

# Chapter: 1

## Introduction

### 1.1. Background and Motivation

In the current global scenario, the growing population is driving an ever-increasing demand for energy. At present, the majority of this demand is met through fossil fuels, which significantly contribute to global warming and environmental pollution [1]. Recognizing the need to address the energy requirements of both the present and future generations, the United Nations has adopted the '17 Sustainable Development Goals (SDGs)'. Among these, 'SDG 7' specifically focuses on ensuring access to affordable, reliable, and sustainable energy for all [2].

Renewable energy sources (RES) such as wind, hydro, solar, biomass, and tidal play a crucial role in achieving SDG 7 and mitigating global climate change and environmental pollution [3-5]. While hydro and wind energy are among the most established RES, they have notable limitations. Hydro projects require substantial upfront investment and can have adverse effects on biodiversity, while wind power plants necessitate more frequent maintenance compared to other RES [6]. Additionally, these sources are not ideally suited for residential systems to address localized energy demands. In contrast, solar photovoltaic (PV) systems offer significant advantages for residential and commercial energy distribution. Unlike wind power plants, solar PV systems lack mechanical moving parts, resulting in reduced maintenance requirements and greater compactness. They also produce no harmful greenhouse gases, unlike biomass energy sources, and can be installed near load centers, making them suitable for large solar plants and small-scale household applications. Among all RES, solar PV systems are widely regarded as one of the most cost-effective and practical solutions for sustainable energy generation [7]. Furthermore, Fig. 1.1 illustrates the trends in electricity generation from various RES in India over the years [8]. Notably, solar energy has shown a remarkable growth trajectory after 2014, with electricity generation from solar sources surpassing wind energy production by 2022. This achievement has been driven by significant technological advancements that have simplified solar

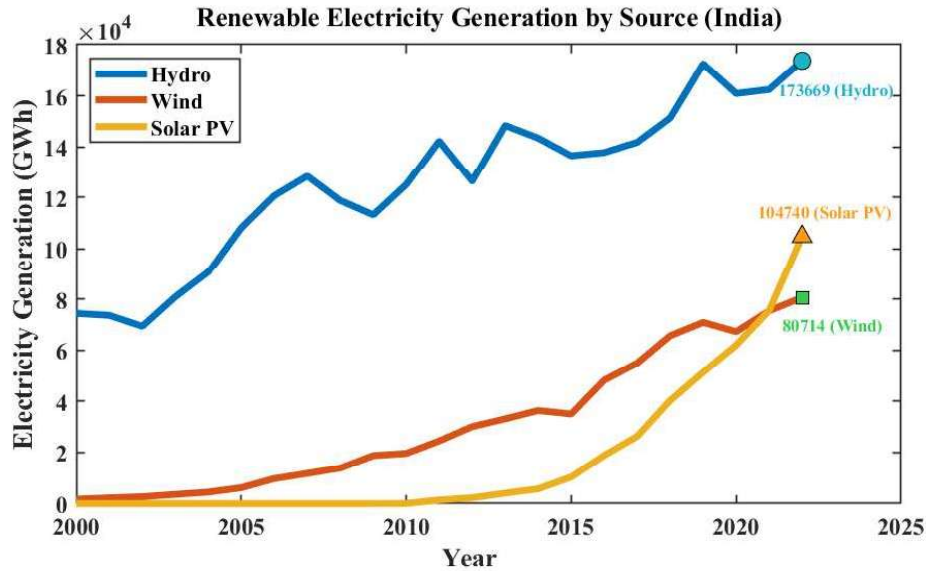


Fig. 1.1. Recent trends in electricity generation from various RES in India.

energy extraction [9]. Additionally, supportive government policies and solar subsidies have greatly improved the affordability and accessibility of solar PV systems, further promoting their adoption.

The cheap and effective accessibility of solar energy [10] highlights the vast potential and adaptability of solar PV as a reliable solution for residential rooftop systems. The layout of a modern residential rooftop system is illustrated in Fig. 1.2. In this setup,

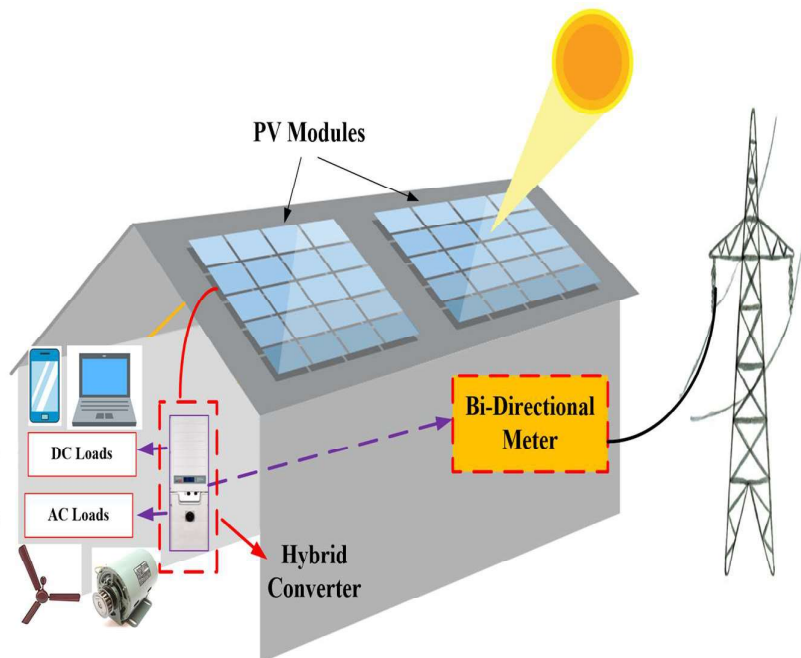
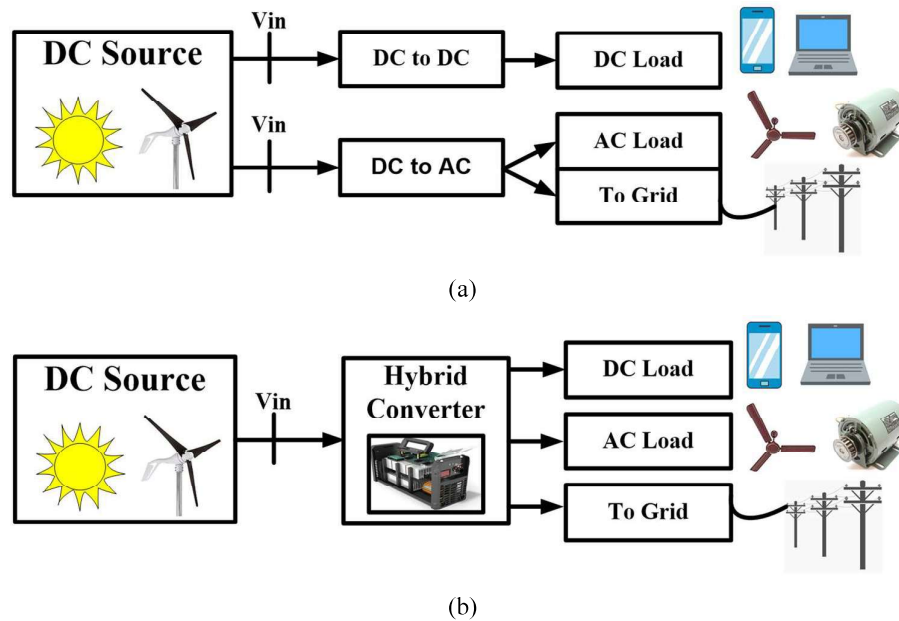


Fig. 1.2 Layout of modern residential PV rooftop system

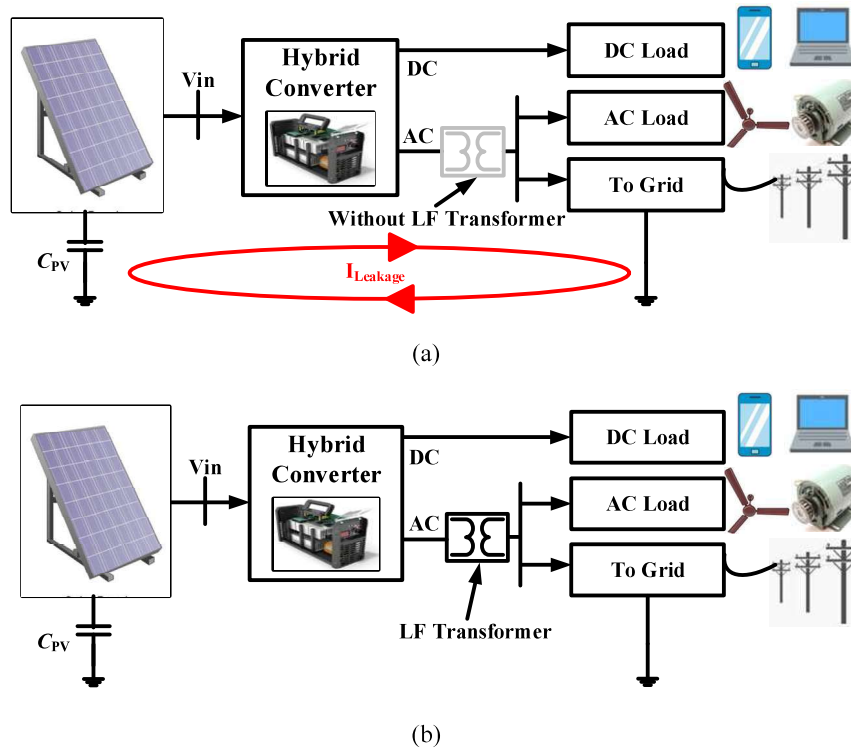


**Fig.1.3** Conventional and hybrid converter (a) Two separate converters for DC and AC loads (b) Single MOHC for Simultaneous AC and DC loads.

solar PV modules harness power from the sun, and a hybrid converter is used to supply both AC and DC loads. Any surplus power is fed back to the grid.

In recent times, the integration of new DC loads alongside existing AC loads has increased the demand for separate DC-DC and DC-AC converters, as illustrated in Fig. 1.3(a). However, employing two different converters to serve AC and DC loads simultaneously results in a cost-inefficient system due to the higher number of switches and components required. Alternatively, a hybrid converter (as illustrated in Fig. 1.3(b)) offers a more efficient solution, as it can handle both AC and DC loads simultaneously using the same set of switches and components in a single Multi-Output Hybrid Converter (MOHC) [11]-[13].

Solar PV sources typically generate low output voltages [14], requiring a boost network to match the voltage levels of DC and AC systems. When a single set of switches is used to simultaneously achieve both AC and DC outputs, a trade-off arises between the duty ratio ( $d$ ) and the modulation index ( $m_i$ ), expressed as  $d + m_i \leq 1$ . Here,  $d$  governs the DC voltage gain, while  $m_i$  controls the AC voltage gain. To address this limitation, converters with a wide operating range ( $d + m_i \geq 1$ ) are employed, though they exhibit nonlinear characteristics [15]. Alternatively, high-gain converters operating at lower  $d$  values are often preferred to overcome this challenge.



**Fig.1.4** Types of MOHC (a) Hybrid converter layout with transformer (b) Hybrid converter layout without transformer

The large conducting area of solar PV panels often creates a parasitic capacitance ( $C_{PV}$ ) [16]. Due to the high switching frequency of the converter, charges may accumulate on the panel, posing a safety hazard. If a person comes into contact with the panel, the accumulated charges could be discharged through the individual. To mitigate this risk, the panel is typically grounded for safety. Similarly, the neutral point of the AC terminal is also grounded to ensure safe operation. However, the high-frequency switching across the parasitic capacitance can result in leakage currents flowing through the system, as illustrated in Fig. 1.4(a). These leakage currents can be effectively eliminated by introducing a Low-Frequency (LF) transformer, as shown in Fig. 1.4(b). The inclusion of a transformer ensures electrical isolation and mitigates the leakage currents. However, the introduction of a bulky LF transformer into the system increases the overall cost of the system and introduces additional losses. As a result, transformerless or non-isolated systems are often preferred in applications where cost-effectiveness and efficiency are preferred [17]-[20].

Moreover, the electrolytic capacitor is one of the most vulnerable and least reliable components in any power electronic converter. Additionally, in a two-stage system, the

electrolytic capacitor in the DC link plays a crucial role in reduces the overall lifespan and reliability of the power converter.

To overcome these challenges, this thesis delves into the development of transformerless Maximum Power Point Tracking (MPPT)-enabled  $L_nC_{2n-2}$  network-based Multi-Output Hybrid Converters (MOHC) and their practical applications in PV-based residential rooftop systems. These advanced converters are designed to improve efficiency, reduce cost, and enhance reliability in solar power integration.

Furthermore, to mitigate the drawbacks associated with electrolytic capacitors—such as their limited lifespan and susceptibility to failure—this research proposes an impedance network-based, electrolytic capacitorless isolated resonant converter. This innovative approach aims to enhance the overall durability and performance of power conversion systems while maintaining stable and efficient operation.

## **1.2. Literature Review**

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

### **1.2.1. Impedance Network**

To ensure compatibility between the voltage specifications of renewable energy sources and utility grids, various power electronic converters are essential. These converters act as an interface, facilitating efficient power transfer between renewable sources and the utility network. They are extensively used in applications such as renewable energy systems, electric vehicles, motor drives, and power supplies. Since most renewable energy sources generate low DC voltage, DC-DC converters are essential for elevating this voltage to usable levels. However, traditional DC-DC converters face several challenges [21-22], leading to the development of various advanced topologies. These converters can be broadly classified into isolated [23-24] and non-isolated types [25].

Isolated DC-DC converters regulate voltage gain by adjusting the transformer's turn ratio. However, including a transformer introduces drawbacks such as voltage spikes, increased size, bulkiness, higher costs, and lower efficiency. Due to these limitations,

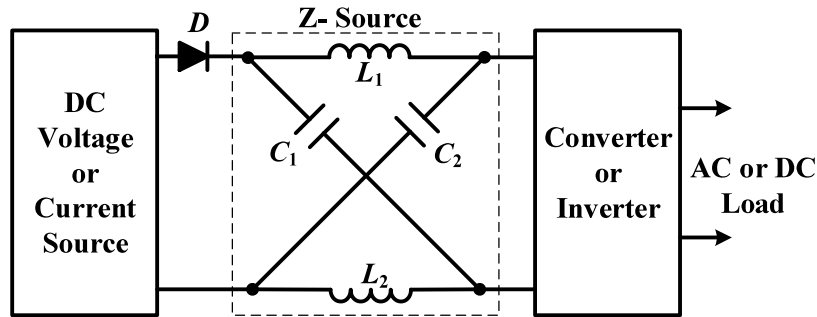


Fig.1.5. Conventional Z- Source network

isolated converters are generally avoided unless DC isolation is a strict industry requirement.

On the other hand, non-isolated DC-DC converters [26] typically offer lower voltage gain, but cascading multiple stages can enhance it. However, this approach increases component count, leading to higher losses, reduced efficiency, and stability concerns [27].

To achieve high voltage gain, topologies utilizing coupled inductors [28] can be employed. However, these designs inherit drawbacks similar to isolated converters. Switched-capacitor-based topologies provide another alternative for high voltage gain, but they suffer from high transient currents, which can impact performance.

An impedance network can be used as the most suitable solution in a non-isolated converter DC-DC converter, which eliminates the limitations of the traditional DC-DC converter. An impedance network (Z source) was introduced [29] to overcome the limitations of a traditional DC-DC converter. The impedance network in a Z-Source Converter (ZSC) comprises two inductors and two capacitors, as illustrated in Fig. 1.5. Moreover, the presence of inductors prevents sudden changes in current, while the presence of capacitors prevents sudden changes in voltage, ultimately reducing electromagnetic interference (EMI). The other advantages of ZSC's are as follows:

- **Single-stage conversion:** The Z-source converter (ZSC) provides a novel power conversion concept, enabling dc-to-ac, ac-to-dc, ac-to-ac, and dc-to-dc power conversion in a single stage.
- **Buck-boost capability:** It can produce an AC output voltage greater or less than the input DC voltage, overcoming limitations of traditional VSC and CSC.

- **Improved reliability:** The ZSC's network eliminates the need for dead time between switching, reducing the risk of shoot-through and improving overall system reliability.
- **Wider voltage range:** It can handle a wide range of input voltages, making it particularly suitable for applications like fuel cells where voltage varies significantly with load.
- **Reduced component count:** The ZSC eliminates the need for an additional DC-DC boost converter in applications requiring voltage boost, simplifying the system and potentially reducing costs.
- **Increased efficiency:** By combining the functionality of boost and buck converters into a single stage, the ZSC can achieve higher efficiency compared to traditional two-stage conversion systems.
- **Flexibility in power source:** The ZSC can be coupled with various DC sources, including voltage sources, current sources, or a combination of both.

These advantages make the Z-source inverter a promising solution for applications such as renewable energy systems, electric vehicles, and distributed power generation, where wide voltage ranges and high efficiency are crucial.

The ZSC offers several advantages over traditional VSCs and CSCs. However, it has certain drawbacks, such as discontinuous input current, making it less suitable for solar PV applications. In contrast, the quasi-Z Source Converter (qZSC) [30]-[31] retains all the benefits of the ZSC while ensuring continuous input current. Additionally, qZSC, as illustrated in Fig. 1.6, uses the same number of components; however, the qZSC's components ratings in the qZSC are lower than those in the traditional ZSC, improving overall efficiency and reliability [32].

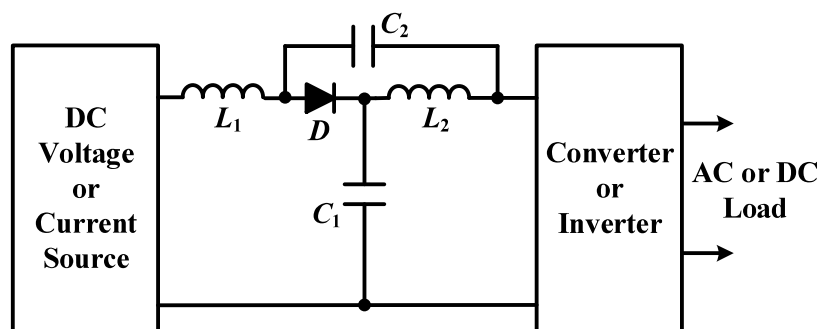


Fig. 1.6. Conventional Quasi-Z Source Network

The quasi-Z-Source Converter (qZSC) exhibits technical superiority over the traditional Z-Source Converter (ZSC); however, both topologies have a fixed voltage gain. Moreover, a step-up impedance network-based  $n$ -stage modular DC-DC converter [33]-[40] is proposed, which improves the characteristics at every stage. Furthermore, in case of a fault in any component, the leverage to easily bypass a faulty module enables the proposed converter to keep operating in parallel with the repair/replacement of the faulty component. As a result, the modular design enhances the overall reliability and robustness of the converter system. However, the modular design adds different reactive elements and switches at each stage, and the number of stages can be chosen as per the application requirement.

### 1.2.2. Multi-Output Hybrid Converter

Most renewable energy sources generate DC power, and while most existing loads operate on AC, there has been a growing trend in the use of DC loads in recent times. Traditionally, two separate converters are required to supply AC and DC loads, as shown in Fig. 1.3(a). However, a single multi-output hybrid converter (MOHC) [41]-[45] can be employed to simultaneously serve both AC and DC loads, as illustrated in Fig. 1.3(b). This approach is more economical, as it reduces the number of required switches and components, leading to lower costs and improved efficiency.

The traditional Multi-Output Hybrid Converter (MOHC) [11] can be viewed as a variation of a DC-DC converter, where the single controlled switch of a conventional boost converter is replaced with a bidirectional single-phase bridge network consisting

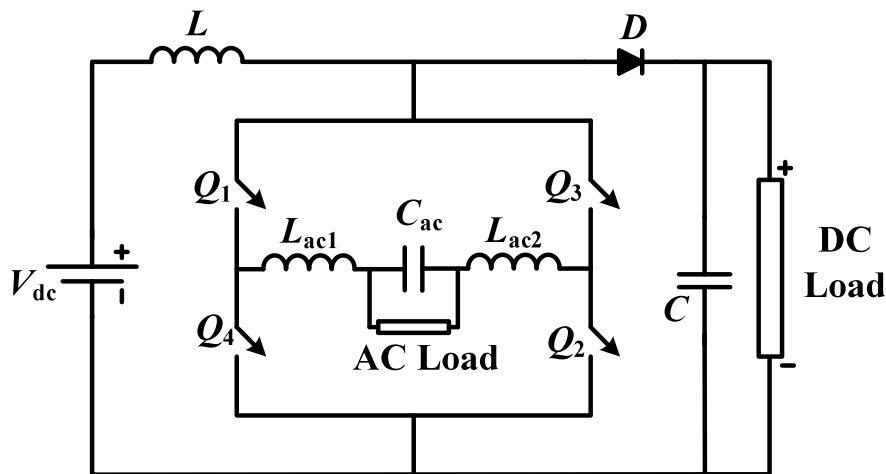
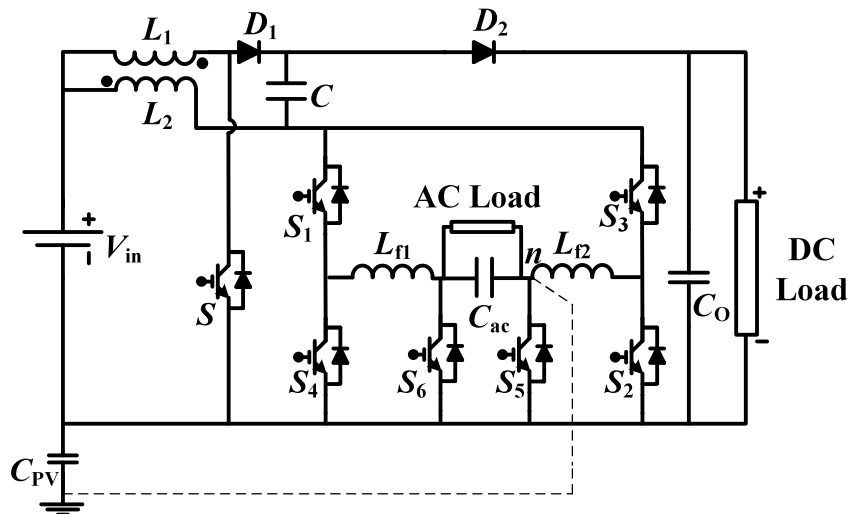


Fig. 1.7. Boost-derived hybrid converter.

of switches (Q1–Q4). This modification results in the boost-derived hybrid converter (BDHC) topology, as depicted in Fig. 1.7. Additionally, since the same set of switches in MOHC governs both DC and AC operations, a tradeoff exists between these functions, constrained by  $d + m_i < 1$ . Here,  $d$  is the duty ratio governing the converter's DC gain, while  $m_i$  represents the modulation index responsible for the AC peak value and the quality of the AC output.

Researchers have made significant efforts in wide operating range minimum phase Interleaved Hybrid Converter to overcome the constraint of  $d + m_i < 1$ , enabling the system to operate beyond this limitation at  $d + m_i > 1$ , as demonstrated in Fig.1.8 [13]. To achieve this, certain topologies incorporate coupled inductors to extend their operating range. However, the use of coupled inductors introduces several challenges, including voltage and current spikes across the components, increased electromagnetic interference (EMI), and additional noise within the system. These factors can degrade overall system performance.

Furthermore, researchers have also explored the development of a Modular Multi-Output Hybrid Converter designed for residential hybrid loads [47]. This topology integrates a multi-level inverter with two DC outputs from a single input, thereby reducing the AC filter requirements while providing dual DC outputs instead of just one. However, this approach introduces an additional number of semiconductor switches into the system, increasing the complexity of control and making the overall operation more challenging. Additionally, the rise in the number of switches leads to



**Fig. 1.8.** Wide Operating Range Minimum Phase Interleaved Hybrid Converter

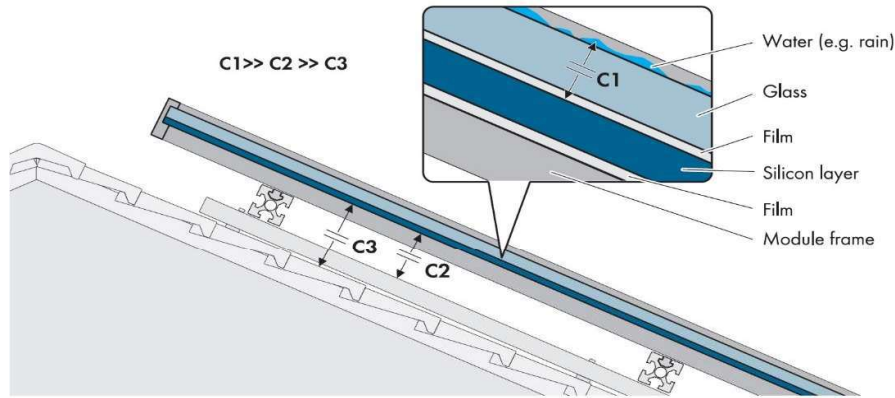


Fig. 1.9 Capacitances formed between different layers of PV modules

higher semiconductor costs, which must be carefully considered in practical implementations.

### 1.2.3. Leakage current Minimization

A PV module consists of an electrically conductive surface positioned opposite a grounded support frame. This PV configuration stores charge when voltage is applied and functions as a capacitor, with its capacitance referred to as parasitic capacitance and denoted as " $C_{PV}$ ". Fig. 1.9 illustrates individual capacitances formed between different layers of PV modules, and  $C_{PV}$  is the total capacitance [47]-[49], which is the sum of all individual capacitance and illustrated as:

$$C_{PV} = C_1 + C_2 + C_3$$

Where,

- $C_1$ : Parasitic capacitance caused by the water film on the glass surface.
- $C_2$ : Parasitic capacitance associated with the grounded support frame.
- $C_3$ : Parasitic capacitance resulting from the roof surface area.

The capacitance is determined using the formula:

$$C = \epsilon_0 \epsilon_r A t$$

where:

- $\epsilon_0$  is the permittivity of free space,

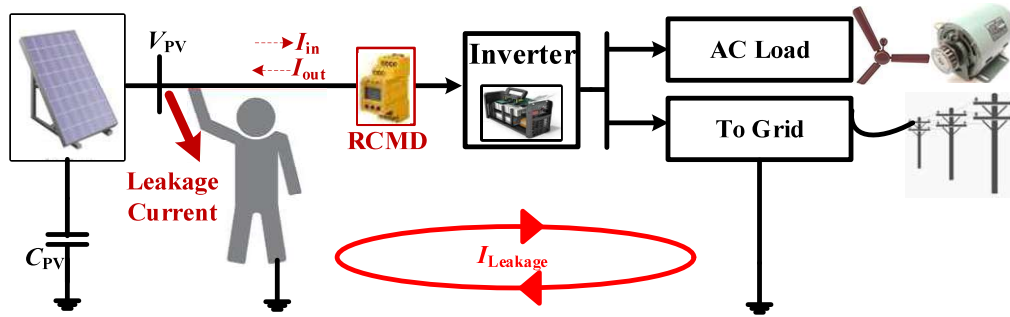


Fig. 1.10. Layout for transformerless grid-connected system

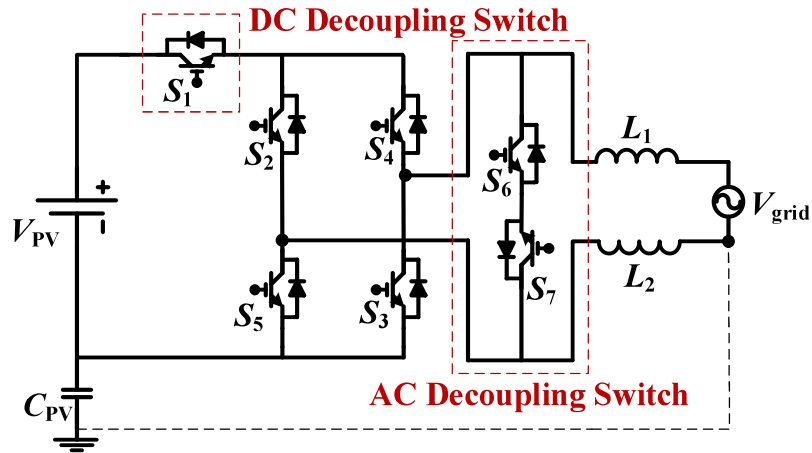
- $\epsilon_r$  is the relative permittivity of the material,
- $A$  is the surface area, and
- $t$  is the separation distance between conductive surfaces.

The value of  $C_{PV}$  is influenced not only by the surface area of the panels but also by the mounting techniques and prevailing climatic conditions. Depending on these factors, it can vary within a range of approximately 50 nF/kW to 150 nF/kW [50].

The developed  $C_{PV}$  accumulated charges on PV panels which must be properly grounded, as they can pose a hazard and may discharge through a person cleaning or coming into contact with the panels. Thus, to ensure safety, the panels are grounded to safely dissipate these charges and prevent potential electrical shocks.

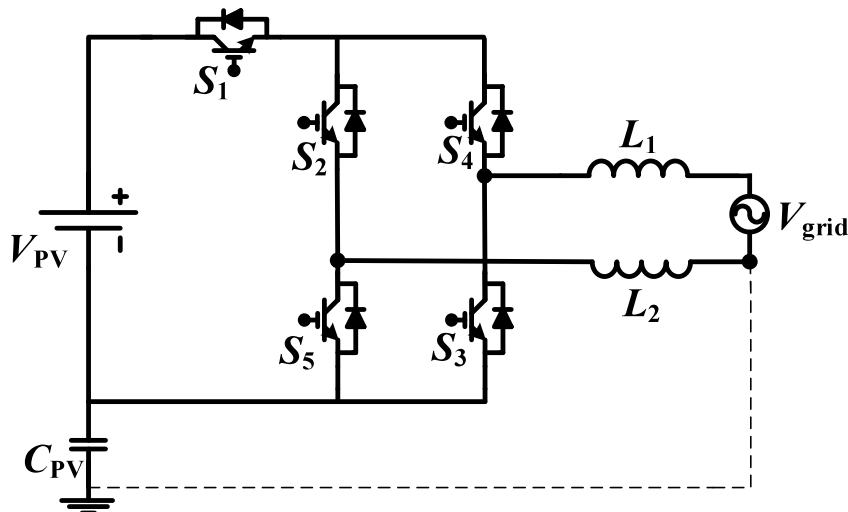
The high switching frequency of the converter/inverter induces a  $d(V_{C_{PV}})/dt$  stress across the parasitic capacitance ( $C_{PV}$ ). Since AC loads or the grid terminal connected to the inverter are also grounded for safety (as illustrated in Fig 1.10), this leads to the leakage current within the system [51]-[52]. Additionally, if a person comes into direct contact with the PV panels while barefoot, the leakage current may flow through their body, posing a serious hazard that must be prevented [53].

Ideally, the input current ( $I_{in}$ ) from the PV panel to the inverter should be equal to the returning current from the inverter ( $I_{out}$ ). Moreover, the leakage current is unidirectional, meaning the difference in magnitude between  $I_{in}$  and  $I_{out}$  represents the residual or leakage current. This difference is detected by a Residual Current Monitoring Device (RCMD). If the measured leakage current exceeds its permissible limit, i.e., 300mA peak, then as per VDE 0126-1-1, the RCMD must trigger a disconnection of the circuit within 0.3 sec to ensure safety [54]-[56].

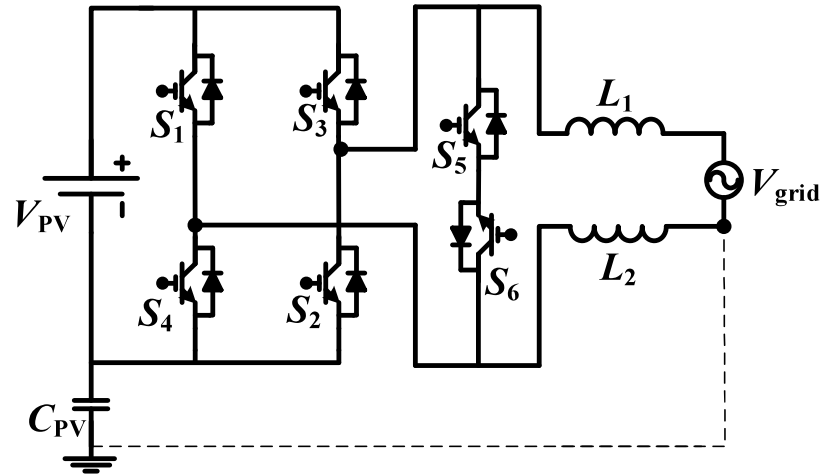


**Fig. 1.11.** Full bridge topology with DC and AC Decoupling

There are two primary types of PV-based single-phase Full-Bridge Inverter (FBI) topologies designed to minimize leakage current: 1) DC decoupling-based FBI and 2) AC decoupling-based FBI [57]-[58]. Fig. 1.11 illustrates these two decoupling techniques. In DC decoupling, a switch ( $S_1$ ) is placed on the PV side to disconnect the PV module from the inverter, effectively reducing leakage pathways. In contrast, AC decoupling utilizes controlled switches ( $S_6$  and  $S_7$ ) on the grid/AC side to isolate the inverter from the PV module during the freewheeling period. These decoupling methods play a crucial role in enhancing system safety and efficiency by mitigating unwanted leakage currents. Some examples based on the above technique are presented below.



**Fig. 1.12.** Conventional H5 topology.



**Fig. 1.13.** Highly Efficient and Reliable Inverter Concept

In 2005, SMA patented the H5 inverter topology [59]-[61], known as Sunny Boy, which is based on DC decoupling. This topology enhances the conventional H-bridge design by introducing an additional fifth switch in the positive bus of the DC link, as shown in Fig. 1.12. This extra switch plays a crucial role in improving system performance. It prevents reactive power exchange between the inductors and the parasitic capacitance of the PV module during the zero-voltage state, thereby enhancing efficiency.

Additionally, it isolates the PV module from the grid in the same state, effectively eliminating high-frequency components of the potential between the PV and ground, thereby reducing leakage current. Similarly, in 2006, Sunways patented a new inverter topology known as HERIC (Highly Efficient and Reliable Inverter Concept), which is derived from the conventional H-bridge and based on AC decoupling [62]. This topology introduces a bypass leg on the AC side, incorporating two back-to-back IGBTs (Insulated Gate Bipolar Transistors), as illustrated in Fig. 1.13. The AC bypass in the HERIC topology serves the same essential functions as the additional fifth switch in the H5 topology. It prevents reactive power exchange between the inductors and the parasitic capacitance of the PV module during the zero-voltage state, thereby improving overall efficiency. Additionally, it isolates the PV module from the grid in this state, effectively eliminating high-frequency components of the potential between the PV and ground, thus reducing leakage current. Some other single-phase transformerless topologies are discussed in [63]-[69].

Some of the Existing microgrids in the Indian markets are compared in terms of their electrical ratings, efficiency, power density, and cost in Table 1.1. Enphase, SMA, and

**TABLE 1.1**  
**SURVEY OF MICRO-INVERTER PRODUCTS IN THE MARKET**

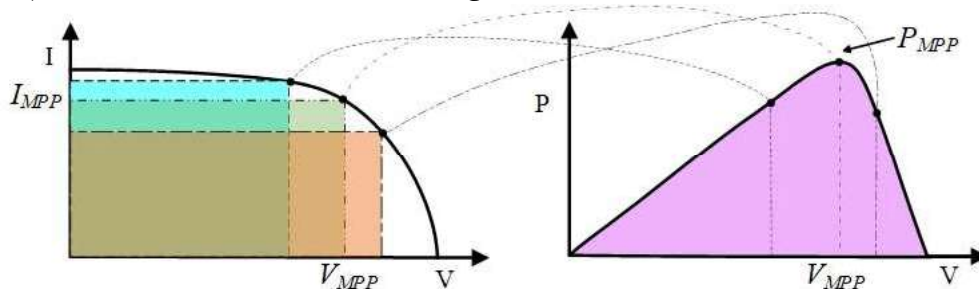
Company	Sunny Boy	Estimated Cost for 5 kW System (₹)	Power Density (W/kg)
<b>Enphase Energy</b>	97.0–97.5 %	₹2,00,000–3,00,000	~30–40
<b>TSUN</b>	97.2 %	₹1,75,000–2,50,000	~35–45
<b>Sofar</b>	97.5 %	₹1,75,000–2,50,000	~30–40
<b>APsystems</b>	97.0 %	₹1,50,000–2,50,000	~32–42
<b>Hoymiles</b>	96.7 %	₹1,50,000–2,25,000	~35–50
<b>Sungrow</b>	~96–97 %	₹1,40,000–2,25,000	~28–38
<b>Kstar</b>	~96.5 %	₹1,25,000–2,00,000	~28–38
<b>Sunny Boy (SMA)</b>	96.5–97 %	₹2,25,000–3,25,000	~30–35
<b>Polycab</b>	~95.5–96.5 %	₹1,10,000–1,90,000	~25–35

TSUN lead in efficiency and reliability but come at a higher cost. Brands like Polycab, Kstar, and Hoymiles offer budget-friendly options with decent performance and power density. For cost-effective 5 kW solar setups in India, Hoymiles and APsystems provide a strong balance of efficiency, price, and scalability.

### 1.2.4. Control Operations

In a modern residential rooftop system [70]-72, as discussed earlier, the full potential of the PV panel is utilized by directly supplying power to DC loads while any surplus energy is fed into the grid. To effectively control an inverter or a Multi-Output Hybrid Converter (MOHC), two key major control requirements must be met: 1) Maximum Power Point Tracking (MPPT) to ensure optimal power extraction from the PV panel and 2) grid-connected operation to facilitate seamless integration of the converter with the grid.

#### 1) Maximum Power Point Tracking

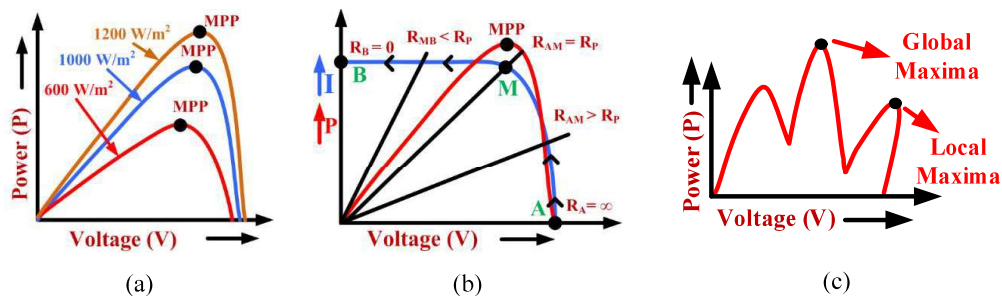


**Fig. 1.14.** Solar PV Characteristics.

The voltage-current (V-I) characteristic of a solar PV panel is inherently nonlinear, and the maximum power point (MPP) represents a unique operating point on both the V-I and voltage-power (V-P) curves [73], as illustrated in Fig. 1.13. This means that for any given set of conditions, there is only one optimal operating point where maximum power can be extracted.

However, the power curve shifts due to variations in solar irradiance, temperature, and dynamic loading conditions, causing the MPP to fluctuate. This makes tracking the MPP challenging. Fig. 1.15(a) demonstrates the variation of the PV curve with changing irradiance levels. Additionally, the PV and IV curves represent an equivalent resistance ( $V/I$ ) at each operating point. Fig. 1.15(b) shows how the resistance at each operating point on the PV curve decreases as the operating point on the curve moves from right to left, starting from infinity. Fig. 1.15(c) depicts the variation of the PV curves under partial shading conditions (PSCs), where the PV characteristics exhibit multiple peak characteristics, with one global maximum and one or more local maxima.

To maximize power extraction, researchers have developed numerous maximum power point tracking (MPPT) algorithms [74–76]. Among these, perturb and observe (P&O) [77–78] is one of the most widely used techniques due to its simplicity. However, it suffers from steady-state oscillations around the MPP. Incremental conductance (INC) [78] improves upon P&O by providing a faster and more efficient tracking method. Despite these improvements, both algorithms still exhibit slow tracking speeds and oscillations at the MPP. To enhance tracking performance, variable step-size methods [79] have been introduced for turbo-tracking.



**Fig. 1.15.** Solar PV characteristics under varying irradiance (a) Variation of equivalent PV resistance with PV and IV curve (b) Variation of MPP with solar irradiance. (c) Variation of PV characteristics under partial shading conditions.

Some MPPT techniques aim to eliminate the need for a current sensor. One approach [80] estimates the PV module's temperature and uses a preset lookup table to determine the PV current [81]. However, this method increases circuit complexity and reduces reliability due to inaccuracies in temperature estimation.

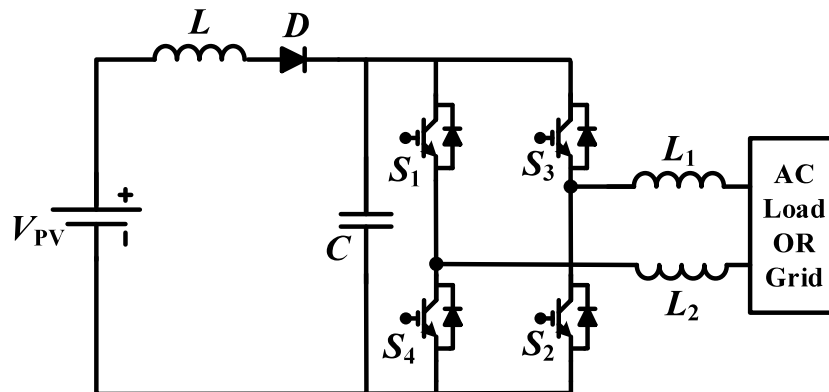
Recently, model predictive control (MPC) [82–83] has gained popularity for MPPT applications due to its ability to accurately track the MPP under dynamic environmental conditions [12]. MPC-based MPPT techniques offer high precision and adaptability, making them a promising alternative for next-generation PV systems.

Additionally, when the PV curve operates with multiple peaks (as shown in Fig. 1.16(c)), thus it becomes essential to use advanced algorithms that can effectively identify the global peak. Algorithms like Artificial Neural Networks (ANN), Particle Swarm Optimization (PSO), and Grey Wolf Optimization (GWO) are commonly employed for this task [85]-[87].

## 2) Grid-Connected Operation

The integration of solar PV systems with the grid enables easy and smaller or large-scale solar power, generated from either PV or concentrated solar power systems, to be fed into the existing utility grid. This technology has gained widespread popularity due to its ability to transfer power efficiently without requiring battery storage.

Various single-phase and three-phase grid-integrated solar PV systems have been explored in [88]-[92]. In [88], a double-frequency sinusoidal pulse-width modulation (SPWM) technique is introduced to maintain a constant total common-mode voltage throughout the switching cycle in a grid-connected H6 inverter. To mitigate leakage



**Fig. 1.16.** Two stage system.

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currents in transformerless inverters with H5 topology, an improved grid-integrated H5 topology is proposed in [89]. Flying capacitor-based single-phase transformerless inverters for grid-connected PV systems are discussed in [90]. A transformerless inverter topology that eliminates both leakage current and pulsating power is examined in [91], while [92] presents a novel analytical method for assessing the reliability of grid-connected PV systems.

Transformerless inverter topologies typically have two-stage systems that incorporate a boost stage at the input side, as shown in Fig. 1.16. The boost stage facilitates maximum power point tracking (MPPT), while the inverter stage regulates the DC input. These topologies achieve efficiencies exceeding 95%, which can be further improved with appropriate LCL filters [93]. Increasing the number of levels can enhance efficiency and add complexity to the inverter design.

Another category of inverters, based on an input-side impedance network known as Z-source inverters, is also employed in transformerless PV grid integration. A single-phase Z-source inverter operates in both buck and boost modes, unlike conventional voltage-source inverters (VSIs) that function only in buck mode. The Z-source inverter introduces a unique "shoot-through" state [94]-[95], during which the DC link is short-circuited by simultaneously turning on both switches in the same leg.

For grid-connected operation, compliance with IEEE and IEC standards is essential to regulate grid current quality. IEEE Standard 1547-2003 [96] and IEEE Standard 519-1992 [97] define harmonic current limits. Additionally, phase-locked loops (PLLs) play a critical role in synchronizing the inverter with the grid, with various PLL design techniques discussed in [98]-[100]. To meet IEEE guidelines [101]-[102] for harmonic injection into the grid, LCL filters are often employed in grid-connected inverters.

### **1.2.5. Electrolytic Capacitorless Impedance Network based Isolated Resonant Converter**

Solar panels typically produce a low-voltage output, which necessitates the use of high-gain DC-DC power converters to effectively harness and utilize the generated power. Depending on the requirement for electrical isolation, DC-DC converters are generally categorized into two types: isolated DC-DC converters and non-isolated DC-DC converters [103].

In the case of non-isolated DC-DC converters, the voltage gain can be regulated by adjusting the duty cycle of the switches. To achieve higher voltage gains, these converters can be configured with multiple cells in an expandable architecture. Several such expandable topologies have been proposed in [104]-[105], demonstrating the potential for high voltage conversion. However, these designs often require multiple input sources and a high number of switches at each stage, resulting in increased cost and reduced efficiency.

An alternative approach was suggested in [33], where an expandable converter with a single input source was presented. Despite the reduced input complexity, the voltage gain achieved by adding more stages remains limited, and the design demands more active switches and passive elements, further complicating the circuit. Another expandable input-sourced network described in [106] offers scalability up to  $n$ -stages, where the voltage gain follows the  $1/(1-nd)$  ratio. A notable advantage of this design is its ability to seamlessly bypass any faulty cell by integrating a new one, ensuring continuous and reliable operation. Nevertheless, the absence of galvanic isolation limits its suitability for many industrial applications [107].

On the other hand, isolated DC-DC converters achieve variable voltage gain by adjusting the turn ratio of a high-frequency transformer. Combining the strengths of both isolated and non-isolated converters, galvanically isolated impedance-sourced DC-DC converters have emerged as a promising solution, offering both high voltage gain and enhanced reliability [108]-[109].

Several topologies utilizing impedance network-based quasi-Z-source converters (qZSC) for high voltage gain and galvanic isolation through high-frequency transformers have been discussed in the literature [110]-[116]. For instance, [110] presents an isolated asymmetric qZS half-bridge DC-DC converter with simplified control. However, a key drawback of this design is that all the converter switches operate under hard-switching conditions, leading to increased switching losses and reduced efficiency.

In [111], two isolated step-up DC-DC converters using both single-phase and three-phase isolation transformers with qZSC are introduced. Despite offering step-up capabilities, these converters also suffer from hard-switching issues. Addressing this limitation, the authors in [112] propose a novel shoot-through control method for qZSC-

based DC-DC converters, enabling soft-switching operation — though only half of the active switches benefit from this feature.

Further improvements are seen in [113], where an isolated boost topology with three switches is presented. However, this design falls short of meeting the requirements for both soft-switching and high voltage gain. In [114], two quadratic qZS-based full-bridge isolated converters are discussed, both of which employ coupled inductors. While these configurations achieve higher gain, they introduce greater design complexity and challenges in practical implementation.

Another noteworthy topology, the  $\beta$ -qZS DC-DC converter introduced in [115], suffers from a discontinuous input current profile, making it less suitable for solar PV integration. Similarly, the Z-source dual active bridge converter presented in [116] also faces the issue of discontinuous input current, further limiting its application. The system described in [117] proposes a PV-to-grid-connected configuration with a synchronous quasi-Z-source (qZS) series resonance DC-DC converter. Despite the benefit of direct PV integration, this design requires two transformers and exhibits slow dynamic performance.

From the comprehensive review of the existing literature, it becomes evident that only one of the high-gain galvanically isolated impedance-sourced converters has been successfully integrated with solar PV systems under partial shading conditions using a heuristic optimization technique. Furthermore, none of the discussed topologies have eliminated the reliance on electrolytic capacitors — a crucial step toward enhancing converter reliability and extending lifespan. The isolated resonant converter presented in [118] incorporates the perturb and observe (P&O) algorithm, which proves effective only for systems with single-peak characteristics, thereby limiting its applicability in more complex PV scenarios.

Moreover, Electrolytic capacitors (ECs) are one of the commonly used components in power converters, utilized to ensure a clean and stable output voltage. However, their vulnerable behaviour makes them unsuitable for the design of converters [4]. Film capacitors (FCs) present a highly preferable alternative due to their reliable performance and significantly longer lifespan compared to electrolytic capacitors (ECs) [5]. One of the key advantages of film capacitors lies in their superior current-carrying capacity. While electrolytic capacitors typically handle around 20mA/ $\mu$ F, small-sized

film capacitors offer a much higher current rating, approximately  $1\text{A}/\mu\text{F}$ . This remarkable difference means that for a given voltage rating, film capacitors can support up to 50 times more current than their electrolytic counterparts [119]-[120]. This makes film capacitors a more efficient and durable choice in power electronics applications.

### 1.3. Challenges with the Existing Systems

In recent years, the demand for DC loads has grown steadily, while most existing power systems are designed to support only AC loads. At the same time, the decreasing cost of solar panels and the abundant availability of solar energy have made clean, cost-effective residential power sources increasingly attractive. In response, researchers have design designed modern residential PV systems that can provide multiple outputs from a single PV input. After studying the advantages and disadvantages of various Multi-Output Hybrid Converter (MOHC) topologies and conducting an extensive literature review, the challenges associated with existing systems can be summarized as follows:

- Most existing loads operate on AC, but there is a growing demand for DC loads. Traditionally, two separate converters are required to supply AC and DC loads simultaneously. However, a single multi-output hybrid converter (MOHC) can serve both purposes.
- Conventional MOHCs are developed by replacing the single controlled switch of a standard DC-DC converter with a single-phase or three-phase VSI. However, these converters operate under the constraint  $d + m_i \leq 1$ .
- The narrow operating range of  $d$  and  $m_i$  creates a trade-off between DC gain and AC output quality.
- Conventional VSI-based MOHC topologies have no inherent shoot-through capability; they require deadtime circuits for their operation.
- Existing MOHCs require more controlled switches, increasing the cost and complexity of the system.
- Grounding of PV panels and AC terminals for safety purposes leads to a circulating current path, causing power loss and safety concerns.
- Using an isolation transformer between AC loads and PV panels can resolve leakage issues, but it significantly increases cost and reduces system efficiency.

- Extracting maximum power from the PV panel while fully utilizing its potential remains challenging in PV-integrated systems.
- Maintaining maximum power (MPP) under dynamic irradiance or partial shading conditions is a critical issue.
- Under partial shading
- Integration of MOHC with solar PV and grid introduces additional technical challenges.
- Low PV voltage levels pose difficulties, and no existing research has demonstrated a grid-integrated PV system that achieves both standard DC and AC voltage ratings.
- Electrolytic capacitors are the most unreliable part of the power electronic converter.
- Isolated DC-DC converters achieve variable voltage gain by adjusting the turn ratio of a high-frequency transformer. Thus, Isolated DC-DC converters lacks smoother voltage variation.

#### **1.4. Objective of Thesis**

From The objective of this thesis is to address the key challenges and limitations associated with existing PV-based transformerless multi-output hybrid converters (MOHCs). Through an innovative approach, this work aims to propose and validate a novel converter topology that enhances efficiency, reliability, and practical applicability in PV-to-grid-connected systems. The following objectives outline the specific goals and contributions of this research:

- **Addressing Limitations of Existing Transformerless PV-Based MOHCs:**
  - Identify and overcome the trade-off between DC and AC voltage gain due to the constraint.
  - Mitigate challenges like leakage current and shoot-through faults, which affect the reliability and efficiency of existing designs.
  - Ensure practical applicability by validating the proposed solution at standard voltage levels (110V RMS AC and 230V DC) in a PV-to-grid-connected multi-output hybrid converter (MOHC) configuration.

- **Development of a Scalable DC-DC Converter Based on the Network:**
    - Design a novel DC-DC converter that leverages the network, offering scalability up to the  $n$ th stage.
    - Achieve higher voltage gain even at lower duty cycles as the number of stages increases.
    - Enhance system robustness with features like immunity to shoot-through misfiring, reduced electromagnetic interference (EMI), and adaptability to wide input voltage variations.
  
  - **Extension to Expandable  $L_n C_{2n-2}$  Network based Multi-Output Operation:**
    - Modify the network-based DC-DC converter by introducing an AC section, enabling simultaneous DC and AC output.
    - Maintain high voltage gain at lower duty ratios, satisfying the condition and expanding the modulation index's operating range.
    - Simplify the system architecture by minimizing the number of controlled switches, enhancing efficiency, and reducing complexity.
  
  - **Maximizing Power Extraction from the PV Panel:**
    - Efficiently supply both DC and AC loads from a single PV input.
    - Implement a maximum power point tracking (MPPT) algorithm to direct surplus power to the AC grid after meeting DC load demands.
    - Ensure optimal utilization of the PV panel's capacity and maximize overall system efficiency.
  
  - **Enhancing System Performance and Stability:**
    - Demonstrate the suitability of the network for isolated resonant converters, achieving significant voltage gain.
    - Simplify the implementation of complex algorithms like Particle Swarm Optimization (PSO), ensuring smoother voltage regulation and improved system stability.
  
  - **Improving Reliability with Film Capacitors:**
-

- Replace vulnerable electrolytic capacitors with film capacitors to enhance system reliability and provide more stable voltage regulation in a two stage system.
- Address wide input voltage variations typical in solar PV applications in a multi-peak PV characteristic by integrating the network with isolated resonant converters, ensuring better compatibility and performance.

This structured approach aims to address critical gaps in existing transformerless MOHC designs while proposing innovative solutions for enhanced efficiency, reliability, and practical deployment in PV-to-grid systems.

## **1.5. Organisation of Thesis**

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

Chapter 2 focuses on the  $L_nC_{2n-2}$  network-based expandable high-gain DC-DC converter. This converter can be scaled up to  $n$  stages, allowing it to achieve the desired high voltage gain based on the required duty ratio ( $d$ ). Its high-gain capability makes this topology particularly well-suited for renewable energy applications, especially for seamless integration with solar PV panels. The chapter also presents the architecture of the expandable  $L_nC_{2n-2}$  topology for  $n=3$  in both continuous conduction mode (CCM) and discontinuous conduction mode (DCM), along with the associated boundary conditions. Furthermore, the performance of the proposed converter is compared with existing topologies, and its operation in CCM, DCM, and under maximum power point tracking (MPPT) is validated through experimental results.

Chapter 3 focuses on the development of the proposed multi-output hybrid converter (MOHC), detailing its operating modes and the unipolar pulse-width modulation (PWM) strategy that has been introduced and used for efficient switching. It also covers the converter's design methodology and steady-state analysis and finally validates the proposed concept through experimental results, demonstrating its effectiveness and reliability.

Chapter 4 dives into strategies to enhance the performance of the proposed system, with a particular focus on addressing the issue of leakage current. It carefully analyzes how

leakage current affects both the safety and efficiency of the converter. The chapter also provides a detailed comparison between the MOHC and other existing multi-output hybrid converters, evaluating key factors like the number of components, overall performance, and practical usability.

Chapter 5 of this thesis focuses on the control operation of the proposed multi-output hybrid converter (MOHC). It explores how the converter works in different scenarios, including supplying AC and DC loads from a DC source and connecting both DC and AC grids to a PV source. The performance of the converter is carefully evaluated under both steady-state and dynamic conditions to ensure its reliability and efficiency.

Chapter 6 demonstrates how the proposed  $L_n C_{2n-2}$  network can be seamlessly integrated with a resonant DC-DC converter. It also shows how the network simplifies the implementation of the Particle Swarm Optimization (PSO) control method using just a single switch, making the system more efficient and easier to manage.

Chapter 7 wraps up the thesis by presenting the conclusions drawn from the proposed work and exploring potential directions for future research and development.