Chapter 1

Introduction

1.1 Background and Motivation

The relentless pursuit of energy has driven humanity to explore various conventional and renewable sources. While traditional energy sources like coal, natural gas, and nuclear power have long been the mainstay, their finite nature and detrimental environmental impact have necessitated a shift towards sustainable alternatives [1], [2]. Despite their efficiency, these conventional sources significantly contribute to pollution [3].

Renewable energy sources such as solar, wind, biogas, geothermal, tidal, and fuel cells have emerged as viable alternatives for electricity generation across various scales. Unlike conventional resources, renewables are clean and free from hazardous emissions, making them an environmentally friendly solution [4], [5], [6]. This transition to renewable energy sources is essential in addressing climate change, ensuring energy security, and promoting sustainable development [7]. To stabilize the global temperature and mitigate the adverse effects of climate change, the annual addition of renewable power needs to be increased to achieve Net Zero, as shown in Fig. 1.1 [8], [9]. Among different renewable energy resources, solar energy has immense potential to serve as a primary energy source for the needs of a modernizing world [10], [11], [12], [13]. In 2023, the annual installation of solar photovoltaics added 407 GW of power capacity to reach a total of 1.6 TW, as shown in Fig. 1.2 [8].

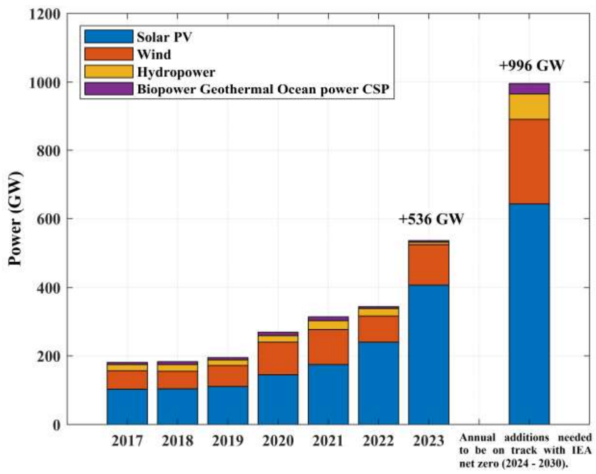


Fig. 1.1 Renewable power additions made from different resources.

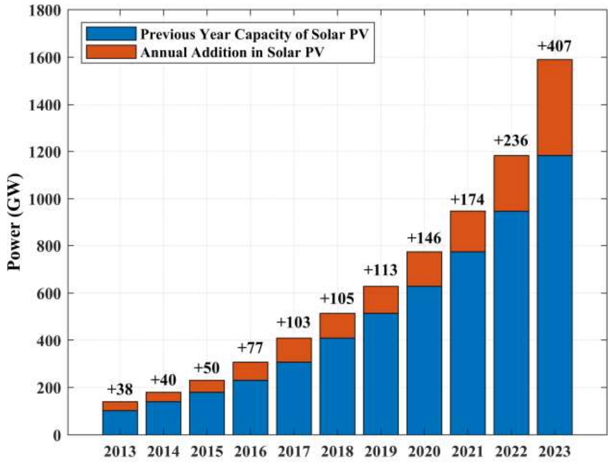


Fig. 1.2 The annual addition of solar power worldwide.

In today's world, there is a rising demand for DC power, complementing the traditional AC power supply [14], [15], [16], [17]. With technological advancements, changing energy needs, and the rise of renewable energy systems, direct current (DC) power is becoming increasingly important. Many devices, including mobile phones, laptops, LED lighting, and battery chargers, rely on DC power. Moreover, large-scale applications like DC-powered household appliances, electric vehicle (EV) charging stations, renewable energy systems, and energy storage solutions increasingly depend on DC power. Key industries, such as transportation, telecommunications, and electric vehicle infrastructure, prioritize DC power distribution over AC power distribution [18].

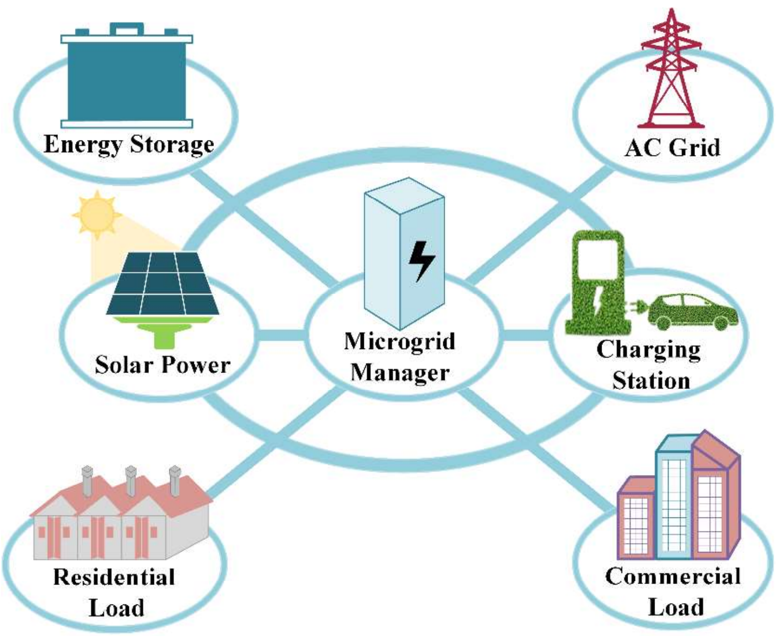


Fig. 1.3 A simple architecture of a solar-based microgrid.

This shift has driven a rising interest in DC microgrids in recent years, as they provide an efficient and reliable means of meeting the growing demand for DC energy across various sectors. In Fig. 1.3, a simple architecture of a solar-based microgrid is shown that utilizes a microgrid manager as a power electronic interface to channel the power to residential/commercial loads, energy storage systems, charging electric vehicles, and ON-OFF grids.

The power generated from solar PV systems is non-linear and depends on unpredictable environmental and shading conditions [19], [20], [21], [22], [23]. To harness and utilize solar power, a reliable and efficient power converter is used in conjunction with a maximum power point tracking (MPPT) algorithm [24], [25]. Since the output of the solar PV is DC in nature, a DC-DC converter can be used to regulate its voltage to a stable level, ensuring optimal operation of the solar panels. Maximum power point tracking (MPPT) algorithms are employed to maximize energy extraction from these panels. DC-DC converters, in conjunction with MPPT algorithms, can efficiently track the maximum power point of the solar panels. This ensures that the system extracts the maximum possible power from the solar panel, even under varying environmental conditions. Also, in some cases, it becomes necessary to isolate the solar panel array from the rest of the system to prevent voltage spikes and ground faults; in such a case, an isolated class of DC-DC converter with a high-frequency transformer is utilized to cater to the residential/commercial AC/DC load as shown in Fig. 1.4 [26], [27].

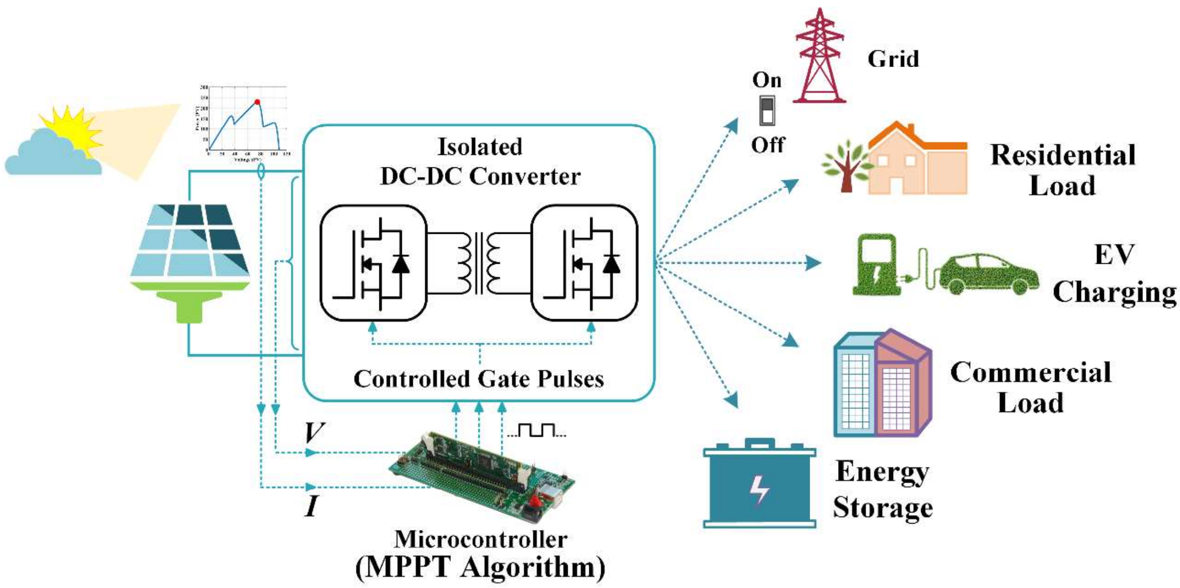


Fig. 1.4 A simple architecture of an isolated DC-DC converter-based solar microgrid.

1.2 Literature Survey on Isolated DC-DC Converters

Based on the isolation provision/ uses of the high-frequency transformer, a DC-DC converter can be categorized as a non–isolated DC-DC converter or an Isolated DC-DC converter. The non-isolated DC-DC converters are efficient and small in size due to the unavailability of the transformer; however, their voltage conversion range is limited and suffers from hard switching. The presence of a high-frequency transformer makes the isolated DC-DC converters enable wide voltage range operation with high voltage standing capability along with ensuring safety, lesser noise, and leakage current-free operation ideal for solar PV integration.

The isolated DC-DC converters can be categorized as voltage-fed and current-fed isolated DC-DC converters. The isolated DC-DC converters can be further sub-categorized into PWM and resonant types. The voltage-fed isolated DC-DC converters employ a capacitor in parallel with the source, and current-fed isolated DC-DC converters employ an inductor in series with the source [28], [29].

1.2.1 Voltage-fed Isolated DC-DC Converters (PWM-type)

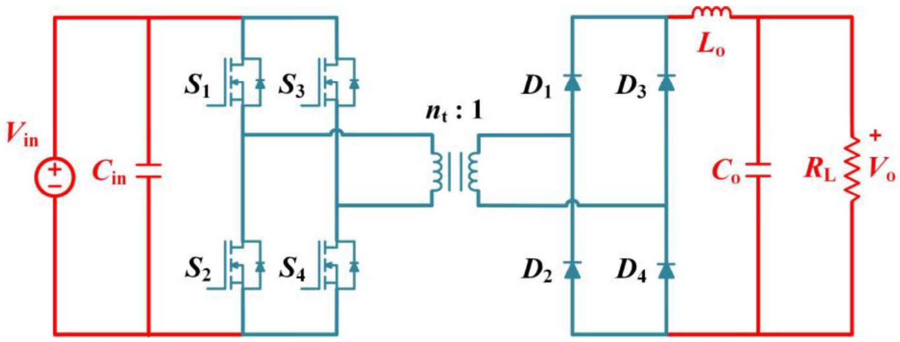
The voltage-fed isolated DC-DC converters typically act like a constant voltage source and can be of two types based on the flux swing direction in the magnetic core, as follows [30], [31]:

1. Single-ended isolated DC-DC converters
2. Double-ended isolated DC-DC converters

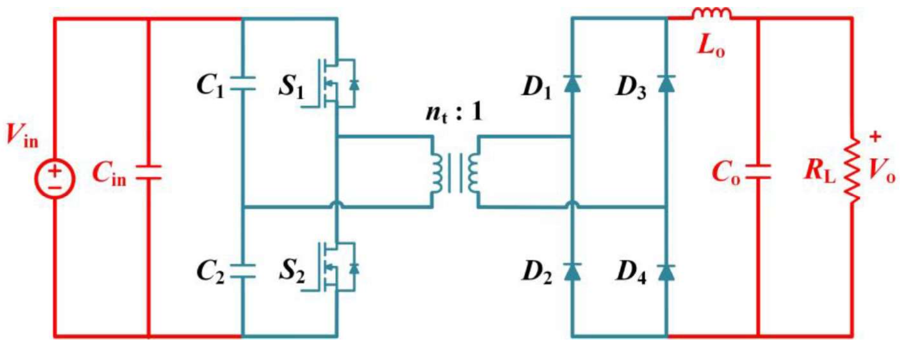
In single-ended isolated DC-DC converters, only one quadrant of the *B-H* loop is utilized, as the magnetizing current is always positive. Hence, they are only suitable for low-power applications. The flyback and forward converter are the examples of the single-ended isolated DC-DC converters [32], [33], [34], [35], [36], [37].

The double-ended isolated DC-DC converters utilize both quadrants of the *B-H* loop, making them more suited for high-power applications with high power density. The three basic configurations of the double-ended isolated DC-DC converters are push-pull, half-bridge, and full-bridge isolated DC-DC converters, as shown in Fig. 1.5 [38], [39], [40], [41].

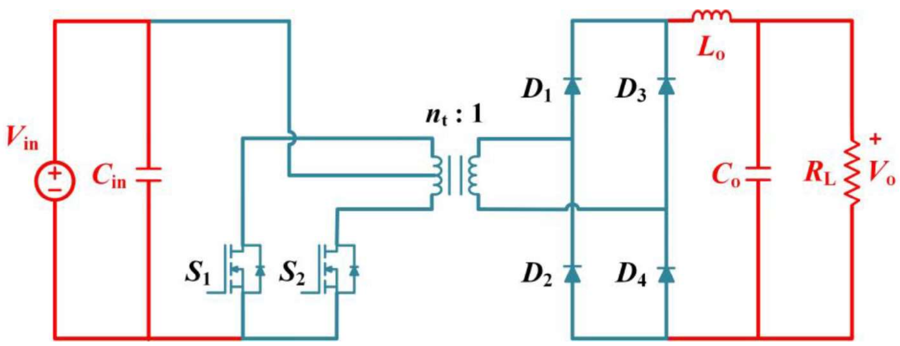
The push-pull isolated DC-DC converters require a lesser number of components; however, switches at the primary side will be subjected to twice the voltage stress of the input voltage. The transformer window utilization of the full bridge and half-bridge configuration is better than the push-pull, so more copper wire can be placed for them. A half-bridge configuration is suitable for low current applications as the current rating required to handle is twice what full bridge switches handle. In a half-bridge configuration, the voltage imbalance could be caused by some problem due to capacitor mismatch causing transformer saturation. Due to better power handling capacity and modular design, the voltage-fed topologies can be adapted for solar PV applications.



(a)

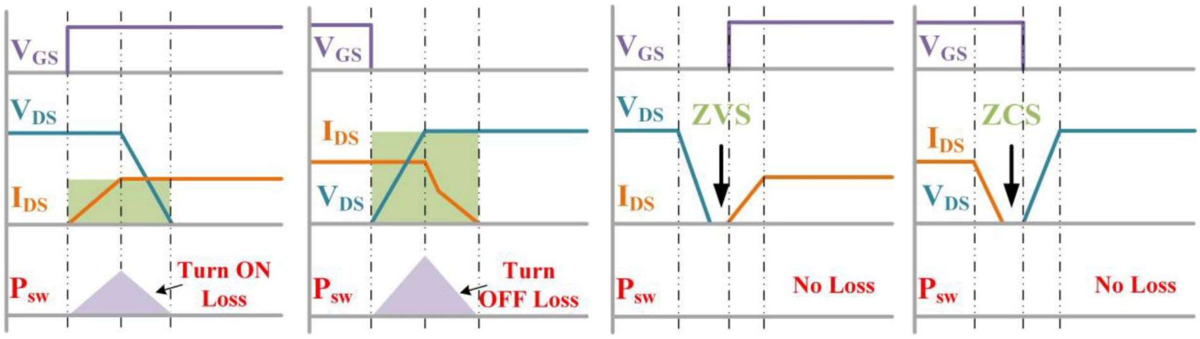


(b)



(c)

Fig. 1.5 PWM type voltage-fed isolated DC-DC converters (a) Full bridge converter (b) Half-bridge converter (c) Push-pull converter.



(a) (b) (c) (d)

Fig. 1.6 Transition of working voltage and current (a) Turn ON switching loss (b) Turn OFF switching loss (c) ZVS turn ON (d) ZCS turn OFF.

In power converters, operating active switching devices like power MOSFETs, IGBTs, etc., with soft-switching is essential as the switching losses increase with switching frequency. Using the soft-switching technique, the active devices' turn ON and turn OFF transitions are controlled to minimize the switching losses and electromagnetic interference (EMI). Soft-switching can be achieved by using large leakage inductance of the high-frequency transformer with PWM-based converters or resonant-based converters. The soft-switching technique can be of two types in general: zero voltage switching (ZVS) and zero current switching (ZCS) [42], [43].

In power MOSFETs, the energy stored in the drain to source capacitances is dissipated when it transits from OFF to ON. If this energy is not dissipated before the application of the gate signals, a high switching loss can be observed at turn-on time. Zero voltage switching is achieved by discharging this capacitance before the gate is applied.

The power IGBTs go through a phenomenon known as current tailing, causing high switching loss, majorly at turn time. A power IGBT is made of a MOSFETs and a BJT. While turning the IGBTs OFF, the gate charges of the MOSFET are removed quickly by applying a negative gate to the emitter voltage. However, the collector current of the BJT keeps flowing due to minority charge carriers, and this current decay slowly over time. In Fig. 1.6 (a)-(b). the switching losses during turn ON and turn OFF are shown. In Fig. 1.6 (c)-(d), the transition of the working voltages and current are shown to achieve ZVS and ZCS [42], [43].

Among different isolated DC-DC converters, the Dual Active Bridge (DAB) converter has gained significant attention in recent decades due to its numerous advantages. It offers high efficiency, high power density, and flexible control over a wide range of operating conditions

[44], [45], [46], [47]. DAB consists of two active H-bridges separated by the high-frequency transformer and its leakage inductance (L_{lk}), as shown in Fig. 1.7. The DAB is a phase shift modulated (PSM) converter where by controlling the phase-shift angle between the switching signals, the power flow and direction can be controlled. DAB-based converters are widely utilized in various applications like renewable energy systems, electric vehicles, data centers, industrial drives, etc. A number of advanced modulation strategies have been developed to enhance the performance and switching behavior of the DAB further [48], [49], [50], [51], [52], [53], [54], [55].

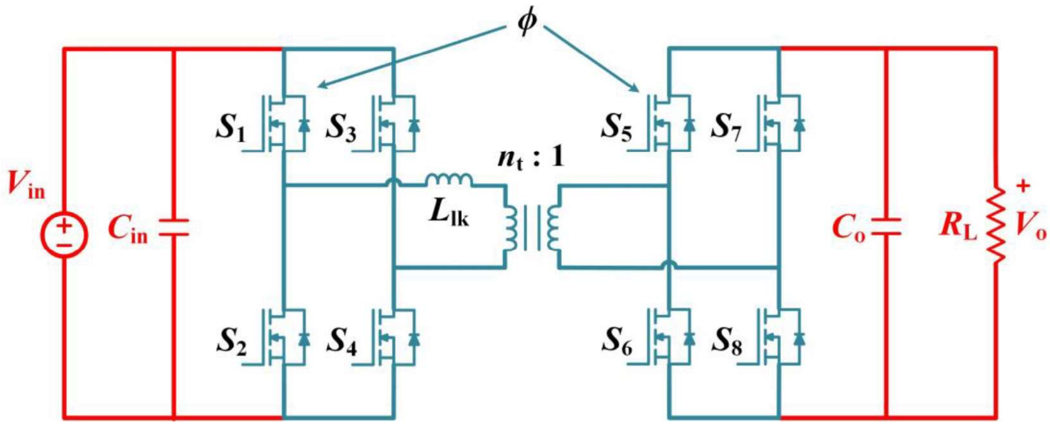


Fig. 1.7 Circuit diagram of the conventional dual active bridge.

1.2.2 Current-fed Isolated DC-DC Converters (PWM-type):

For high-current applications, voltage-fed isolated DC-DC converters can be susceptible to high pulsating input currents and high circulating currents through the devices, potentially degrading the converter's efficiency [28], [29]. The current-fed isolated DC-DC converters have the following advantages:

1. Input current has less ripples than the voltage-fed isolated DC-DC converters.
2. The current-fed isolated DC-DC converters are boost-derived converters, reducing the need for a high transformer turn ratio.
3. Lesser diode ringing due to the capacitive filter at the output terminal.

The various current-fed isolated DC-DC converters utilize full-bridge, half-bridge, and push-pull configurations with an input inductor at the low-voltage input side for power conversion. For the secondary side, diode rectifiers with full-bridge, half-bridge, and center-tapped configurations can be utilized. One of the major drawbacks associated with current-fed isolated DC-DC converters is the voltage spike across the devices due to energy stored in the inductive elements. Snubbers are utilized to prevent the breakdown of the switching devices, prevent them from voltage spikes, and limit their switching stress. Several snubbers have been given to minimize the voltage spikes like dissipative, regenerative, etc, as shown in [56], [57], [58], [59], [60], [61].

The capacitive snubber uses single capacitors that are parallel to the switching element. They snub the voltage spikes by providing a bypass path through them. However, their use may create a ringing due to resonance with the circuital inductance. RC snubbers are simple in design and suitable for low-power applications. RCD snubbers are more efficient than RC snubbers; however, they require proper tuning, and diode recovery time may limit their applications for high-frequency operation. These snubbers carry the boost inductor current until it reaches the rated current. The LC snubbers store energy using a capacitor during the device's turn-off, and when the switch is turned ON, the energy is fed back via an inductor. The snubber utilizing switching devices and passive components is an efficient snubber that can reuse the energy stored in leakage inductance. However, they are complex to design and costly, reducing the converter's power density. Besides the snubbers mentioned above, active clamping and auxiliary circuit-based snubbers are also utilized for the protection of the switching elements [40], [62], [63], [64], [65], [66].

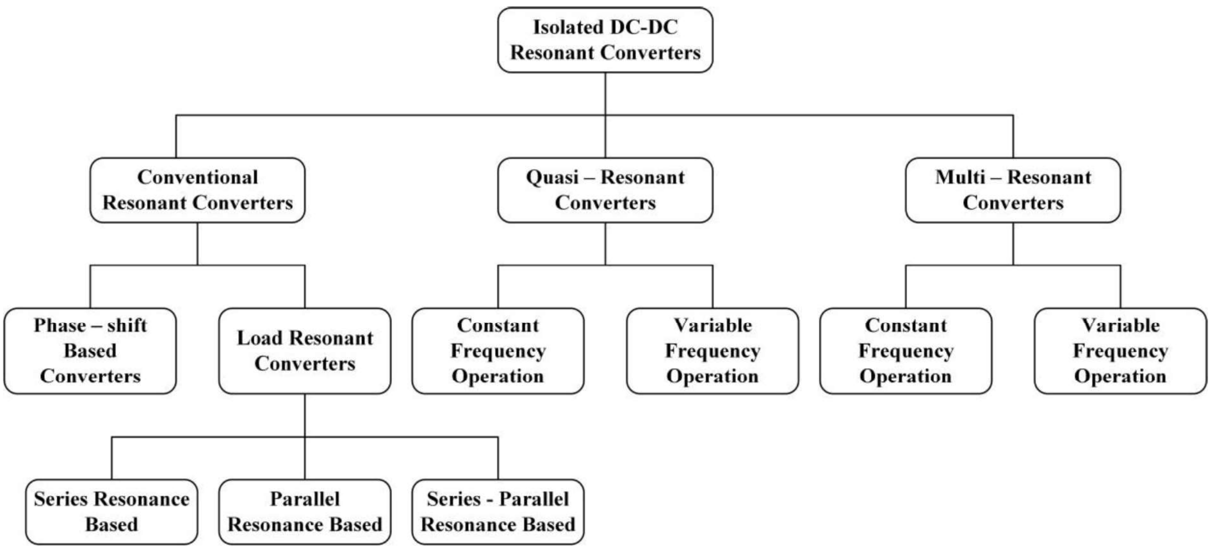


Fig. 1.8 Types of the isolated DC-DC resonant converters.

1.2.3 Isolated DC-DC Converters (Resonant-type)

The isolated DC-DC resonant converters can be classified based on the uses of resonant elements and their connections within the circuitry. The broad classification of the isolated DC-DC resonant converter is shown in Fig. 1.8. In general, they are of three types: series resonant converter, parallel resonant converter, and series-parallel resonant converter [67]. To enable wide-range soft-switching, these converters require precise resonant tank design.

In the case of a series resonant converter (SRC), the switch currents are proportional to the load current and hence offer better efficiency over a wide load range [68], [69], [70]. However, their voltage regulation is poor under light load conditions, so a significant change in switching frequency is required. So, they are suitable for constant load-based applications.

The parallel resonant converter (PRC) doesn't have an issue with light load voltage regulation as observed in the series resonant converter, and a small change in frequency is sufficient to provide enough voltage regulation [71], [72], [73]. However, the circulating current is much higher in the case of the parallel resonant converter for low load also, as it has a resonant capacitance parallel to the load. The parallel resonant converters are suitable for variable load applications.

The series-parallel resonant converter (SPRC) contains good properties in both the series and parallel resonant converters. The conduction losses resulting from circulating currents in the resonant tank are widely acknowledged as a significant challenge in resonant converter design. A major limitation of these resonant converters is the difficulty in preserving soft-switching over a wide range of input voltages and load conditions, which can result in substantial switching and conduction losses, particularly at elevated input voltages [74], [75], [76], [77], [78].

The quasi-resonant converter can be identified as a hybrid of PWM and resonant converter, which uses resonance for a small fraction of the switching period. In a quasi-resonant converter, the switching devices are replaced with the resonant switches to achieve quasi-sinusoidal waveforms, which can create ZVS or ZCS operation [79], [80], [81], [82]. The quasi-resonant converter may be utilized with variable frequency modulation ON time and OFF time control and soft-switching capability.

The concept of the multi-resonant converter was introduced by Tabisz and FC Lee [83]. The multi-resonant converter accounts for all significant parasitic, including switch and diode junction capacitance and transformer leakage inductances, enabling soft-switching for all semiconductor devices. Many resonance-based isolated DC-DC converters have been developed in the last two decades due to their inherent soft-switching properties, high power density, and various circuital features. Although using isolated resonant converters offers higher efficiency with reduced EMI, their high resonant current may cause higher conduction losses than the isolated DC-DC PWM converters. Besides these constraints, considering the optimal dead band is crucial as it prevents shoot-through for reliable and safe operation. The optimal dead time depends on various factors, including the switching frequency, the device characteristics, and the operating conditions [84], [85]. It is typically determined through theoretical analysis and experimental testing to achieve a balance between minimizing shoot-through risk and maximizing efficiency [86], [87], [88].

1.2.4 Impedance Network-based Isolated Converters

Efficient high-voltage gain power converters are essential for boosting the voltage from low-voltage solar PV to usable voltage levels while providing safety through galvanic isolation. An impedance network-based DC-DC converter may be employed at the input side of a conventional isolated converter to achieve high voltage gain. These input impedance networks effectively accommodate a wide input voltage range, maintaining a regulated DC output by adjusting the duty cycle [89], [90], [91]. Furthermore, these networks protect against shoot-through faults and short circuits caused by misfiring, thus improving the system's immunity to electromagnetic interference (EMI). The impedance network of non-isolated DC-DC converters can regulate voltage gain through duty cycle control, and this gain can be further increased by cascading multiple cells. While expandable topologies like those in [92], [93], [94] offer high gain, their use of various input sources and switches per stage can lead to increased cost and reduced efficiency. Although [91] presents an expandable converter with a single input, its gain increase per stage is limited, requiring more active switches and passive components. Also, the lack of galvanic isolation limits the applicability of the converters in many industrial applications [95].

Isolated DC-DC converters can achieve varying voltage gain by adjusting the turns ratio of their high-frequency transformers. Galvanically isolated impedance-sourced DC-DC converters, combining the advantages of isolated and non-isolated types, are becoming increasingly popular [96], [97]. Many topologies, such as those in [98], [99], [100], [101],

[102], [103], [104], [105], employ impedance networks for high voltage gain, incorporating a high-frequency transformer for isolation as shown in Fig. 1.9. Article [98] presents an isolated asymmetric qZS half-bridge DC-DC converter with simplified control, but all its switches operate under hard-switching conditions.

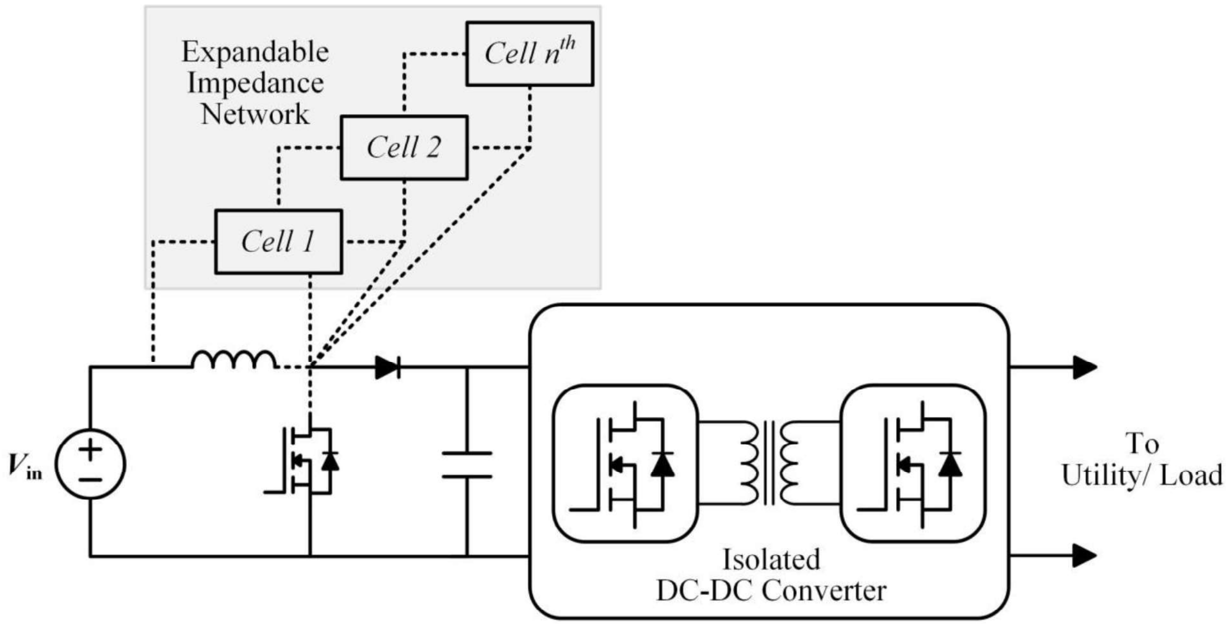


Fig. 1.9 Isolated DC-DC converter with an expandable impedance network at input.

Article [99] presents two isolated step-up DC-DC converters using single-phase and three-phase isolation transformers with a qZSC, but these converters operate with hard switching. While [100] introduces a novel shoot-through control method for efficient qZSC-based DC-DC converters, it only achieves soft switching for half of the active switches. The isolated boost topology with three switches discussed in [101] lacks both soft switching and the high voltage gain required in many applications. Two quadratic qZS-based full-bridge isolated converters are explored in [102], but their use of coupled inductors complicates the design. Although [103] introduces a β-qZS DC-DC converter, its discontinuous input current makes it unsuitable for solar PV integration. Similarly, the Z-source dual active bridge converter in [104] suffers from a discontinuous input current due to its Z-source configuration. Finally, [105] presents a PV-to-grid system using a synchronous quasi-Z-source (qZS) series resonant DC-DC converter. Still, despite its solar PV application, it requires two transformers and exhibits slow performance.

1.2.5 Vulnerability of the Electrolytic Capacitors in Power Converters

In DC-DC converters, electrolytic capacitors (ECs) are generally used to filter out the high-frequency noise from the output voltage to provide a cleaner and more stable output. These ECs are one of the most vulnerable and unreliable components of power electronics due to their physical and operational properties [106], [107], [108]. The electrolytic capacitors utilized in power converters have 5-6 years of life. If they are used as a smoothening filter they might have to be replaced several times in a single life span of a solar panel as their life span varies from 15 to 20 years. Besides this, an extra maintenance cost for their continuous health monitoring of the ECs will be required [109], [110], [111]. So, they are one of the power converter's most vulnerable and unreliable components. When voltage ripple is a prime concern, Film capacitors (FCs) can be a suitable alternative to electrolytic capacitors. However, their design limits their application and power/ voltage rating [112]. The electrolytic capacitors can be replaced with film capacitors based on the current carrying capacity per unit farad [113]. The current carrying capacity of a film capacitor is approximately 50 times of the electrolytic capacitors. The humidity could be a matter of concern for outdoor MPPT operations when film capacitors are utilized for voltage smoothening in power converters [114].

Now, to develop an electrolytic capacitor-less isolated DC-DC resonant converter, various single-stage and two-stage isolated power converters are studied. In [115], an interleaved boost-integrated *LLC* resonant converter using four active switches and two diodes has been proposed for renewable applications. A combination of electrolytic and film capacitors was used on the output side for filtering. In [116], an efficient resonant converter with six active switches and two diodes was presented, and the perturbation and observation (P&O) algorithm was used to achieve uniform irradiance conditions. In [117], a dual PV input-based *LLC* resonant converter using four active switches and four diodes has been proposed and operated under uniform shading conditions using the P&O algorithm. In [118], a design example for the *LLC*-type bridge resonant converter with a center-tapped configuration is presented. In [119], an isolated current-fed resonant converter for PV/fuel cell application has been given with an electrolytic capacitors-based voltage doubler configuration. In [82], the concept of partial resonance has been used for soft-switching for push-pull converter configuration. In [120], a dual bridge series resonant converter was presented with a limitation in soft-switching at a lower load. The various voltage-fed resonant converters presented in [121], [122] have more switching devices and passive elements, resulting in complex circuitry and relying on vulnerable electrolytic capacitors for voltage smoothening.

As the MPPT control constantly adjusts the power output of the isolated DC-DC converter, a cascaded voltage source inverter (VSI) can be employed to efficiently transfer this variable power to the AC grid, maximizing the utilization of solar energy [123], [124], [125]. In two-stage DC-AC topology, a heavy DC-link capacitor is often utilized to act as an energy buffer between the converters and help maintain the stable DC link voltage. Additionally, it effectively filters out the high-frequency ripple currents generated by the inverter's switching operation, ensuring a stable and reliable DC link voltage [112], [113].

In an earlier proposed DC–AC two-stage electrolytic capacitor-less systems [126], [127], [128], the DC-link capacitors are removed either by making the DC-link voltage a pulsating DC (as shown in Fig. 1.10), by proposing a new complex modulation scheme or by using power decoupling circuit [129], [130]. In [126], a dual three-pulse modulation technique is proposed to eliminate the need for an electrolytic capacitor at DC-link, causing the DC-link voltage to be a pulsating DC. In [127], a synchronous one-leg modulation is adapted for inverter operation, requiring a small film capacitor at the DC link. In [128], an electrolytic capacitor-less six-pulse DC-link bidirectional three-phase grid-tied inverter is presented.

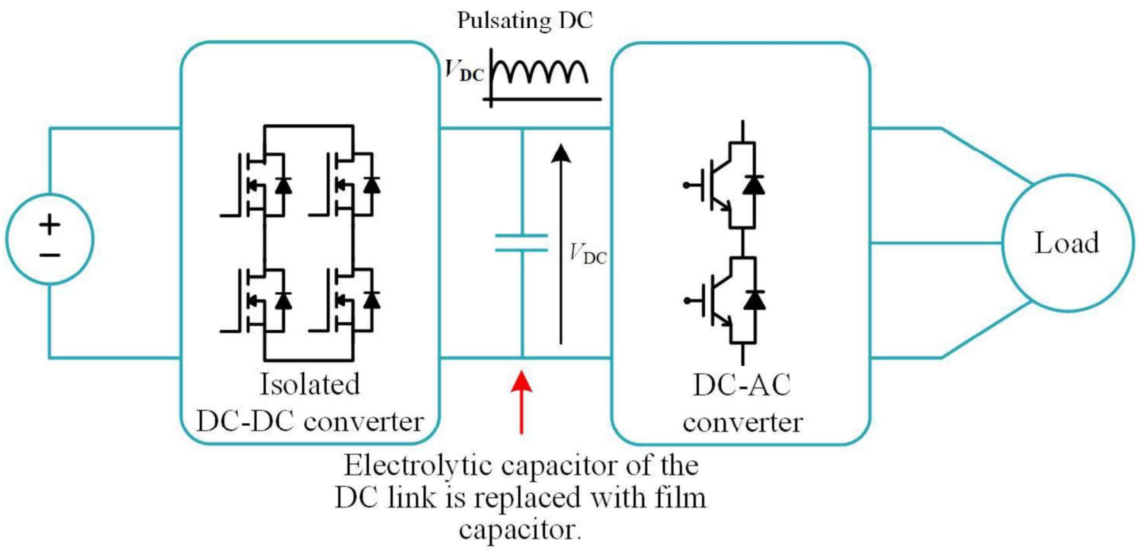
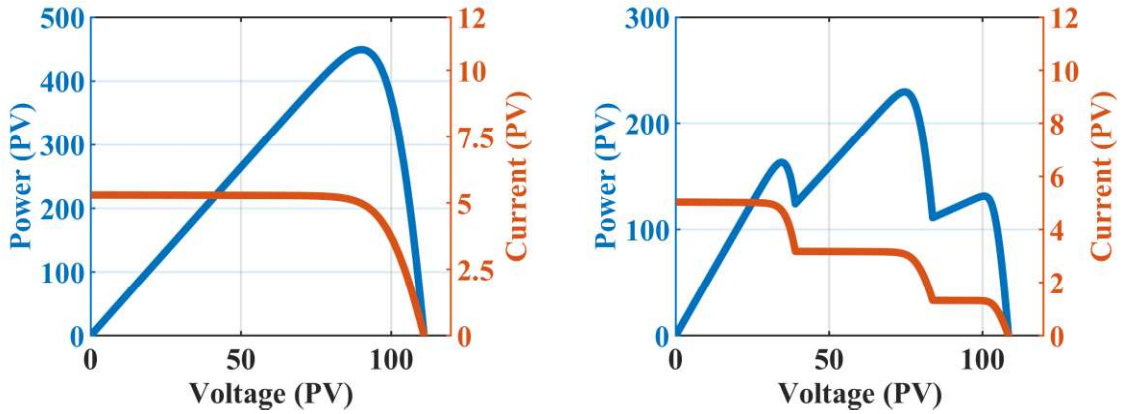


Fig. 1.10 Existing two-stage electrolytic capacitor-less system.

1.2.6 Maximum Power Point Tracking under Partial Shading Conditions

Solar photovoltaic (PV) systems convert sunlight directly into electricity. However, the power output of a solar panel is not constant; it fluctuates depending on several factors, like solar irradiance (the amount of sunlight falling over the panel), temperature, etc. Understanding this variability is essential because each solar panel has a specific operating point at which it generates maximum power [21], [22], [131]. This optimal point is called the Maximum Power Point (MPP). Maximum Power Point Tracking (MPPT) is a technique used to optimize the energy output of a photovoltaic (PV) system. Essentially, MPPT acts like an intelligent controller that ensures the solar panels consistently operate at their highest efficiency, maximizing the electricity generated [132], [133]. In solar PV, the power-voltage curve of the peak is observed when the irradiance is uniform; however, when the irradiance is non-uniform or partially shaded, a multi-peak PV curve can be observed, as shown in Fig. 1.11. The partial shading conditions may be caused by the obstruction of the solar rays with the buildings, poles, moving objects, etc. [134], [135], [136].



(a) (b)

Fig. 1.11 P-V and I-V curves under (a) Uniform irradiance conditions and (b) Partial shading conditions.

The Perturb and Observe (P&O) and incremental conductance (INC) are some of the basic MPPT algorithms that are often utilized to cater to uniform irradiance conditions [137], [138], [139], [140]. However, both algorithms exhibit oscillations when the system is at the maximum power point (MPP). Also, to cater to the partial shading conditions, a modified version of the algorithms is required. To determine the optimal step size for effective Maximum Power Point Tracking (MPPT) operation, it is necessary to balance steady-state accuracy (the precision of the output around the MPP) and dynamic response. To resolve the issue of optimal step size and achieve fast maxima point tracking, a variable step size-based MPPT algorithm is developed [141], [142]. For precise determination of the MPPT, various continuous and discrete model predictive control (MPC)-based algorithms have been presented. Literature [143] delves into the Discrete Model Predictive Control (DMPC) evaluation process based on maximum power point tracking. Unlike continuous control, MPC-MPPT, DMPC-MPPT exhibits reduced sensitivity to model parameter mismatches and superior dynamic performance [144]. The dynamic response of nonlinear converters plays a pivotal role in the effectiveness of MPPT operations in photovoltaic (PV) systems. Due to their nonlinear characteristics, these converters can cause numerous algorithms to generate inaccurate duty cycle values [145].

Heuristic-based optimization-based MPPT algorithms play a crucial role in enhancing the efficiency and performance of photovoltaic systems by addressing challenges associated with dynamically locating the maximum power point under varying conditions [146], [147]. These algorithms leverage mathematical optimization techniques to achieve precise and reliable MPPT. There are several heuristic-based optimization algorithms, such as particle swarm optimization, grey wolf optimization, ant colony optimization, artificial neural network, etc. [148], [149], [150], [151]. Optimization-based MPPT algorithms allow the direct control approach of generating control variables, eliminating proportional integrator (PI) control loops, and reducing the steady-state oscillations at the MPPT point.

1.3 Challenges with the Existing Systems

Solar energy could be one of the most promising solutions for current energy demand and a pollution-free environment. However, harnessing and utilizing the low voltage solar power requires an efficient high-gain DC-DC power converter integrated with an advanced computational MPPT algorithm so it doesn’t get underutilized. Also, optimized components should be used to design the power converter so that it doesn’t get affected or deteriorate with time. The power generated from solar PV can be fed to the AC grid by cascading the isolated DC-DC resonant converter with a voltage source inverter for continuous operation while addressing the reliability concerns among the conventional isolated DC-DC resonant converter. Based on the literature survey observed for the solar PV integrated power electronics converter, the following challenges are observed in the existing systems:

1. The existing isolated DC-DC converters used in solar PV integration utilize electrolytic capacitors, one of the power electronics' most vulnerable and unreliable components.
2. The electrolytic capacitor makes the converters age faster, and continuous health monitoring may be required for such converters.

3. The DAB-derived isolated resonant converter may lose soft-switching property at unity voltage gain, especially under light load conditions.
4. An optimized resonant tank design can reduce the circulating current and losses.
5. The isolated DC-DC converters suffer from switching losses at higher frequencies.
6. The partial shading conditions caused by trees, buildings, etc, may lead to poor solar energy utilization.
7. A heuristic-based optimization algorithm is required to harness the solar PV efficiently under partial shading conditions.
8. Integration of an electrolytic capacitor-less isolated DC-DC converter with an expandable DC-DC converter to match the utility voltage level.
9. Integrating an electrolytic capacitor-less two-stage topology with a three-phase AC grid.
10. Designing of cascaded control structure for the proposed electrolytic capacitor-less two-stage system for smooth power transfer.

1.4 Objective of the Thesis

It can be observed from the literature review that an efficient power electronics interface with an optimization-based maximum power point tracking algorithm is required for an efficient solar PV interface. The life span of a solar panel is approximately 15-20 years, while an electrolytic capacitor serves actively for a life span of 3-5 years without losing its property. When these electrolytic capacitors are employed for solar PV-based power converters, they may need to be replaced several times over one life span of the solar panels. Also, continuous health monitoring is required for the electrolytic capacitors, which leads to substantial maintenance costs.

To address these challenges, two electrolytic capacitor-less isolated DC-DC resonant converters are proposed. The proposed topologies utilize a half-bridge configuration at the output side with two small-sized film capacitors in one leg. The per unit (μF) rms current carrying capacity of the film capacitors is approximately 50 times more than that of the electrolytic capacitor. Leveraging the same benefit for the design of the proposed converter, a reliable and small-sized film capacitor is used to avoid the use of bulky electrolytic capacitors.

Further, soft-switching conditions are derived to operate the proposed converters with high efficiency. Dead time is calculated based on the given conditions, and all the switches are operated with zero voltage switching. For mathematical analysis, a fundamental harmonics approximation technique is adopted where bridge voltages and currents are considered sinusoidal quantities, and the tank resonant circuit acts like a bandpass filter for the power signals. A series-parallel resonance tank (*LLC* resonant tank) is chosen for resonance purposes. The proposed topologies are operated with a phase-shift modulated technique where, based on the direction of the power transfer, the phase angle of one active bridge is made to lead with respect to the other. The proposed converter has the following advantages: 1. The need for vulnerable and bulky electrolytic capacitors is eliminated. 2. The converter operates with soft-switching for the full load of the operation. 3. Lesser active switches are required compared to the state-of-the-art dual active bridge. 4. The resonant tank components are optimally designed to reduce the magnetizing and circulating current for better efficiency.

The conventional MPPT algorithms like perturb and observe (P&O), incremental conductance (INC), etc., can easily track the maximum power under uniform irradiance conditions (UICs), as the PV curve is characterized by a single peak. However, when the irradiance is non-uniform or shaded, the PV curve becomes a multi-peak curve, the traditional algorithms fail, and optimization/intelligence-based algorithms like grey wolf optimization (GWO), particle swarm optimization, ant colony optimization, cuckoo search, etc., offer solutions for tracking power at global peak point. An optimization-based MPPT algorithm can be preferred over conventional algorithms, as they provide faster MPP tracking with negligible oscillations and lower noise sensitivity. The proposed topologies are integrated with solar PV using particle swarm optimization and grey wolf optimization to cater to the partially shaded conditions. Using Chroma's solar PV emulator, different shading patterns are formed, and using the optimization techniques, maximum power is drawn with significantly less tracking time.

The power generated from solar PV is harnessed efficiently using an optimization-based MPPT algorithm; however, the output voltage is still uncontrolled, depending on temperature and irradiance. The harnessed power can be further fed to the DC microgrid using another DC-DC converter or to the AC grid using a voltage source inverter. The proposed isolated resonant converters are cascaded with a conventional three-phase voltage inverter, and the film capacitor leg of the proposed converters is utilized as the DC-link, forming an electrolytic capacitor-less two-stage topology as shown in Fig. 1.12. To feed power to the AC grid, grid synchronization of the inverter is required. Using a cascaded control structure, the DC link voltage is fixed, and the current corresponding to the solar power is fed to the grid. The transfer functions for the control structure are derived, and tuning criteria are applied to achieve smooth power control. The proposed idea is verified using the simulation software and laboratory-built prototype by feeding the solar power to the AC grid.

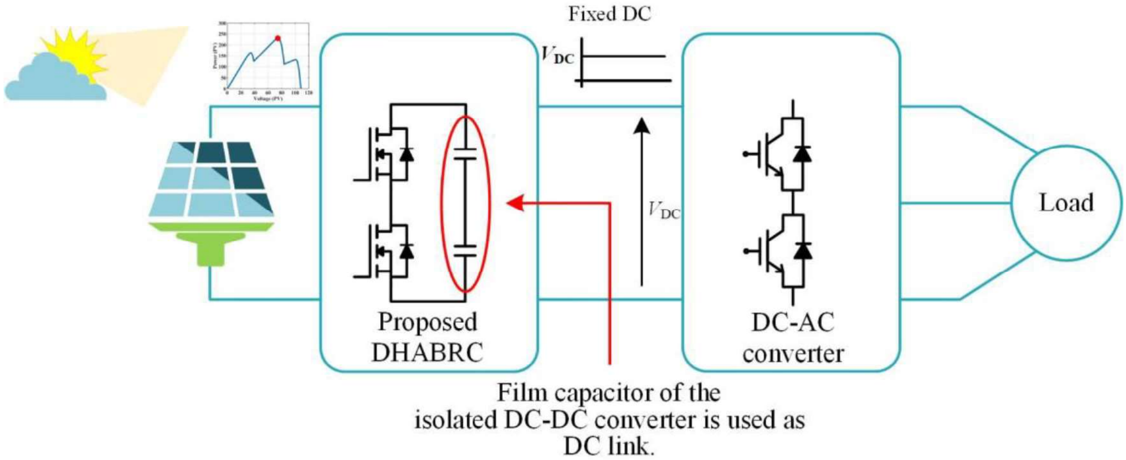


Fig. 1.12 Block diagram representation of the proposed two-stage system.

The low voltage output of the isolated DC-DC converter can be stepped up using an expandable impedance network in an isolated resonant converter to match the voltage level of the utility side. Adding the impedance network can enhance the range of input PV voltage and the inbuilt shoot-through protection for the converter's protection. Besides this, the gain of the converter can be varied by including more stages as the impedance network is expandable. Since the solar PV integrated DC-DC converter's output voltage is regulated, it can be cascaded to another power converter to stabilize the DC output voltage for further utilization or integration with the AC/DC microgrid.

1.5 Organization of the Thesis

Besides the current chapter, there are four more chapters. A summary of the other chapters is as follows:

Chapter 2 of the proposed work introduces two electrolytic capacitor-less isolated DC-DC resonant converters for solar PV integration. In power electronics, electrolytic capacitors are well known for their vulnerability and unreliable operations. The proposed converters utilize half-bridge configurations at the secondary side of the converter, where one leg has reliable and small-sized film capacitors. The life span of film capacitors is multi-fold better than that of electrolytic capacitors when used for solar PV integration. The operation of the proposed converter is discussed in detail, and mathematical modeling is presented. The proposed converter is designed optimally to operate with soft-switching for the full range load. A 500 W laboratory prototype is developed and tested for steady-state operation. To verify their accuracy, the mathematically derived equations are compared with the simulation and experimental results for 100% and 20% of the load at steady-state conditions. Also, the feasibility of using film capacitors is proved using different tests like startup transient and load dynamics.

In Chapter 3, the proposed electrolytic capacitor-less isolated DC-DC resonant converter is integrated with solar PV panels. The power produced by solar panels depends upon variable atmospheric conditions, so we require a power-tracking algorithm to harness power at peak points. Also, the partial shading conditions caused by clouds, trees, buildings, etc., lead to a multipeak PV characteristic with multiple local and global peaks. To cater to the partial shading conditions, two optimization algorithms (i.e., particle swarm optimization and grey wolf optimization) are utilized to harness the PV power efficiently. A Chroma Solar PV emulator is utilized to test the partial shading conditions, and partial-shaded curves of different voltage and current ratings are developed. A Texas Instrument's TMS320F28335 microcontroller operates the algorithm, drawing peak power from PV panels.

In Chapter 4, the proposed topology is cascaded with a conventional three-phase voltage source inverter to form a two-stage DC-AC topology. The proposed pseudo-DC-link-based two-stage topology feeds the power to the three-phase AC grid. To integrate solar power into the grid, inverters must be synchronized to match the grid's phase, frequency, and voltage. A synchronous reference frame (SRF) based phase locked loop (PLL) is employed in this work. A cascaded control structure is used, with an inner current control loop for precise grid current control and an outer voltage control loop for regulating the DC-link voltage. The modulus optimum tuning criterion and symmetrical optimum tuning criterion are employed for tuning the PI controllers of the inner current loop and outer voltage loop, which are easy to use. At last, a scaled-down laboratory prototype is developed and tested to deliver power to the AC grid.

In Chapter 5, an impedance source network is connected at the front side of the isolated DC-DC resonant converter. By placing the impedance source network before the isolated DC-

DC resonant converter, the voltage gain of the isolated DC-DC resonant converter can be further improved, making it suitable for high-voltage utility integration. The impedance source network also provides shoot-through protection for better reliability. The impedance source network can be expanded for *n*-stages. With the addition of each stage, the voltage gain changes correspondingly. The proposed converter is further integrated with solar PV using the particle swarm optimization-based maximum power point tracking algorithm. A 500 W laboratory scale prototype is designed, and maximum power from solar PV is harnessed under uniform irradiance and partially shaded conditions to verify the proposed idea.

Finally, in Chapter 6, the thesis work is concluded, and the future scope of the work is discussed.