Chapter 1

Introduction

The well-being of a nation is determined by factors such as the quality of life within its communities, the effectiveness of its transportation systems, and the potential of its industries. The availability of energy supply is closely tied to these aspects. However, the demand for energy is usually more than the supply. Over the past few decades, traditional energy sources like coal, petroleum, and natural gas have experienced a decline in their availability and failed to keep up with the increasing rate of demand. While coal remains an essential fuel for electricity generation catering to the energy needs of industries and residential areas, more is needed to replace petroleum products utilized by automobiles.

Constant challenges are posed by population growth and rising energy demands by industries and households. Given the scarcity of traditional resources and worries about carbon dioxide emissions and environmental effects, there is an increasing push to use renewable energy sources to meet rising energy demands by harnessing maximum power from these sources. Power electronics (PE) technology plays a crucial role in converting and regulating electric power. A notable benefit of the switching mode power conversion is its extraordinary efficiency, which ranges between 93 % – 99 %. This high efficiency translates into energy savings. There is also an inclination towards utilizing environmentally friendly and secure renewable energy sources (PV, FC) and storage devices such as batteries, which rely significantly on power electronics (PE) technologies.

Solar energy is widely available in india for longer duration over the years. It's output voltage is in the form of DC. Until recently, the transmission and distribution of energy have predominantly relied on AC systems. However, in order to integrate it into the distribution grid, a DC-DC converter is necessary in addition to an inverter (DC/AC). On the other hand, DC transmission offers several advantages, including the use of reduced conductor material, lower insulation requirements, immunity to the skin effect, and also does not suffer from stability and synchronization issues. As a result, the concept of DC grid has emerged in recent years. Good number of household equipments are operated from DC supply, like LED lights, TV, laptop and cell phone. The DC supply can be readily available from DC grid [1], [2], making it robust and cost effective. A specific region of interest linked to the DC grid, is depicted in Figure 1.1.

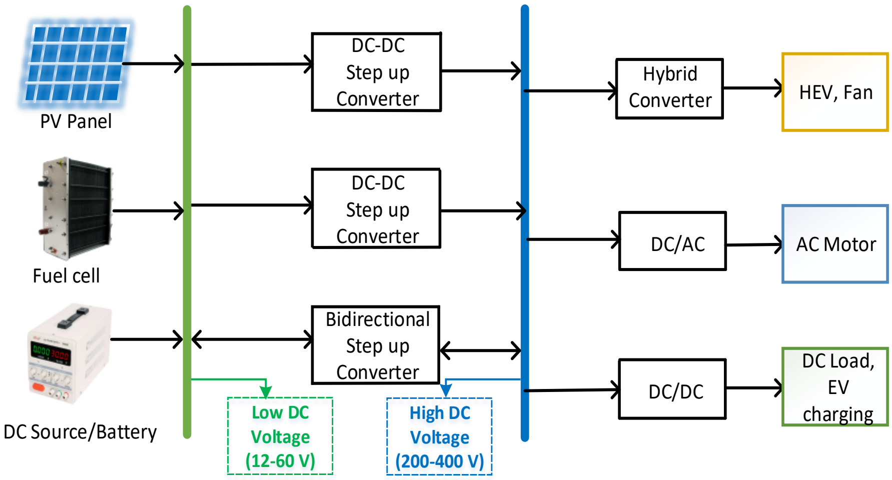

Figure 1.1: Typical struture for DC nanogrid and application of DC-DC converter.

This thesis introduces novel topologies for DC-DC conversion that offer enhanced voltage conversion ratios. The main objective is to develop a control mechanism by utilizing a duty cycle to manage the available DC power generation effectively. By controlling the duty cycle, increasing the voltage from low-voltage sources becomes feasible, thereby regulating the DC bus voltage connected to the grid. Minimizing voltage and current stress on the utilized components is the main contribution to achieving a higher conversion ratio. The thesis investigates explicitly off-grid scenarios, including stand-alone operations, providing a comprehensive analysis to address the benefits of the proposed topologies.

1.1 Gain enhancement approaches in DC/DC converters

DC-DC converters equipped with voltage boosting capability find extensive application in a wide range of power conversion scenarios, ranging from a fraction of volts to several hundred volts at power levels ranging from milliwatts to megawatts. The magnitude of the boosted voltage primarily relies on the width of the pulses during each switching period. The fundamental principle behind voltage boosting in converters is the storage of magnetic energy for a specific duration and the subsequent release of that energy for the remaining period. With the progress of semiconductor technologies, high-voltage gain converters have experienced a significant boost in their performance and efficiency. Field-effect transistors (FETs) have been instrumental in this advancement, as they can operate in frequency ranges extending up to hundreds of kHz. In this thesis, the choice is made to utilize MOSFETs with low on-state resistance to minimize power losses.

Boost converters in DC-DC converters have two operating modes, determined by the behavior of the inductor current. Continuous conduction mode (CCM) is preferred over discontinuous conduction mode (DCM). In CCM, the inductor current follows a triangular profile during each switching period, while in DCM, the inductor current reaches zero and remains zero for a certain period of time. CCM is preferred due to its load-independent voltage gain, low ripple current, and higher efficiency. On the other hand, DCM is well-suited for applications where the main priorities are increased stability and reduced inductance size. Furthermore, DCM operation offers a higher voltage gain compared to CCM. In literature, two main types of DC-DC converters are commonly discussed: isolated and non-isolated converters. Isolated converters are predominantly employed when there is a need for isolation between the load and the power source. However, these converters necessitate the use of high-frequency transformers, which results in increased size and cost. Additionally, the leakage inductance of the transformer can cause spikes in the converter operation [3],[4]. On the other hand, non-isolated DC-DC converters are the preferred choice to avoid isolation transformers. The traditional boost converter can increase the voltage level using an inductor, diode, switch, and capacitor. Theoretically, the voltage gain may be infinite. However, practical constraints, such as nonlinearities and parasitic effects, limit the gain to three to four times the input voltage for conventional boost converter [5]. Furthermore, getting a higher gain necessitates a longer duty cycle, which increases the stress on semiconductor devices. The researchers have reported various techniques to achieve a higher voltage conversion ratio. The classification of various techniques for boosting the voltage is depicted in Figure 1.2.

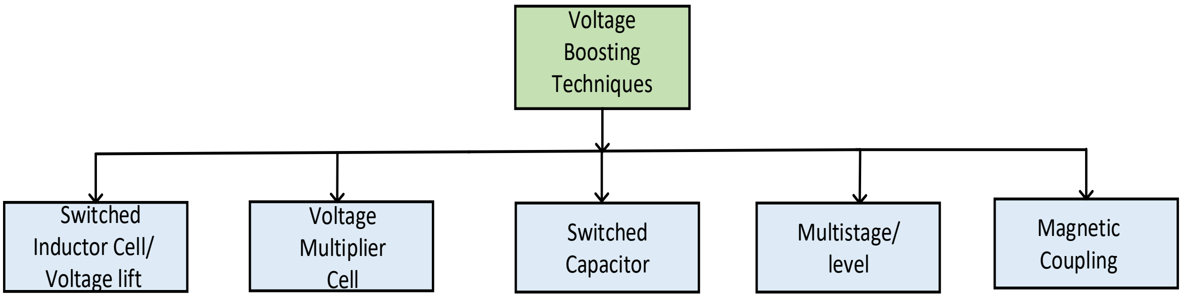

Figure 1.2: Classification of voltage boosting techniques.

Switched Inductor and Voltage lift cell

The voltage lift (VL) approach is an effective technique for boosting the output voltage level in DC-DC converters. This method includes charging a capacitor to a specified voltage, commonly the input voltage, and then using the charged capacitor's to step up the output voltage. By repeating the procedures and using additinal capacitors known as self-lift, triple-lift, and quadruple-lift circuits can be used to increase the output voltage level even higher. The self-lift based VL structure shown in Figure 1.3.

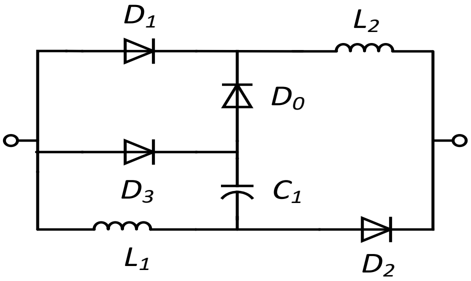

Figure 1.3: Self-lift cell structure.

Axelord introduced the switched inductor (SL) concept to lift the voltage gain in [6] as shown in Figure 1.4.

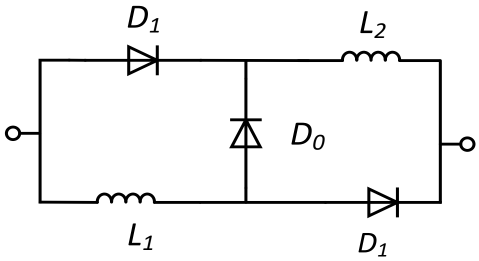

Figure 1.4: Basic SL cell.

VL techniques can also be applied in VL cells within step-up DC-DC converters. Figure 1.4 illustrates the configuration of voltage lift switched inductor (VL-SL) cells, with their typical placement in place of the inductor in a conventional DC-DC boost converter. In basic SL cells, the inductors are magnetized in parallel and demagnetized in series. By ensuring that both inductors have identical inductance values and operate under the same conditions, it becomes feasible to integrate them into a single core. This integration serves the purpose of reducing the overall size and weight of the converter. Various structures have been employed to implement the VL cell, as documented in [7] and [8]. More recently, Ye and Cheng [9] introduced a small resonant inductor with an inductance value of less than $1\mu H$ into the circuit of a basic VL cell. By strategically adjusting the placement of the components, they successfully developed novel DC-DC converters with high conversion ratios. These converters offer the advantages of simple structures and high efficiency. Instead of basic SL cell an active switched based network is presented in [10]. The three diodes of SL cell is replaced by the two active switches is required to boost the voltage. Further, to achieve more gain hybrid active network (AN) is reported in [11].

Voltage Multiplier

Voltage multiplier circuits are popular due to their efficiency, cost, and simplicity. These circuits are made up of diodes and capacitors to produce a high DC output voltage. A multiplier circuit is often positioned in the middle of a circuit, often after the main switch to reduce the voltage stress. There are various generic configurations of voltage multiplier cells (VMCs) commonly used in DC-DC converters, one of the configuration is shown in Figure 1.5. These cells, often referred to as switched/diode capacitor VMCs in literature, typically comprise only diodes and capacitors. They

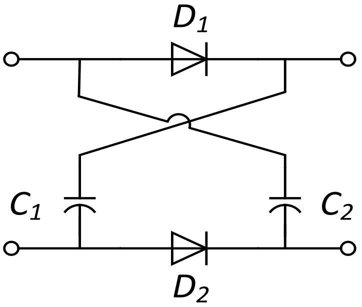

Figure 1.5: Voltage multiplier cell.

have been extensively studied and documented in [12], [13].

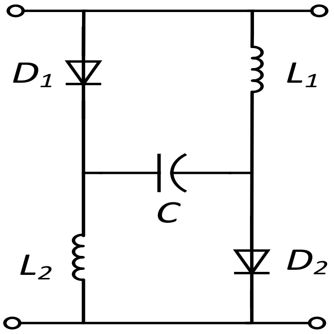

Figure 1.6: Voltage multiplier cell with inductor and capacitor.

The VMC shown in Figure 1.6 utilizes capacitors and inductors to enhance the boost factor of converters [14]. A horizontal version of VMC was implemented and presented in [15]. Typically, this VMC is placed before the main switch, aiming to increase the voltage level of extremely low voltage sources (below 50 V). A different class of voltage multiplier is called voltage rectifier. These configurations can only be used if the input is either alternating current or pulsating direct current. Greinacher voltage doubler rectifier (G-VDR) can be used in DC-DC converter but it has higher voltage stress across diodes and output capacitor [16].

Switched Capacitor

The switched capacitor (SC) method is widely recognized for its ability to boost voltage level in various DC-DC converters. It relies on the charge pump (CP) circuit and finds application in numerous systems. In a CP circuit, the voltage augmentation occurs solely through capacitive energy transfer, without any involvement of magnetic energy transfer. Figure 1.7 illustrates a schematic circuit known as a CP circuit, where two switches are turned ON and OFF sequentially. Initially, when switch I is turned ON, capacitor C_1 charges up to the input voltage level. Subsequently, when switch II is turned ON, the energy stored in C_1 transfers to capacitor C_2. This alternation between the switches happens in phases, with odd-numbered switches (I) active during phase 1 and even-numbered switches (II) active during phase 2. The underlying principle is referred to as "energy pumping" since it involves transferring energy from one capacitor to another. After multiple cycles, the output voltage eventually reaches the steady value and reaches to its final value [17]. Continuous input current based SC converter is reported in [18]. The cell utilizes two different sets of MOSFET's, namely Q_{S1} to Q_{S2} and S_1 to S_2, which work in complementary triggering mode. Throughout a switching period, their duty cycles remain fixed at 0.5. The circuit is shown in Figure 1.8. In the first phase, Q_{S1} and Q_{S2} are actively operating while S_1 and S_2 are kept open. The capacitors $(C_1 - C_2)$ are linearly charged using a constant current sourced from the supply voltage through diode D_1 to D_2 . On the other hand, in the second phase, Q_{S1} and Q_{S2} are open, S_1 and S_2 and are are closed. All capacitors are connected in series with the input source, providing power to the output load.

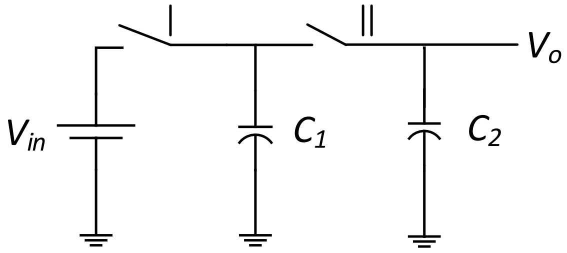

Figure 1.7: Basic charge pump circuit.

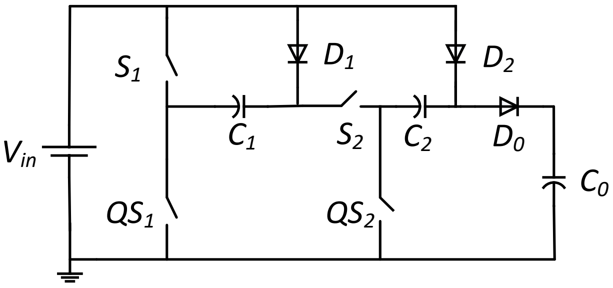

Figure 1.8: SC based network.

Multistage/level

In order to enhance the voltage gain of a DC-DC converter, a widely recognized approach is to utilize multiple stages of converter modules using different ways. This involves combining several identical or different converter modules with various voltage boosting techniques. In this subsection, cascaded, interleaved, and multilevel converter topologies, are classified under multistage/level. The cascading connection of converters is a straightforward method for enhancing the voltage gain. Figure 1.9 illustrates a schematic of a cascaded DC-DC converter. According to the depicted arrangement, two or more boost converters can be connected in a cascaded configuration, (referred as a quadratic group).

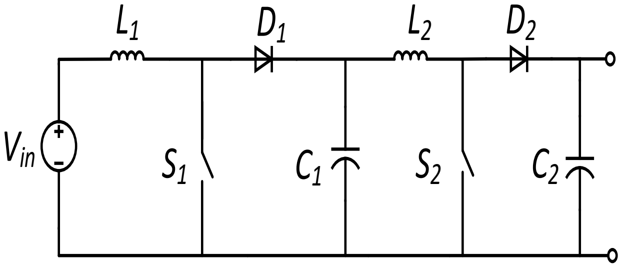

Figure 1.9: Cascade network.

Alternatively, different types of step-up converters can also be connected in a cascaded form, which is known as a hybrid cascade. To make the circuit simpler, the switches of a cascaded boost converter can be combined into a single switch. This is called a quadratic boost converter. But a problem with quadratic boost or 2-stage boost converter is that the duty cycle can no longer be adjusted independently, as shown in Figure 1.9. Reference [19] describes a multistage version of converter with multiple voltage-boosting modules using single switch. arious configurations of a hybrid cascaded connection, comprising quadratic boost and voltage multiplier modules, can be found in the literature. Cascaded DC-DC converters with quadratic boosting in the first stage, coupled-inductor modules in the second stage, and output series connection are described in [20].

For achieving the high gain, handling of inductor current is a challanging task. To resolve this, multiphase interleaving method is a promising way to reduce ripple current and increase power density in high step-up DC-DC converters. SC voltage multipliers can be used to connect various interleaved DC-DC converters in series [21]-[22]. Figure 1.10 shows a SC cell that can be used with or without input inductor coupling in interleaved arrangement DC-DC converter but size is the major concern. Multilevel DC-DC converters have been gaining significant attention in both industry and academia, primarily due to their effectiveness in high-power high-voltage applications [23]. These converters offer the advantage of reducing or even eliminating the need for magnetic components, resulting in a decrease in converter size and weight [24]-[25]. From the perspective of the input voltage, multilevel DC-DC converters can be categorized into two main types: those with a single DC source or with multiple DC sources. The single-source multilevel modular structures are particularly valuable for applications such as electric vehicles (EVs) or hybrid electric vehicles (HEVs) and motor traction. A boost converter featuring multiple submodules that incorporate switches, diodes, and capacitors represents a suitable topology for single input multilevel configurations [26]. This design offers notable benefits including its straightforward nature, modular construction, and adaptable characteristics. Nonetheless, these converters that rely on a single source tend to demand substantial current from the source, thereby introducing a certain level of constraint. In scenarios involving multiple DC sources, numerous DC-DC converters with lower output ranges are interconnected in cascade, and supply power to a single load. The primary hurdle associated with this configuration is chllanges in maximizing power extraction from the multiple sources.

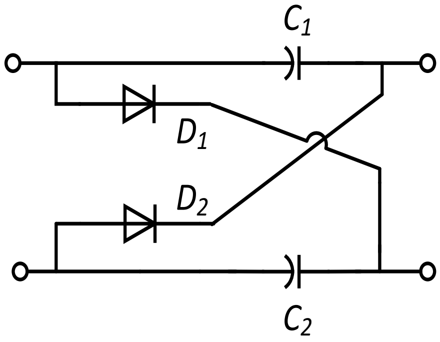

Figure 1.10: SC voltage multiplier.

Magnetic coupling

Magnetic coupling serves as a widely employed method for increasing voltage levels in both isolated and non-isolated DC-DC converters. Utilizing a coupled inductor helps in minimizing the requirement for magnetic cores, which are typically the largest components in the converters. Although this approach offers advantages like a predominant boost capability but it can also introduce challenges, such as dealing with leakage inductance, which necessitates attention when it comes to harnessing and managing the energy lost due to leakage. Magnetically coupled structures as shown in Figure 1.11, uses the CP and passive clamp circuit to increase the voltage gain and decrease the switch stress of the switch.

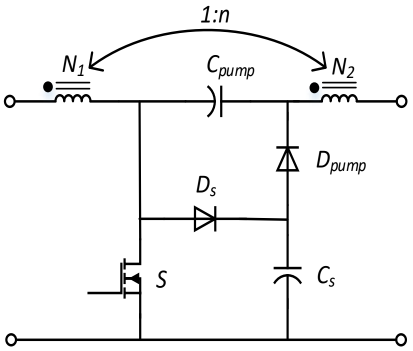

Figure 1.11: Coupled inductor based network.

The gain enhancement approaches discussed above can also be extended to DC-AC inverters also known as impedance source converters.

1.2 Impedance Source Converters

In recent times, distributed generation (DG) systems have gained immense popularity, primarily due to their compact size, ease of installation, and versatile control options. These DG systems harness renewable energy sources like photovoltaic (PV) panels, which generate DC voltage. However, most industrial and household systems rely on AC power. To bridge this gap, traditional voltage source inverters (VSIs) or current source inverters are employed to efficiently convert the DC voltage from DGs into the required AC supply. The conventional method is boost converter cascaded with VSI, as shown in Figure 1.12. However, it has the following drawbacks;

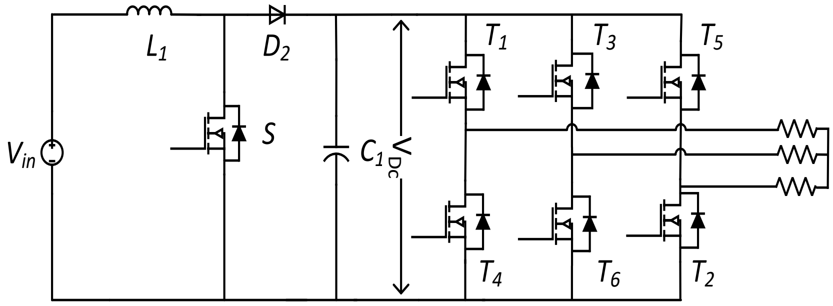

Figure 1.12: Boost converter with VSI.

- One of the primary challenges faced in pulse width modulation voltage-source inverter (PWMVSI) drives is the nonlinear voltage gain resulting from the nonideal characteristics of the power inverter. This nonlinearity is predominantly caused by the mandatory blanking time, which prevents the accurence of shoot-through on to the DC link. To ensure that both the switches in an inverter leg never conduct simultaneously, a slight time delay is introduced into the gate signal of the turning-on device. This delay, combined with the device's finite turn-on and turn-off times, introduces a magnitude and phase error in the output voltage resulting distortion of the output waveforms [27]-[28].

- The lifespan of the DC link capacitor in the VSI is influenced by the occurrence of shoot-through. This leads to the degradation of the capacitor's properties primarily due to the presence of high ripple current and with increased dielectric losses [29].

- Traditional VSI has the ability to buck the source voltage. For this reason, a DC-DC boost converter is connected at the front end [30], as shown in Figure 1.12. For high rated AC applications conventional boost converter gain is not enough to achieve the desired output.

To resolve the issue of two stage conversion in VSI, the impedance (Z)- source inverter was proposed in 2003. It has a distinctive capability to boost the output voltage by employing the shoot-through mode, a feature that is not allowed in traditional voltage source inverters [31]. This uniqueness enables the Z-source inverter to offer a more cost-effective, simple and single-stage solution. Additionally, this technology significantly enhances the inverter's reliability since the shoot-through operation can no longer cause damage to the system. The concept of the Z-source network is versatile and can be utilized for various power conversions, including DC-DC, AC-AC, AC-DC, and DC-AC. The typical arrangement of Z-source converter as shown in Figure. 1.13. The Z-source inverter consist of symmetrically positioned inductors and capacitors, both with equal values, along with diodes at the input. However, it has certain limitations, such as high inrush current, more capacitor voltage stress and discontinuous input current and lack of common ground between source to load. The absence of common ground and continuous input current in traditional Z-source is mitigated by the quasi-Z source (qZS) converter [32]. The voltage gain achieved by the qZS is the same as the traditional Z-source. Trans-Z source isolated DC-DC high gain converter is reported in [33], but pulsating input current and larger size are matters of concern. Non-isolated common ground Z-source converter is available in [34], but input current is discontinuous. The embedded Z-source (EZ) [35] involves utilizing an LC network with the DC source embedded within, resulting in more consistent and smoother source current from the input. A unique quasi-Z-source converter (qZSC) utilising the voltage-lift technique

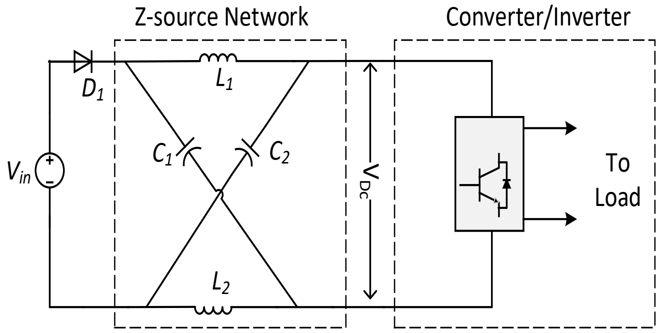

Figure 1.13: General structure of Z-source converter [31].

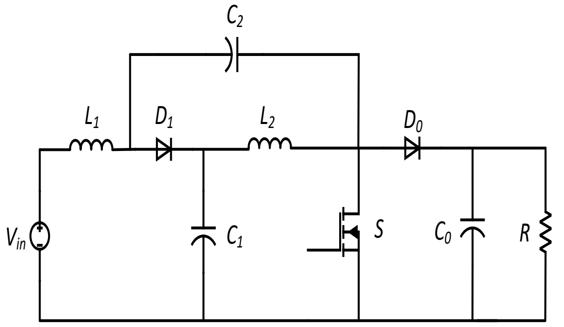

Figure 1.14: Quasi-Z source converter.

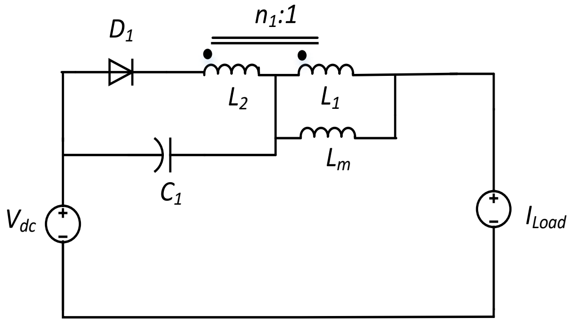

Figure 1.15: Trans-quasi-Z source converter [33].

has been introduced by Takiguchi et al. [36]. This novel design combines the voltage-lift cell and the qZS network, resulting in a significant increase in voltage gain with maximum duty restricted to 0.33.

An alternative method involving coupled Z-source converters with coupled inductors offers the advantage of attaining a high step-up gain through adjustments to the turns ratio of the coupled inductors [37], [38]. Despite this advantage, these converters may experience considerable voltage spikes due to the leakage inductor present in the coupled inductor. A different qZS network to enhance the voltage gain is shown in [39]. Nevertheless, the presence of pulsating input current and the need for additional inductors contribute to enlarging the size of this converter. An alternative approach, as described in [40]-[41], involves cascading multiple modules of the qZS network to achieve a higher total voltage gain. However, this method comes with a significant trade-off. As the number of components increases, it leads to several drawbacks, including elevated power loss, reduced efficiency, and an increased likelihood of failure. Consequently, this approach cannot be considered a suitable and optimized solution. The converter reported in [42] presents a two-stage and a generic multistage configuration for qZS converters. By incorporating multiple stages, this converter offers an improvement over the basic qZS converter, particularly in achieving similar voltage gains with lower duty cycles. But, this advantage comes with the trade-off of additional elements requirement in the circuit. The basic qZS converter has been improved in reference [43] by incorporating switched capacitor (SC) into the circuit. This modification improved voltage gain neither by increasing voltage stress on the individual elements nor by reducing the duty cycle of the switch. This specific converter still confronts practical difficulties in reaching high voltage gains. An innovative approach has been introduced in [44] to enhance the performance of the qZS converter. This improvement is achieved by the combined use of switched inductors (SL) cell and active switched capacitors (ASC). This resulted in enhanced voltage gain with ASC/SL network as shown in Figure 1.16. Likewise, an improved switched inductor qZS converter is reported in [45] with commmon electrical connection between load and source. Currently, the pursuit of non-isolated converters with high DC gain is a thriving field of research, leading to the proposal of numerous configurations. However, there remains an opportunity to explore and develop high-gain DC-DC converters with improved

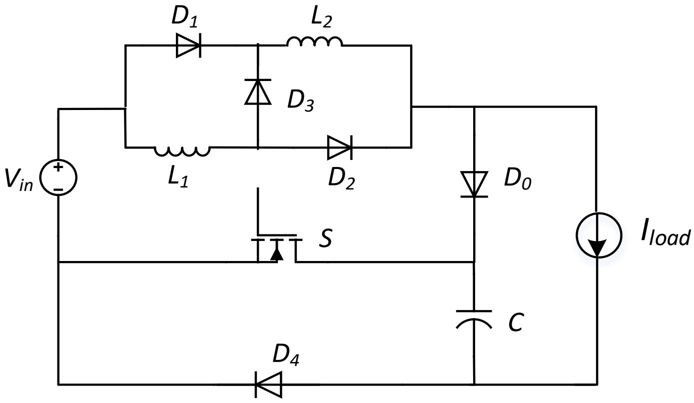

Figure 1.16: Active switched capacitor/ SL qZS converter [44].

features.

A comprehensive classification of some of the non-coupled based impedance source topologies is shown in Figure 1.22. The structure of these non-coupled based Z-source converters is shown in Figure 1.17 to Figure 1.21. The salients features of these inpedance based topologies illustrated in Table 1.1. This thesis introduces a improved qZS high-step-up DC-DC converter, incorporating the concept of switched capacitors (SC) to cater to DC, AC, and hybrid loads.

Table 1.1: Salient features of impedance source topologies

Topology	**Features**
Quasi-Z source	Continuous input current, common ground, low capacitor stress
Diode assisted	Expandability, Increase boosting range by cascade connection of another stage without need of active switch
Capacitor assisted	Expandability, increase boosting range with limited duty range
Switched Inductor	Low current stress through inductor
Switched Boost	Low voltage stress of capacitor and switch
Embedded Z-source	consistent and smoother source current

In summary, there are two classes of Z-source converters distinguished by their inductor arrangements. The first class is the non-coupled converter, which requires more elements to achieve high gain. On the other hand, the second class is the coupled/isolated converter, where the gain depends on the coupled turns ratio. However, it is essential to utilize proper magnetic cores in the isolated topology to avoid leakage

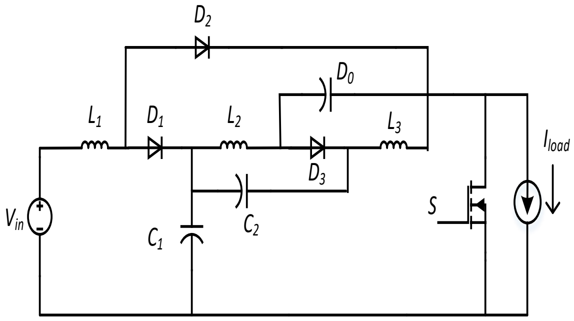

Figure 1.17: Diode assisted Z-source converter.

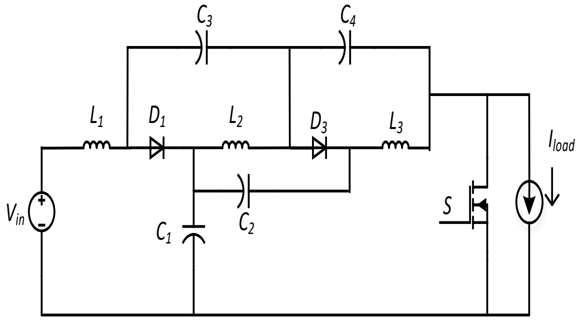

Figure 1.18: Capacitor assisted Z-source converter.

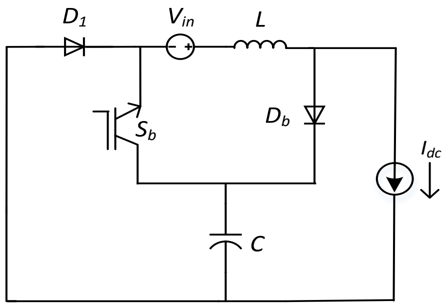

Figure 1.19: Embedded Z-source converter

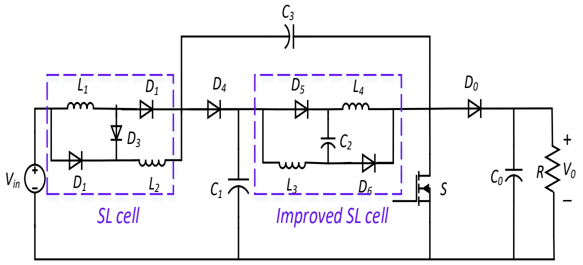

Figure 1.20: SL/Improved Quasi Z-source converter.

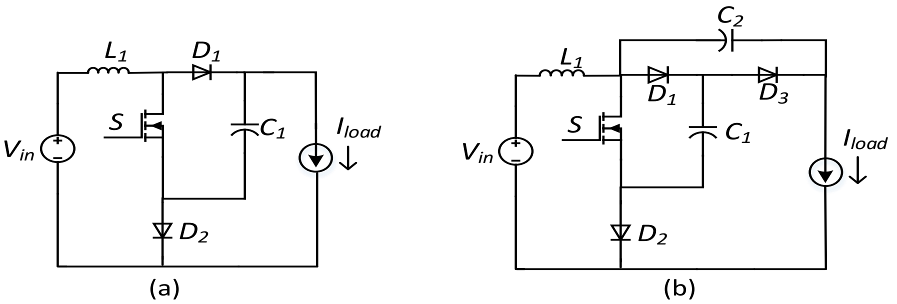

Figure 1.21: (a) Switched boost network (b) SC-Quasi switched boost converter.

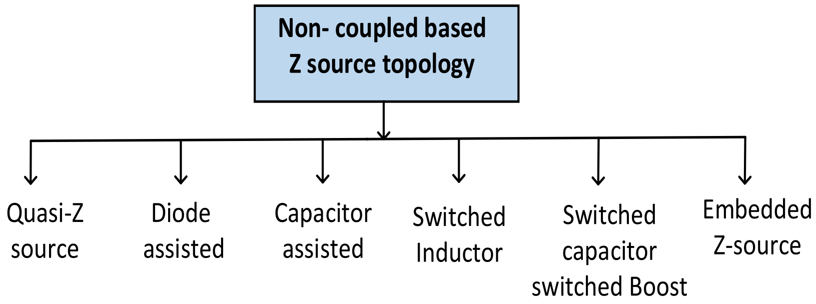

Figure 1.22: Impedance source topologies and its classification.

effects. Based on these, novel power converters are derived and proposed in this thesis. These new converters are expected to offer more promising prospects compared to the existing ones, addressing some of the limitations and drawbacks associated with the previously reported converters.

Moreover, Table 1.2 offers a comparative overview of different voltage-boosting techniques based on their key characteristics.

Table 1.2: Boosting techniques in DC–DC converters

Voltage boosting Techniques	**Advantages**	**Disadvantages**
Switched inductor and voltage lift cell	• High boost factor • Ameanable in many converter	• More passive component • Not suitable for high power
Voltage multiplier	• Very high boost ability and simple in structure. • Can be integrated in various structure. • cell based ..	• More voltage stress on components. • Need more cell with high rating for high power rating.
Switched capacitor	• Cheap and lightweighted circuits. • high power density and easy to be integrated. • cell based .	• High inrush current at start-up. • Sensitive to ESR of capacitor. • lack of output volatge regulation.
Multistage/level	• Modular strucrure. • high power capability. • High voltage/current level .	• Large amount of component. • Efficiency deorates with number of stage/level. • Relatively heavy, bulky and costly.
Magnetic Coupling	• High boost ability depens on turns ratio. • High efficient due to soft switching capability.	• Negative impact of leakage inductance such as large spikes. • Need precise coupled inductor design. • Relatively bulky.

1.3 Objective

The primary goal of this thesis is to optimize the extraction of energy from low-voltage distributed energy resources to fulfill the energy requirements on the utility side. To achieve the specific voltage level requirements, a thorough analysis, design, and testing of new converters tailored for low-power applications have been undertaken. In the evolving field of high-gain converters, the goal is to explore possibilities for achieving more efficient solutions with a reduced number of components. The main emphasis of this study is to identify and develop high-gain power electronic converters which can effectively address the energy conversion challenges, particularly for low-power scenarios.

- Initially, an extensive review of the available literature is carried out to identify gaps in previously reported studies. Subsequently, simulations are performed based on this literature to evaluate their performance.
- To develop the converter with a higher voltage conversion ratio during low-duty cycle operation.
- As the high voltage gain converter is generally current fed circuit. Inductor magnetizes with the source voltage and demagnetizes its energy to other components. The challenge is the current rating of inductor increases at higher range of duty cycle. Therefore, the objective is to design a compact inductors with the ability to attain lower current rating.
- To reduce the size/rating of inductor by the splitting low voltage side into parallel paths, similar as active switched inductor network. Eventually to achieve high gain with low currrent stress through inductors.
- To achieve higher gain with low device count by modifying the switching scheme.
- To develop experimental prototype for the proposed converters and validate the theoretical claims.

1.4 Structure of the thesis

This thesis is arranged into six chapters. A brief discussion of each chapter is as follows:

Chapter 1 is introduction of the thesis to discuss the existing methodologies and relevant literature related to high gain DC-DC converters. This chapter effectively presents the research's motivation and outlines the key objectives of the research work.

Chapter 2 describes the single switch based impedance source converter to achieve high gain. A detailed steady state analysis in continuous conduction mode is carried and design guidelines is presented. Moreover, the comparison with existing Z-source converter is carried. Finally low power rating prototype is developed and tested.

Chapter 3 presents quasi impedance source based DC-DC converter with restricted range of duty cycle. The theoretical analysis is carried out and further analytical results are validated using experimental setup. Moreover, proposed converter is extended for hybrid (AC+DC) load applications.

Chapter 4 proposes active switched inductor with wide range of duty cycle. The CCM and DCM gain is discussed for the proposed converter. Moreover, to show the feasibility of converter experiment is carried under different operating conditions.

Chapter 5 describes the improved active switched inductor based converter operation using different modulation techniques to achieve flexible higher voltage gain. Comparison with exiting method and experimental results are shown to confirm the feasibility of the converter.

Chapter 6 contains the conclusion of the thesis. Possibilities for improving the investigated topologies are outlined for future work.