1

INTRODUCTION

1.1 Introduction

In recent times, renewable energy sources such as solar photovoltaic (PV) based microgrid has become a prevalent solution to the green house generation [1]-[5]. Microgrid has many advantages such as 1) it utilizes renewable energy resources which have almost zero emissions and it is freely available, 2) it saves the cost of transmission and distribution of power system and supplies the local demand additionally, 3) typical power supply to the microgrid area is maintained during natural disasters, blackouts, etc., 4) cost per unit of energy is reduced by setting up a microgrid with locally available renewable energy source in the remote locations, and 5) reliability and quality of power received by a customer are enhanced by setting up a microgrid.

The structure of classical dc microgrid consisting of solar photovoltaic (PV) and power electronics interfaces (dc-dc conversion and dc-ac conversion) is shown in the Fig. 1.1. It can be observed from Fig. 1.1 that the classical microgrid uses two different converters, dc-dc converter and dc-ac converter. The input to these converters is generally given from the renewable energy resources. The solar PV based renewable energy is freely available and have zero pollution to the environment. However, solar PV renewable resource-based microgrid has drawbacks of low voltage generation, more number of conversion stages, and reduced efficiency. Thus, in order to step-up the voltage of the renewable sources, a high step-up converter is an essential part in the microgrid [6]-[8]. Following subsections describe about the conventional high gain converters in microgrid, state-of-art of conventional high gain converters, and challenges associated with conventional high gain converters. Based on the literature review and challenges associated with the conventional high gain converters, some desired characteristics of high gain converters for microgrid applications are also identified and finally, scope of the thesis is discussed.

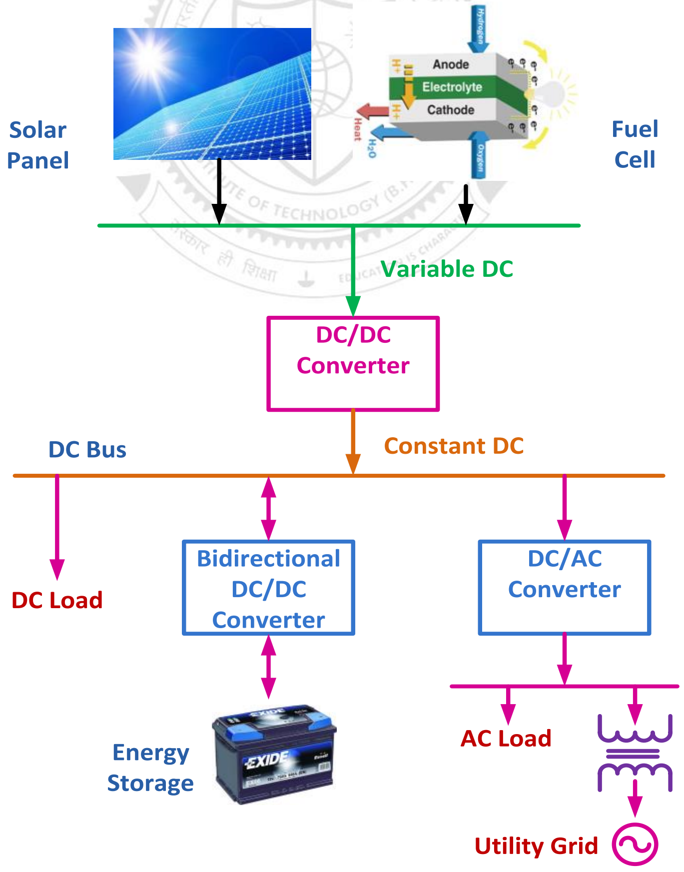


Fig. 1.1. Typical microgrid.

1.2 High Gain Converters in Microgrid

The high gain converter is essential in several renewable energy resources such as small roof-top solar PV and fuel cell application. These renewable energy sources generally generate low voltages which are to be converted into high dc-dc or dc-ac output voltage. Conventional two stage converter consisting of a boost converter followed by a voltage source inverter (VSI) is widely used in the renewable energy system [9]-[11]. Fig. 1.2 shows conventional two stage voltage source inverter. It may be seen from Fig. 1.2 that VSI is cascaded with boost converter in the conventional two-stage converter. The input voltage V_{dc} to the converter shown in Fig. 1.2 is the output of solar PV system. Moreover, to achieve higher gain some times it is essential to use transformers at the output terminals.

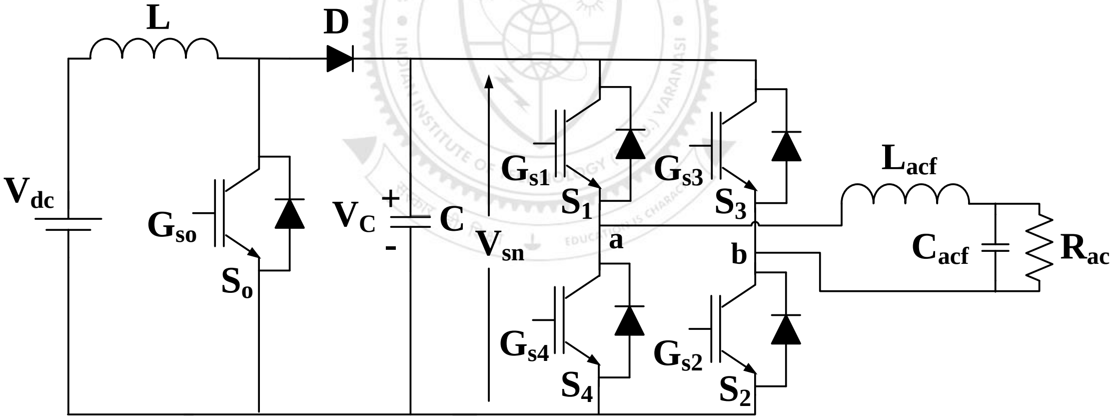


Fig. 1.2. Conventional two stage high gain inverter.

To achieve high voltage gain, boost derived converter needs to operate at an extreme duty cycle. In order to obtain high voltage gain, boost derived converter practically operates at the extreme duty $D = 0.8 \sim 0.85$, due to the parasitic parameters of the converters. This leads to severe reverse recovery of the diodes, increases EMI, increase losses and decreases efficiency [12]-[14]. The conventional VSI also have several challenges. One of the major limitations is that its peak ac output voltage is always less than the input dc voltage. The shoot-through problem in voltage-fed inverters caused by misgating due to electromagnetic interference (EMI) is also one of the main causes of concern in terms of inverter's reliability [15]. Although, dead times between the signals are provided to avoid the shoot-through of the inverter legs, the chances of a short circuit due to EMI remains. At the same time due to dead band insertion in the switching frequency inverter legs causes ac distortion. Thus, a complex dead band compensation circuitry is required in classical VSI [16]-[17].

The two stage converters are either classical voltage source converter (VSC) or current source converter (CSC). Limitations of classical VSC and CSC are eliminated by the impedance (Z) - source converter. The Z-source converters have buck-boost capability, improved reliability, single stage conversion, etc. [18]. However, Z- source converter has discontinuous input current, low voltage gain capability and higher switch stresses [19]. Moreover, conventional Z- source converter is best suitable converter for boost factor (B) < 1.5 as compared to the cascaded boost VSI [20].

1.3 State of the Art of High Gain Converter

The basic dc-dc converters are boost, buck and buck-boost converter. The dc-dc converter is broadly classified as bi-directional [21]-[23], coupled inductor/transformer [23]-[27], boost derived converters [28]-[31], impedance source converters [32]-[34], interleaved [35]-[37], soft switching [38]-[39], high efficiency converters [40]-[42], multilevel converter [43]-[45], right half plane zero [46]-[48] and switched inductor/ capacitor [49]-[52]. Similar topologies are also found for the dc-ac converters. In order to obtain high gain, inverter bridge circuits are used after the dc-dc converters for high gain. Power converter architecture having multiple output ports are also widely used in the wide variety of applications [53]-[56]. This is due to the higher power processing density, compact size and increase reliability [33], [57].

The voltage source inverter (VSI) is derived from the buck converter. The VSI is nothing but differential connection of two buck converters. Thus, VSI peak output voltage is always less than or equal to the input dc link voltage [9]-[10]. Due to the topological link between dc-dc and dc-ac converter, the same topology is valid for both the converters [15], [18]. Therefore, high gain converters discussed in this thesis can be operated as either dc-dc converter or dc-ac inverter.

The conventional boost derived converters have to operate on very high duty ratio to achieve high voltage gain. This leads to severe reverse recovery of the diodes, increased EMI problem, increased losses, and therefore, reduced efficiency [9], [14]. To achieve high gain, different topologies are found in the literature such as cascading of converter [58]-[60], and hybrid cascading [61]-[62]. In dc-ac conversion, cascade H-bridge inverter topology is popular for microgrid connected solar PV [63]. However, due to the higher number of components count of switches and diodes, the related switching losses and conduction losses increase which lead to decrease the efficiency.

To improve gain, different topologies such as voltage multiplier, switched-capacitor, switched-inductor, and voltage lift techniques are also used in dc-dc converter for high gain applications [64]-[68]. These voltage boosting techniques at the same time increase passive components as well as diodes and switches. The drawback of voltage multiplier techniques is that, it has high voltage stress on components; need several cells with a high rating for the high voltage rating [65]. The switched-capacitor technique suffers from the high inrush current at start-up and sensitive towards equivalent series resistance (ESR) of capacitors and switched-inductor techniques have increased the number of components count [70].

One of the popular methods is to use coupled inductor/ transformer based topologies for high gain. By regulating the turn’s ratio of the transformer in isolated converters, high voltage step-up can be achieved [71]-[73]. However, the isolated converter has a problem with control switches, which suffer from high voltage spikes. Leakage inductance of the transformer also causes power losses [74]. The converter weight, volume, and size are also increased due to the presence of the transformer. As the transformer losses are the function of switching frequency therefore, the maximum operating frequency is also limited in the case of isolated dc-dc converters [75]-[76]. However, in microgrid applications, non-isolated high gain converters are popular over isolated high gain converters for dc-dc conversion [77].

The high gain converters and inverters are mostly derived from the boost or buck-boost converters. These boost or buck-boost derived converters/ inverters topologies suffer from right half plan zero (RHPZ) problem. The problem with boost and buck-boost derived converter/inverter is that when they operate in a feedback loop controlling continuous conduction mode, due to RHPZ converter tends to oscillate [9]. Also, the presence of RHPZ causes the controller design complex. By adjusting the pole –zero location of control-to-output transfer function, RHPZ is restricted in certain operating limits [78]. The RHPZ problem is also eliminated by operating the converter in discontinuous conduction mode (DCM) [79]-[81]. However, operating in DCM degrades the converter efficiency and input current becomes pulsating.

In recent times, Z-source converters (ZSCs) have become popular choice over classical voltage-source and current-source converter [15]. The traditional Z-source converter [18] is shown in Fig. 1.3. The classical Z-source inverter (ZSI) has discontinuous input current profile problem. These problems are eliminated by continuous input current quasi-ZSI (qZSI) [34]. The qZSI have same voltage gain as that of classical ZSI with reduced capacitor voltage stress and also it does not have inrush current. Continuous input current based quasi-Z-source converter and discontinuous input current quasi-Z-source converters are shown in Figs. 1.4(a) and 1.4(b), respectively. The boost factor of ZSI/qZSI is as follows:

$$B = \frac{1}{1-2D} \tag{1.1}$$

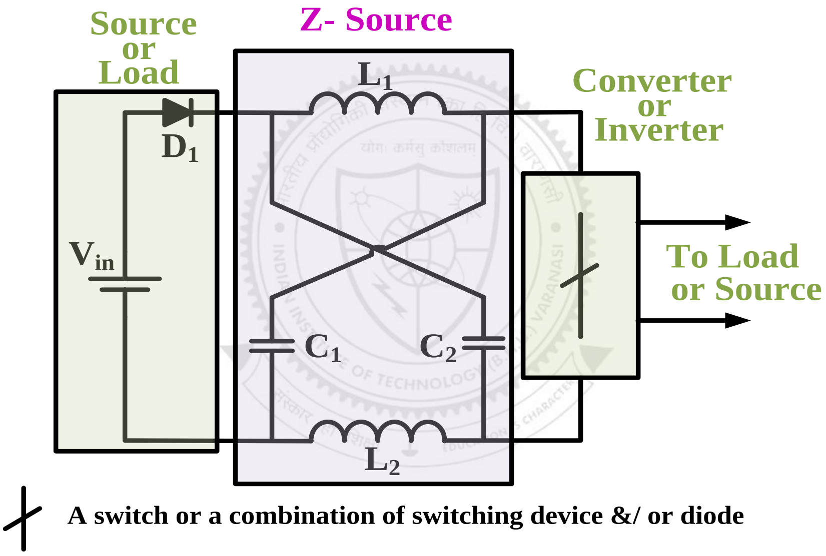
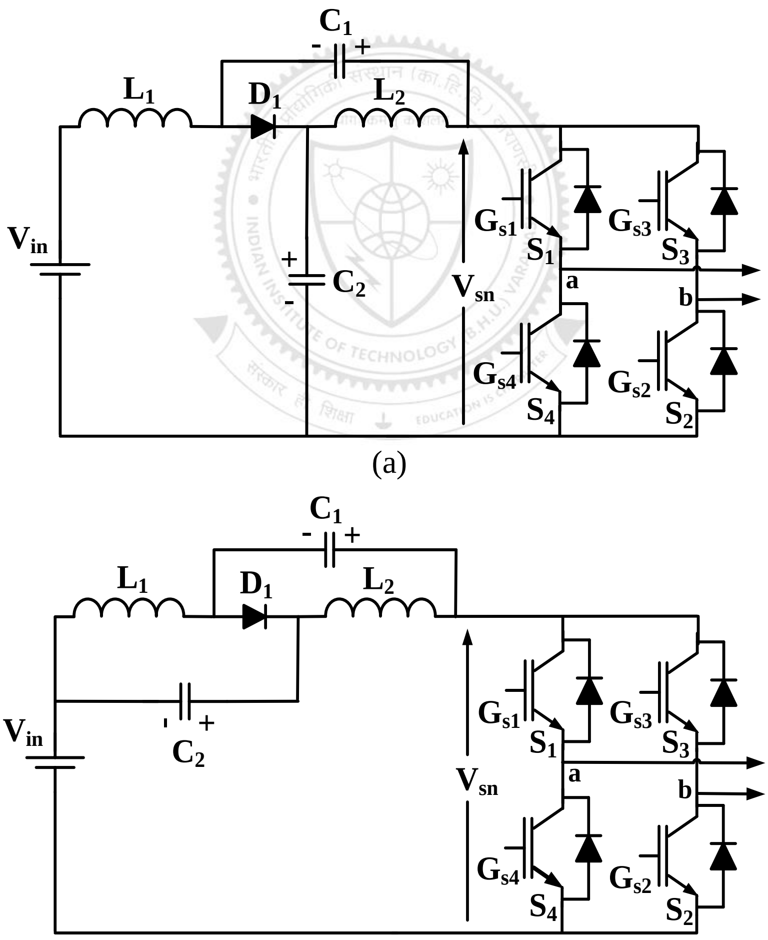


Fig. 1.3. Basic Z-source converter.

Switched boost inverter (SBI) and current fed switched inverter (CFSI) based topologies are having the same characteristic as that of ZSI [82]-[87]. The SBI and CFSI are shown in Fig. 1.5 (a) and (b), respectively. The switched boost inverter (SBI) and current fed switched inverter (CFSI) also give simultaneous ac and dc outputs. The SBI have less number of passive components as compared to classical ZSI/CFSI. CFSI and ZSI have same boost factor but CFSI has continuous input current profile in contrast to classical ZSI and SBI.

As, the ZSI/qZSI/ SBI/CFSI have less boost capability, different topologies are suggested to enhance the output voltage. To achieve high voltage gain with small shoot-through duty cycle, coupled inductor/ transformer based topologies are used in [88]-[91]. The coupled-inductor topologies have problems associated with leakage inductances and spikes appears across the dc-link voltage [74]. Recently, for achieving high boost factors, different topologies are proposed such as switched-inductor (SL), switch-capacitors (SC), hybrid switched-inductor-capacitors (LC), multiplier cells, voltage lift, and cascaded topologies [92]-[98]. By using these topologies, higher gain is achieved but this increase component counts which leads to decrease in efficiency.

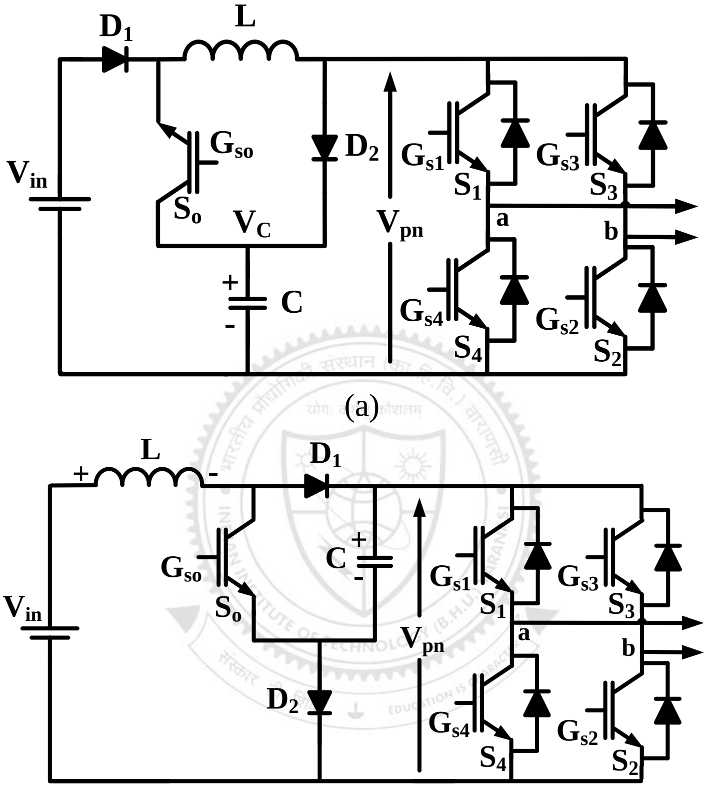


(a)

(b)

Fig. 1.4. quasi-ZSI (a) continuous input current qZSI, (b) discontinuous input current qZSI.

Switched topologies [99]-[100] are implemented in conventional ZSI for enhance boost factor but these converters have discontinuous input current profile. Converter modifications with switched topologies are also suggested in continuous input current based qZSI to improve the boost factor [101]. Fig. 1.6(a) shows SL-qZSI which gives higher voltage gain compared to the qZSI.



(a)

(b)

Fig. 1.5. Hybrid output based ZSI (a) switched boost inverter, (b) current fed switched inverter.

Switched topologies [99]-[100] are implemented in conventional ZSI for enhance boost factor but these converters have discontinuous input current profile. Converter modifications with switched topologies are also suggested in continuous input current based qZSI to improve the boost factor [101]. Fig. 1.6(a) shows SL-qZSI which gives higher voltage gain compared to the qZSI.

The boost factor of SL-qZSI is as follows:

$$B = \frac{1+D}{1-2D-D^2} \tag{1.2}$$

To further increase the voltage gain, both the inductors of classical ZSI is replaced with switched inductors [102] which is shown in Fig. 1.6. (b). The boost factor of the inverter [102] is written as follows.

$$B = \frac{1+D}{1-3D} \tag{1.3}$$

The problem with this inverter is that, it has higher number of components count. The ASC/SC-qZSI discussed in [105] has same boost factor as shown in (1.3) but has less number of components count. The problem with ASC/SC-qZSI [105] is that it has ripple input current profile.

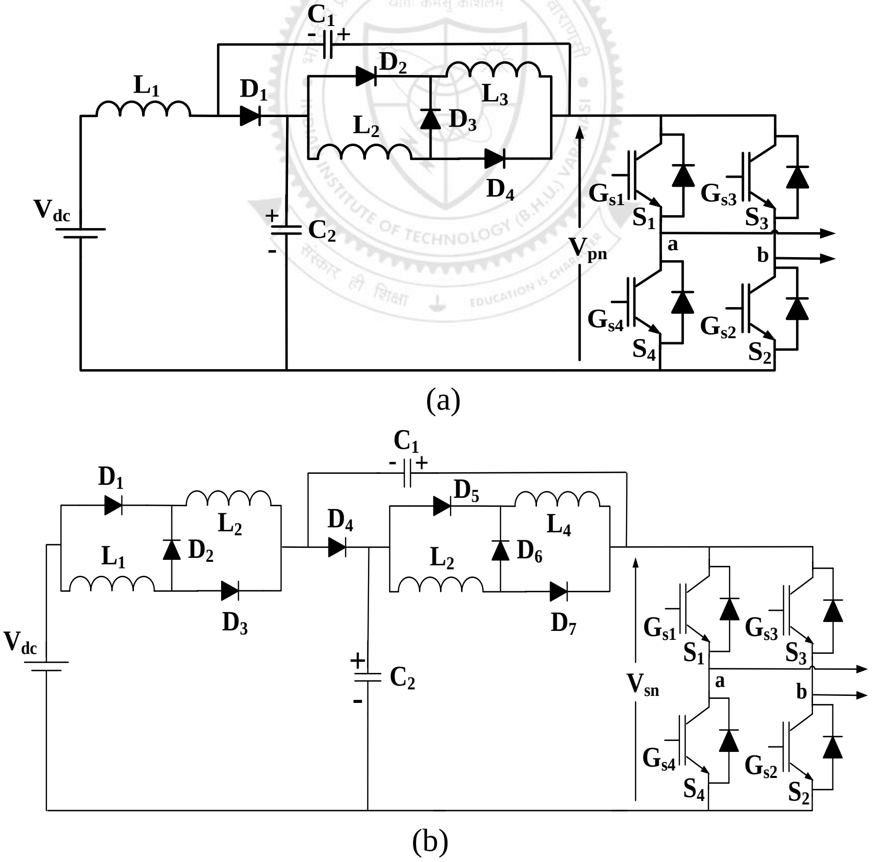


Fig. 1.6. Switched network topologies (a) SL-qZSI [101], (b) two SL-qZSI [102].

1.4 Challenges Associated with the Conventional High Gain Converters

As per the state-of art discussed in section 1.3, it has been observed that the conventional high gain converters have following challenges:

1) The high gain converters and inverters are mostly derived from the boost or buck-boost converters. These boost or buck-boost derived converters/ inverters topologies suffers from right half plan zero (RHPZ) problem [9]. The presence of RHPZ in control-to-output transfer function makes the system non-minimum phase and thereby controller design becomes complex. This occurs because, during a transient, the phase lag of the RHPZ causes the output to initially change in the wrong direction. Presence of RHPZ in the system even poses the problem of a lower bandwidth of the system (slower system) and gives difficulty in achieving adequate phase margin (less relative stability) [21]-[22], [46]-[48].

2) The converters used in microgrid application have to use different dc-dc and dc-ac converters for different load requirements. For example, for n- number of dc-ac outputs, n-number of dc-ac converters is required. So, use of more number of converters for more load requirement increases the size and volume of the overall system. This also decreases overall system efficiency. The multiple output architecture system is required for higher power processing density, reduced losses and compact size system [54]-[57].

3) The conventional VSC and CSC have limitations such as a) these converters cannot be buck-boost converter, i.e, either it will be a buck or boost converter, b) it cannot be open circuited or short circuited, c) the main circuit is not interchangeable and d) susceptible to EMI noise [32]. Impedance source converter eliminates the disadvantages of classical VSC and CSC. The Z-source

converters are one of the most promising converters which overcome the disadvantages of the classical VSC and CSC. However, conventional ZSI have less voltage gain capability and in order to get higher boost factor converter need to operate at higher shoot-through duty cycle. Operating at higher duty cycle leads to increased EMI and decrease in efficiency.

4) The conventional ZSI has numerous advantages but has less boost factor ability. Also, the cost functions of the conventional ZSI are higher which increase voltage stress and current stress of switches and diodes [20]. It is also depends upon the stored energy of the inductors and capacitors. Therefore, new Z-source topologies are required which meet the requirement of microgrid application with improved voltage boost ability, less cost and improved efficiency.

1.5 Desired Characteristic for High Gain Converter

Based on the literature review of section 1.3 and challenges associated with the conventional converters discussed in section 1.4, few desired characteristics for high gain converter are identified in this section. The desired characteristics for high gain converters are summarized as follows:

1) The continuous input current should be drawn from the input DC power supply which is suitable for renewable energy application. The continuous input current based converter does not require any input filter.

2) Number of passive components should be least.

3) Converter should have high boost inversion capability, as the renewable energy resources such as solar PV has less voltage generation capability.

4) The converter should not operate at extreme shoot-through duty cycle to achieve high voltage gain. Operating on extreme shoot-through duty cycle leads to lower values of modulation index and thereby increase in total harmonics distortions.

5) Converter should have good EMI noise immunity similar to impedance source inverters.

6) The converter should have higher power processing density and should have inherent shoot-through protection for increased reliability.

7) The converter should not require dead band for the switching so that waveform distortion is avoided for dc-ac conversion.

8) Transformer based topology consists of magnetic cores because of which weight and volume of the system is increased. These topologies also suffer from leakage inductance problem that further leads to decrease in efficiency. Therefore, non-isolated class of converters has become popular in microgrid applications.

1.6 Scope of the Thesis

In order to overcome the shortcomings of the conventional high gain converter and to satisfy the desired characteristics of the high gain converters for microgrid applications various high gain converters are proposed in this thesis. The proposed converters are suitable for various dc-dc and dc-ac power conversions for microgrid applications where the available low input voltage is to be converted into high dc-dc or dc-ac output voltage.

The first proposed converter is a hybrid ac-dc converter with no RHPZ which overcomes the problem of non-minimum phase behavior and also reduces weight volume of the system. It is important to note that presence of RHPZ makes the system non-minimum phase and due to this, bandwidth of the loop becomes less (speed of overall system becomes less) and getting adequate phase margin becomes difficult (relatively less stable system),

In step two, two converters capable to give n number of simultaneous ac outputs along with one dc output are proposed. The proposed converters can directly (without any extra regulator or adaptor) supply more than one different ac load demands. The proposed multi-output hybrid converter topologies have higher power density and improved reliability (due to inherent shoot-through protection property) which make them suitable to be used in compact systems with multiple ac and one dc loads.

Finally, improved ZSI topologies having higher boost factor at low duty ratio compared to the conventional ZSIs are proposed. The advantages of these topologies are that they have improved efficiency and less cost function as compared to the conventional ZSIs. The improved voltage gain is achieved by adding one auxiliary switch and one diode without using additional passive components. The proposed topologies give high voltage gain at low D as compared to the traditional ZSIs. The proposed ZSIs can be applied to dc-dc and dc-ac power conversion for renewable energy sources where low voltage input and high voltage gain is required. In the proposed ZSIs, higher voltage gain can be achieved from low D, therefore, it gives flexibility to operate with wide ranges of M as the converter operation is limited with the condition, $D + M \geq 1$.

Overall, the contributions of the thesis are summarized as follows:

1) A high step-up hybrid inverter suitable for hybrid microgrid is presented in this thesis. The proposed hybrid inverter does not display any RHPZ in the control-to-output transfer function and therefore, it gives minimum phase behaviour unlike the conventional inverters. The proposed hybrid inverter provides simultaneously ac and dc outputs and thus, gives better processing density and high reliability (due to inherent shoot through protection). This proposed hybrid inverter is also capable of operating on wide range of shoot-through duty cycle. The proposed converter is validated with the mathematical modelling, simulation and experimental results.

2) In order to supply n number of simultaneous ac outputs along with one dc output without using any extra adapter, two (series and parallel combination) high gain hybrid multi-output converter topologies are proposed for typical microgrid applications. The proposed hybrid multi-output converters are capable of giving two simultaneous ac and one dc outputs. The proposed multi-output hybrid converter topologies have higher power density and improved reliability which make them suitable to be used in compact systems with multiple ac and one dc loads.

3) In the thesis modified ZSIs topologies are proposed for improved boost capability with less cost as well as improved efficiency. The proposed inverters are suitable for renewable energy applications where high voltage gain is required from a low input voltage. The comparative analysis shows that the proposed ZSIs have higher boost factor (B) and higher efficiency with lesser capacitor voltage and switch current stresses as compared to conventional qZSI. Moreover, proposed ZSI has lesser stored energy in the passive components and

lesser peak switch device power (SDP) to output power ratio as compared to conventional qZSI when operating at $B \geq 2$.

In Chapter 2, proposed high gain minimum phase quadratic boost hybrid inverter is discussed. Detailed operating principle of hybrid inverter, small signal modeling, hybrid PWM control technique and simulation studies are performed in chapter 2.

Chapter 3 deals with the quadratic boost derived hybrid multi-output converters for n- ac outputs and single dc output. The detailed operating principle of the multi-output converter topologies, steady state analysis and simulation studies are discussed in the chapter.

In chapter 4, the switched-boost modified impedance source inverter topologies are presented. The detailed operating principle, steady-state analysis, passive components design, and PWM control technique are discussed. The detailed comparative analyses such as components count, gain, switch stress, diode stress, stored energy analysis and efficiency. To enhance boost capability further, extended continuous input current based ZSI is also discussed. Simulation studies of the proposed ZSIs are carried out in the chapter.

Chapter 5 deals with experimental verification of all the proposed converters. Chapter also deals with the detailed discussion on the obtained results of each of the proposed converters.

Chapter 6 provides the concluding remark on the proposed work. Future scopes of the research related to this thesis are also discussed in chapter 6.