damping network is used to damp out the LC resonance and magnetically coupled inductors are used to eliminate the RHPZs of the converter [74]. A magnetically coupled boost converter with enhanced filter capacitor makes the converter minimum phase as discussed in [75]. Combining both Ćuk and SEPIC converters with some modifications, a bipolar converter is reported in order to get a minimum phase system in [76]. In [77], a two-phase interleaved inverse-coupled boost converter is proposed to transfer the zeros of open-loop control-to-output voltage transfer function from right half plane to left half plane. The hybrid converters are basically derived from DC-DC boost converters. In order to understand the nonlinear behaviour of the hybrid converter, the circuit operation of boost converter for non-minimum phase property is discussed in [76]. Fig. 1.7 shows the circuit operation of DC-DC boost converter for the analysis of non-minimum phase behaviour.

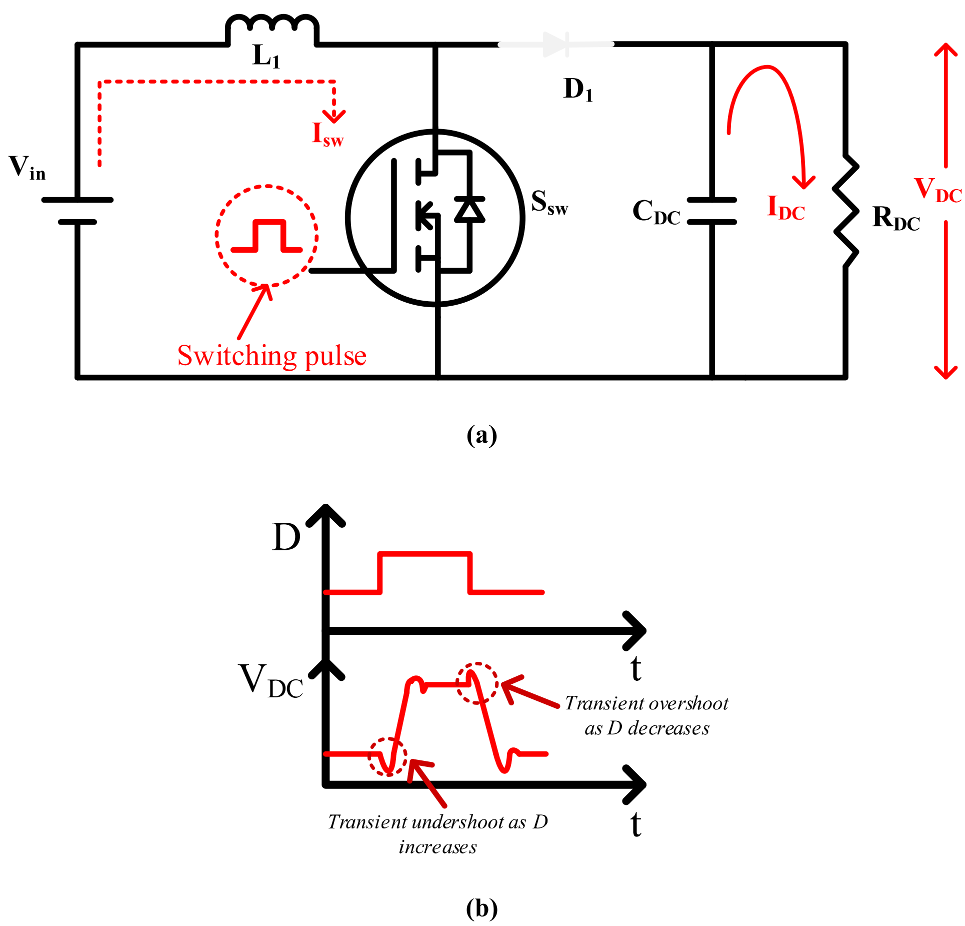


Fig. 1.7 Circuit operation of DC-DC boost converter for non-minimum phase behaviour. **(a)** Boost converter operation during the switch-on interval and **(b)** Duty ratio and voltage profile of output capacitor with respect to time.

The circuit operation of DC-DC boost converter during the switch-on interval is shown in Fig. 1.7 (a). In this interval, when the switch S_{sw} is in ON position and the diode D_1 is in reverse biased condition, the output load is disconnected from the main circuit. So, during the switch-on period direct power from the source to the load is not transferred and the filter capacitor C_{DC} is in discharging mode. Therefore, when D increases, transient undershoot occurs in the output voltage response due to the discharge of C_{DC}. Similarly, when D decreases, transient overshoot occurs in the output voltage response due to the overcharging of C_{DC}. Both increase and decrease of D and its effect on the output voltage is shown in Fig. 1.7 (b). According to the circuit physics, when the switch is in ON position and the power is not transferred from the input side to the load, the RHPZs exist in the converter. In the reference [74]-[80], some circuit modifications have been made in the DC-DC boost converter to reduce/remove the effect of RHPZs from it.

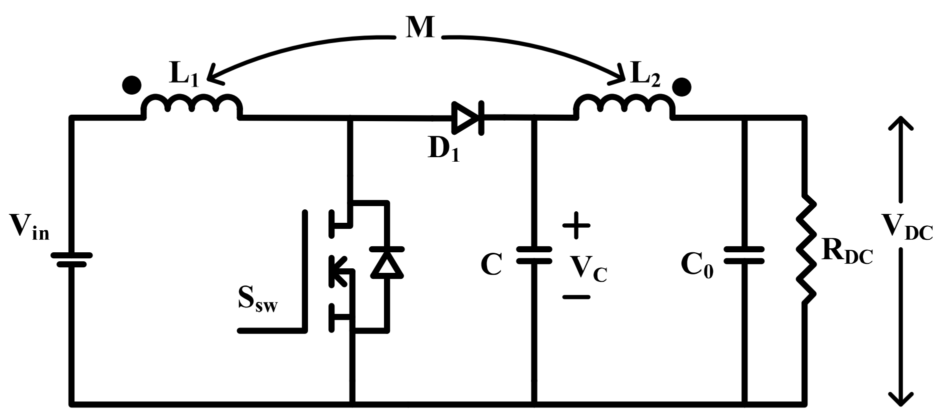


Fig. 1.8 Boost converter with magnetic coupling inductors to eliminate the RHPZ effect.

Fig. 1.8 shows the boost converter with magnetic coupling inductors to eliminate the RHPZs as discussed in [79]. In this topology, the magnetic coupling is present between the conventional boost inductor L_1 and the upright filter inductor L_2 along with a capacitor C placed in the output side of the converter. Here, L_2 is inversely/differentially coupled with the boost inductor coil. As both the inductor coils are magnetically coupled with each other, the inductor coil L_2 along with C supplies power to the load during the switch-on period of the converter. Further, the output filter capacitor (C_0) is not over charged or under charged during the sudden change in D. So, the RHPZs are eliminated from the control-to-output voltage transfer function of the boost converter. However, there is an important issue to be observed in this type of topologies. The magnetic coupling between the coils L_1 and L_2 requires a low value of coupling co-efficient (K) or addition of one extra inductor. Otherwise, due to low value of K, it is difficult to implement these topologies in practice. Therefore, another kind of topology is reported in [80]. In the reported topology, the minimum phase property is achieved by providing the required amount of energy from the source to load during the switch-on period.

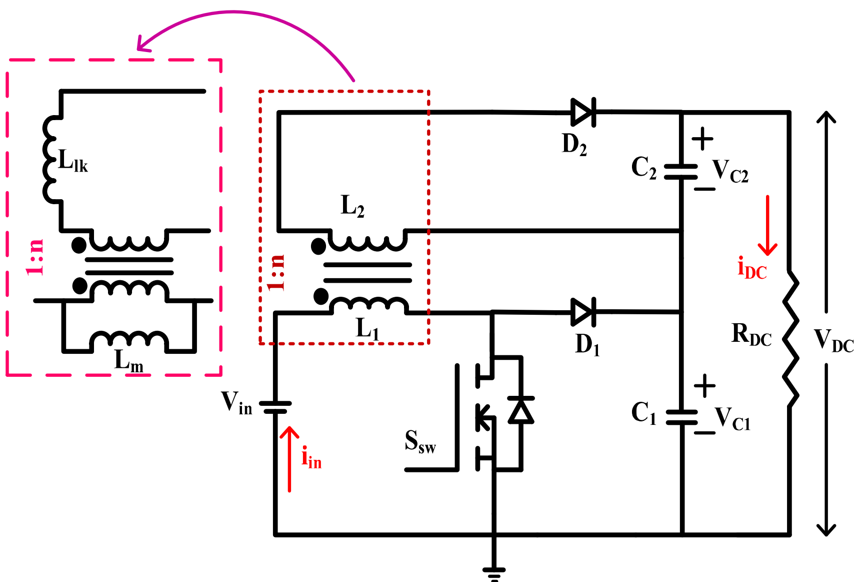


Fig. 1.9 DC-DC Boost converter with forward path during the S_{sw} turn-on position.

Fig. 1.9 shows a DC-DC boost converter having a forward path during the S_{sw} turn-on position. This reported converter [80] has two magnetically coupled differential coils L_1 and L_2, one extra capacitor C_2 and extra diode D_2. From the circuit point of view, it can be observed that the magnetic coils are coupled with one another in such a manner that a part of the energy is directly transferred to the load when the switch S_{sw} is ON. Here, the forward path for energy transferred to the load during the S_{sw} ON period is containing the components L_2, D_2 and C_2. Consequently, if the converter components are appropriately intended, the total energy transferred to the load increases and the initial dip in the output voltage is eliminated. Further, in this topology K can be increased near to unity.

1.2.3 Minimization of Leakage Current

In the PV system, due to the large conducting surface area of the PV panel, a capacitance is formed between the PV panel and grounded frame, which holds the panel. This capacitor is called PV to ground parasitic/stray capacitor (C_{PV}) [81]. A general layout of single-phase transformerless inverter for stand-alone PV system is shown in Fig. 1.10. As, no transformer is used in the system, a galvanic connection exists between the inverter neutral and the PV array through C_{PV}, if the inverter neutral is grounded/inverter is grid connected. Under these conditions, if a high frequency $\frac{dv}{dt}$ is impressed across the C_{PV}, it leads to flow of leakage current/ground current in the system. According to DIN VDE 0126-1-1 standards, for personal safety, a residual current monitoring device (RCMD) is required in transformerless inverters. RCMD monitors ground current and incase the ground current is more than 300 mA; inverter should be disconnected within 0.3 sec of detection [82]. The flow of leakage current increases the losses in the system, injects harmonics in the grid and creates EMI related issues with nearby grounded systems.

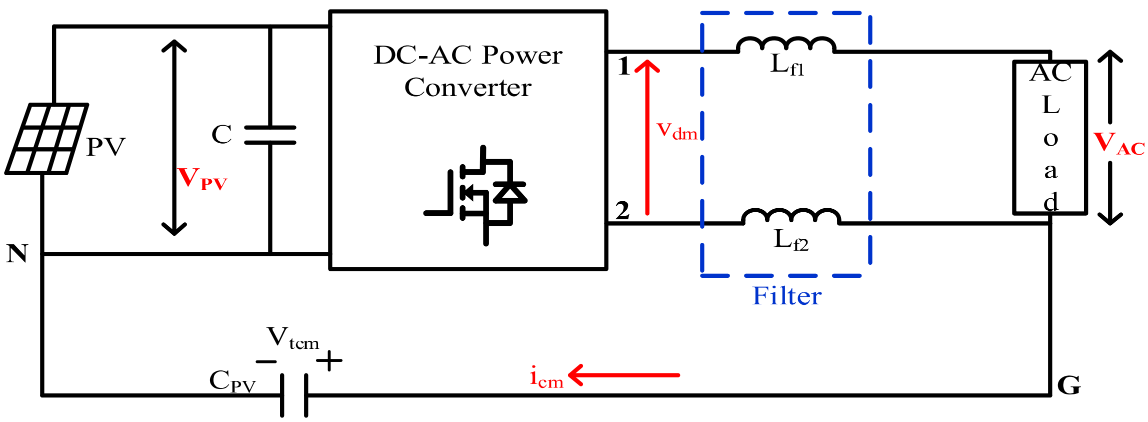


Fig. 1.10 General layout of a single phase transformerless inverter in stand-alone condition.

In order to minimize the flow of leakage current in the system, various transformerless inverter topologies are discussed in [83]-[88]. In all the cases, it is observed that the total common mode voltage (v_{tcm}) that appears across the parasitic capacitor must be kept constant or varied only at low frequency (at grid frequency or inverter output voltage frequency). Since at low frequency, the leakage current/ground current is very small, the Thevenin's equivalent model is realized for finding the v_{tcm} across C_{PV} for medium frequency range (< 50 KHz) [84]. A family of neutral point clamped full bridge topologies are reported in [85] to reduce the leakage current in transformerless topologies. Further, an advanced hybrid-bridge transformerless inverter is reported in [86] to minimize the leakage current. The reported topology is a combination of half bridge and neutral point clamping (NPC) modules. A modified single-phase, three-level diode-clamped transformerless topology is reported in [87] to not only reduce the leakage current but also to restrict the injection of DC current into the grid. In [88], a hybrid unipolar based SPWM technique is implemented to minimize the leakage current in transformerless H6 inverter topology. Also, in this paper a comparison in terms of leakage current, THD and efficiency among some PV-based transformerless inverter topologies are studied. The comparison and analysis of various single-phase transformerless inverter topologies in terms of leakage current minimization, efficiency and some other parameters are discussed in [89]. In [90], a full-scale leakage current analytical model for PV based grid connected inverter is reported. From the aforesaid transformerless PV inverter topologies, it can be concluded that for minimizing the flow of leakage current one should either modify the existing topology or implement proper switching techniques to the control switches such that the total common mode voltage across C_{PV} is constant throughout the switching cycle. Basically, there are two types of PV based single-phase full bridge inverter (FBI) topologies, which are 1) DC decoupling based single-phase FBI topology and 2) AC decoupling based single-phase FBI topology. Fig. 1.11 shows the full bridge topology with DC and AC decoupling technique. In DC decoupling technique, a high frequency-controlled switch (switch S_7 in Fig. 1.11) is used in the PV side to disconnect the inverter output part/utility grid from the PV part during the freewheeling period. Similarly in AC decoupling technique, the controlled switches (switches S_5 and S_6 in Fig. 1.11) are available in the grid side to isolate the inverter part and PV part during the freewheeling period.

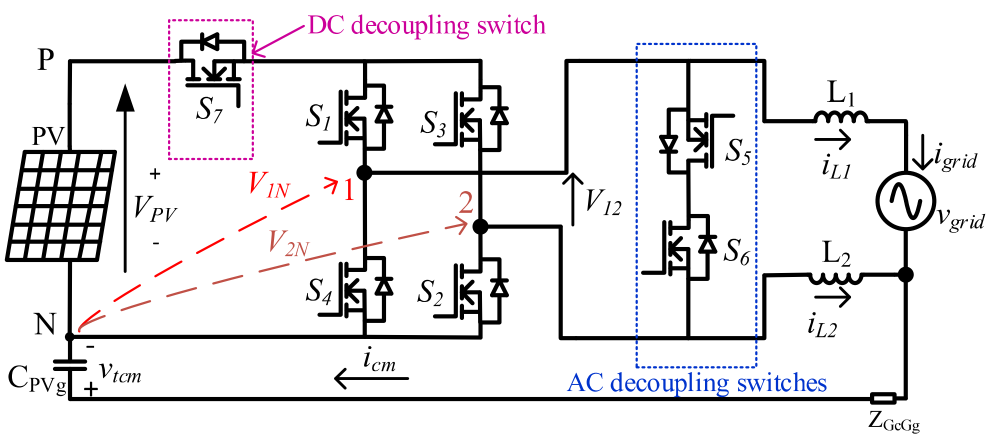


Fig. 1.11 Full bridge topology with DC and AC decoupling technique.

By isolating the inverter part/grid part from the PV part during the freewheeling period, the transition in the inverter terminal voltage is avoided. This causes a constant common mode voltage across the PV panel to ground parasitic capacitance throughout the switching cycle resulting into zero leakage current. Various single-phase transformerless DC and AC decoupling topologies are reported in [86]-[91], these are H5 topology [86], H6 topology [88], highly efficient and reliable inverter concept (HERIC) topology [90] along with their modified versions for minimizing the leakage current [91].

1.2.4 Grid Integration

Solar PV-grid integration is the technology that allows large scale solar power produced from the solar PV (SPV) system or concentrated solar power system to penetrate the already existing utility grid. This technology nowadays has become very popular, since the power generated from the SPV systems can then be optimally. The grid can sink any amount of power and no storage equipment is required for storing it. A family of single-phase and three-phase grid integrated SPV systems are discussed in [92]-[96]. In [92], a double-frequency SPWM technique has been proposed to keep the total common mode voltage constant throughout the switching cycle of the grid connected three-level H6 inverter. In order to effectively suppress the leakage current in the transformerless inverter with H5 topology, an improved grid integrated H5 topology is reported in [93]. Some flying capacitor based single-phase transformerless inverters for the grid connected PV systems are discussed in [94]. A transformerless inverter topology that can simultaneously eliminate the leakage current and pulsating power in grid connected PV systems is discussed in [95]. A new analytical technique to evaluate the reliability of the grid connected PV systems is reported in [96].

The transformerless inverter topologies consist of a boost-stage in the input side of the system. Fig. 1.12 shows two-level dual-stage transformerless single-phase inverter with boost stage in the input side. Normally, boost stage/boost converter is used in the input side instead of buck stage/buck converter since the solar PV cells are low voltage energy cells. Also, the buck stage is not used because of its discontinuous nature of input current. Further, boost stage is used for MPPT operation and the inverter stage is used to regulate the DC input. The main advantage of these topologies is the higher efficiency. More than 95% of efficiency can be achieved in these topologies and it can be further improved by using proper LCL filters [97]. Further improvements in efficiency can also be possible by increasing the number of levels, however it leads to the complexity in the inverter stage [98].

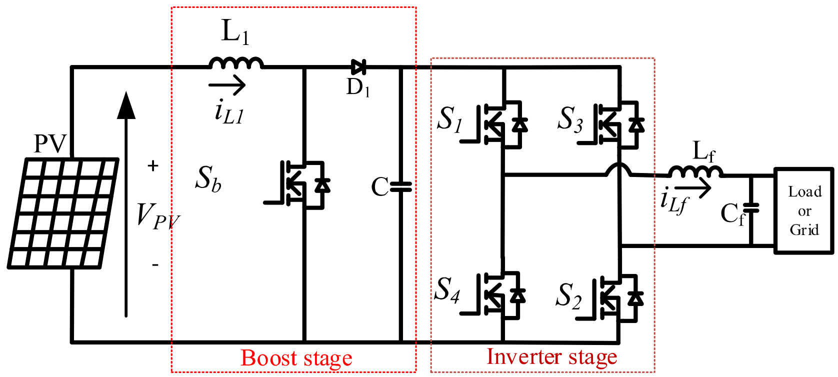


Fig. 1.12 Two-level dual-stage single-phase inverter with boost stage in the input side.

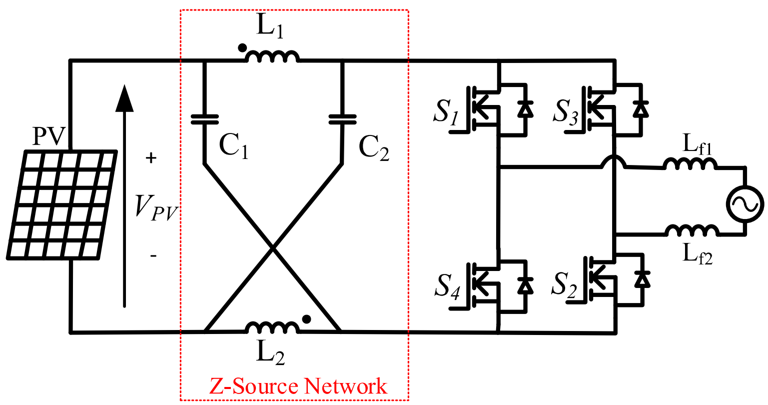


Fig. 1.13 Single-phase Z-source inverter.

Another set of inverters based on an input side impedance network called Z-source inverters are also considered in transformerless PV based grid integration applications. Fig. 1.13 shows a single-phase Z-source inverter. The Z-source inverter can operate in both buck mode and boost mode, whereas the conventional VSI can operate only in the buck mode. For the boost mode of operation, these inverters have an additional switching state, which is called the shoot-through state [99]. During the shoot-through state, the DC link is short circuited by turning on both the controlled switches of the same leg. The main disadvantage of the Z-source inverters is the sensitivity to the parasitic impedances in the Z-source network. There can be significant over-voltage stresses in the semiconductor devices and hence the devices will have to be either oversized or the snubber protected [100].

For grid connected operation, IEEE and IEC have laid down several guidelines to take care of the grid current. The IEEE standard 1547-2003 [101] and IEEE standard 519-1992 [102] specify the limits of harmonic currents in the grid. Another important control loop in the grid connected systems is the phase-locked loop (PLL). The design of different types of PLL techniques is discussed in [103]-[105]. The PLL is required to synchronize the inverter to the grid and to keep it locked with the grid. Further, an LCL filter is required in grid connected inverters to comply with the IEEE recommended limits [106]-[107] on the injection of harmonics into the grid.

1.3 Challenges with the Existing Systems

In recent times, due to the gradual increment in DC loads along with the existing AC loads, the hybrid output (simultaneous DC and AC outputs) based solar PV systems are getting more and more popularity. To obtain hybrid outputs, recently in last few years researchers have proposed some hybrid converters instead of using two different converters for two different outputs. Further, to fed the surplus amount of power back into the utility grid, lots of PV based inverter topologies have been proposed. Basically, the PV based inverter topologies are of two types; galvanic isolated type and galvanic non-isolated type (transformerless type). Both advantages and disadvantages of these two types of PV based inverter topologies have been studied. After carrying out detailed literature review, the challenges of the existing systems are summarized as follows:

- Basically, the existing hybrid converters are developed by replacing the control switch of a conventional DC-DC boost converter by a single-phase/three-phase VSI. These hybrid converters can only operate in the operating condition $D + M_i \leq 1$.
- Due to the narrow operating range of D and M_i, there is a trade-off between the DC gain and the quality of AC output voltage.
- As the DC part of the existing hybrid converters behave like conventional DC-DC boost converters during their steady-state operations, the RHPZs exist in their control-to-output voltage transfer functions.

- Due to the existence of RHPZs, they behave as non-minimum phase systems.
- The presence of RHPZs cause instability during the dynamic operation of the hybrid converters.
- The controller design of hybrid converters is complex due to the inverse variation in bandwidth and PM of the system.
- As both DC-DC and DC-AC power conversion are occurred through a single PEC, the efficiency of the overall system is deteriorated.
- A large number of power conversion stages are required to transmit power from the solar PV source to residential loads.
- In case of the solar PV inverter topologies, one extra stage is needed to increase the input voltage of the VSI type topologies.
- As the existing conventional VSI based topologies have no inherent shoot-through capability, they require deadtime circuit for their operation.
- In case of Z-source type solar PV inverters, due to significant over-voltage stress on the semiconductor devices, they require either oversized devices or snubber networks for the semiconductor devices.
- The transformerless solar PV inverters are preferred for better efficiency and reduced overall weight, volume, size and cost. However, they suffer from harmful leakage currents. So, it is required to minimize the flow of leakage current well below the recommended standards.
- Most of the existing transformerless PV topologies operate both in off-grid and grid-tied modes with reduced common mode leakage current. However, they cannot regulate both DC and AC loads simultaneously.

1.4 Objective of Thesis

It is evident from the literature survey that the existing hybrid converters and transformerless solar PV inverters have various operational and stability issues, like incapable of operating in wide operating range of D and M_i, non-minimum phase property, leakage current minimization, shoot-through problem and requirement of deadtime circuit. Various topologies have been proposed over the years to take care of these issues; however, all these issues have not been taken care of either in one single unit of hybrid converter or in transformerless solar PV inverter.

In order to solve the above-mentioned issues, a new transformerless hybrid converter (THC) is developed, termed as transformerless minimum phase hybrid converter (TLMPHC). The proposed TLMPHC is capable of achieving minimum phase property, while minimizing the common mode leakage current. Additionally, this converter provides inherent shoot-through capability without requiring any deadtime circuit. Further, during the freewheeling period, the AC load/grid is decoupled from the main circuit, which results in improved quality of AC output current. However, while studying the developed TLMPHC, it is observed that the TLMPHC operates only in a narrow operating range of D and M_i.

To operate the THC in a wide operating range of D and M_i ($D + M_i \geq 1$), two independent controlling elements/factors are required, rather than one single controlling element, which is responsible for both D and M_i at the same instant. Basically, in case of boost derived type THCs, the controlled switch of the boost converter is replaced by a voltage source inverter/current source inverter to give both DC and AC outputs simultaneously. So, the important operating constraint in these types of converters is $D + M_i \leq 1$. Hence, for achieving two independent controlling elements to attain a wide operating range operation of THC, the concept of interleaved converters (interleaving of two converters) is incorporated. In this manner, a transformerless interleaved hybrid converter (TLIHC) is developed by incorporating the concept of interleaving in TLMPHC. The proposed TLIHC achieves all the features of TLMPHC along with the wide operating range of D and M_i. In this way, two different transformerless hybrid PECs are proposed in this thesis.

To develop the proposed TLIHC, the proposed TLMPHC is incorporated with a conventional DC-DC boost converter. The controlled switch of boost converter is responsible for D and the proposed TLMPHC is responsible for M_i. The block diagram representation of the proposed TLIHC along with its salient features is shown in Fig. 1.14. Due to the wide operating range of D and M_i, inherent shoot-through capability and minimum phase property of the proposed TLIHC, it has various advantageous features as compared to the conventional hybrid converters. These are 1) no compromise between the DC gain and AC output voltage quality, 2) no need of deadtime circuit, 3) it can achieve both high bandwidth and PM, 4) it has simpler controller design, 5) it has lower ripple content in the input current and 6) it has high DC gain with low voltage stress in the DC side. Further similar to the TLMPHC, the THD of the TLIHC is also reduced as the inverter part is decoupled from the main circuit during the freewheeling period. The robustness of the controller is verified by changing various passive parameters of the proposed TLIHC. Also, the controller behaviour and dynamic response of TLIHC is verified to check the performance of the controller. All the above advantageous features and performance analysis of the proposed TLIHC are verified for both off-grid and grid-tied mode operation of TLIHC.

In grid connected operation, harmonic analysis is carried out to check the quality of the grid current in case of proposed TLIHC. It has been observed that the TLIHC complies to the grid integration standards of IEEE 519-2014. To check the robustness of the proposed TLIHC, sudden change in grid current is made and its effect is studied and found to be satisfactory.

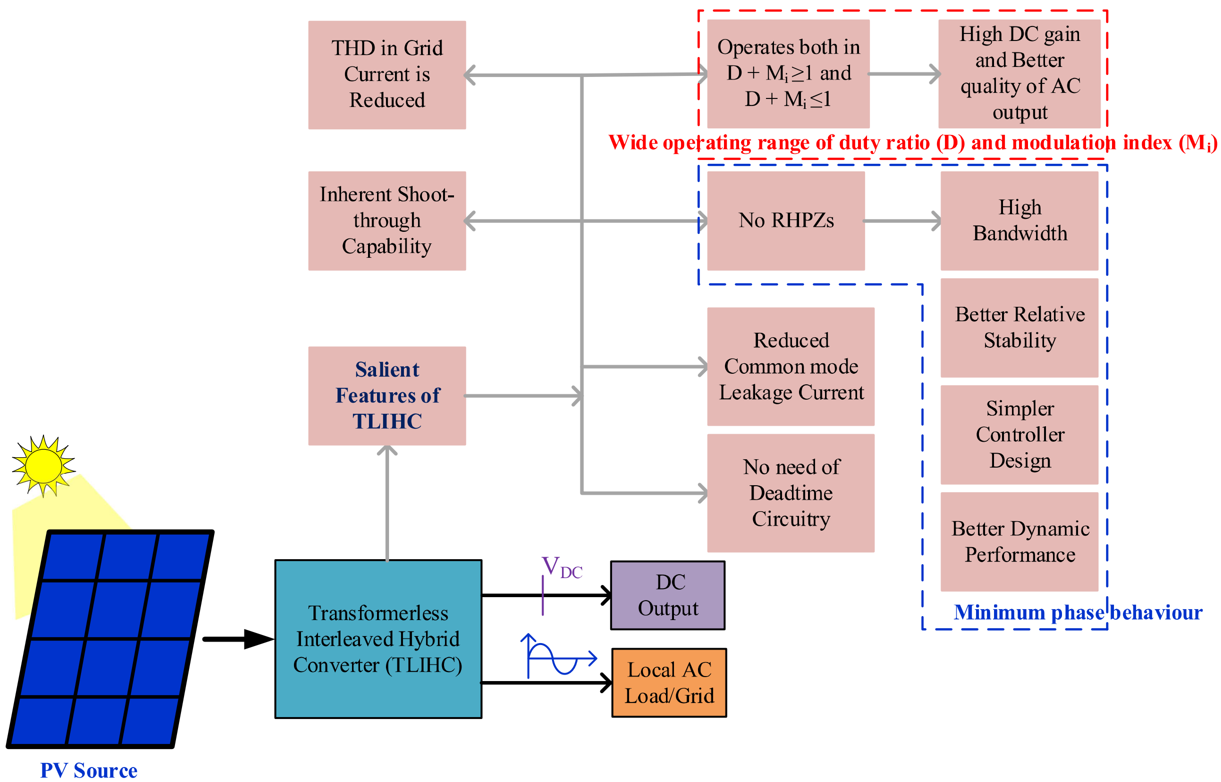


Fig. 1.14 Block diagram representation of TLIHC along with its salient features.

The various issues discussed in the literature have been taken care of using TLMPHC (incapable of operating in wide operating range) and TLIHC. The simulation studies are carried out for verifying the theoretical investigations using both Power SIM (PSIM) and MATLAB/SIMULINK. The laboratory prototypes are developed to verify the performance of the proposed transformerless hybrid converters (TLMPHC and TLIHC).

1.5 Organization of the Thesis

Apart from this chapter, the thesis consists of five more chapters. A brief discussion of the remaining chapters is outlined as follows.

Chapter 2 discusses the topology development and operation of both TLMPHC and TLIHC. The various operational characteristics of both the proposed THCs are presented in this chapter. A unipolar based sinusoidal pulse width modulation (SPWM) technique for both the developed hybrid converters are discussed in this chapter. The performance of the TLIHC is compared with some of the reported hybrid converters and also with TLMPHC. Finally, the simulation and experimental verifications are carried out for validating the operational behaviour and salient features of TLMPHC and TLIHC in this chapter.

In Chapter 3, mathematical modeling and small signal analysis of TLMPHC and TLIHC are presented. Detailed analysis of key features of both TLMPHC and TLIHC are discussed in this chapter. The performance of TLIHC is compared with some of the existing hybrid converters in terms of voltage and current stresses, number of elements used, DC and AC voltage gains and efficiency. The simulation and experimental verifications are carried out for validating the performance of TLMPHC and TLIHC in this chapter. Additionally, Loss distribution among the various elements of TLMPHC and TLIHC is discussed in this chapter. Finally, various applications and limitations are also presented.

In Chapter 4, the verification and analysis of all the key features of the proposed TLIHC during the dynamic conditions are presented. The detailed design procedure of both DC and AC side controllers and their advantageous features are discussed in this chapter. The behaviour of the controller used in the proposed TLIHC, for variations in passive components values are also presented. The cross-regulation behaviour of TLIHC is conferred during the dynamic loading conditions in this chapter. Leakage current comparison between the proposed TLIHC and one of the transformerless boost derived hybrid converter is also presented in this chapter.

Chapter 5 discusses the grid-tied mode operation of TLIHC. The detailed analysis of grid side filter inductors (L_{g1} and L_{g2}), phase-locked loop (PLL) design and fast Fourier transform (FFT) analysis of grid current (I_g) of the proposed TLIHC are discussed in this chapter. Also, the closed loop control strategy of I_g is discussed in this chapter. Finally, the simulation results for the performance verifications of the grid integrated proposed TLIHC is presented in this chapter.

Conclusions to the research work in the thesis and scope for the future work are discussed in Chapter 6.

In order to show the relationship among different chapters, a chapter wise block diagram representation of overall thesis is shown in Fig. 1.15. From the figure, it is observed that all the chapters are related with each other and chapter 6 shows the overall conclusion of the work.

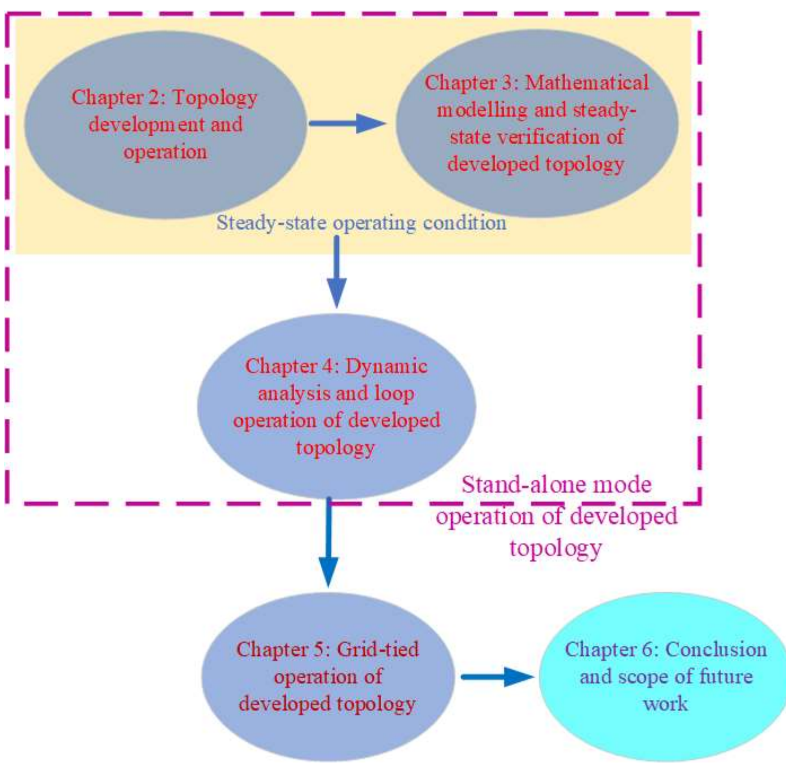


Fig. 1.15 Chapter wise block diagram representation of overall thesis.