1

CHAPTER

INTRODUCTION

1.1 Background and Motivation

The demands for electricity are unquestionably increasing, and the present power system infrastructure is nearing capacity. In the meantime, public concern over environmental protection is growing. All of these issues are major motivators for the development of renewable-based microgrid systems that enable clean and renewable energy sources like hydro, solar photovoltaic, wind power, fuel cells, and electric car integration. The increasing integration of such distributed energy sources into the grid is already an unstoppable trend around the world [1]-[4].

The smart grid is the next generation of electrical systems, and it is expected to drastically alter people's lifestyles in the not-too-distant future. The next-generation smart grid would be capable of delivering intelligent and environmentally friendly power to all types of distributed generations and energy storage devices. Users would pay less for electricity if they used their appliances during off-peak hours.

1.1.1 Power Generation in India (Jul 2021)

The total installed capacity including renewable and non-renewable energy resources in India in gigawatt (GW) is as follow:

Figure 1.1 shows the percentage contribution of renewable and non-renewable energy resources in power generation. The national electric grid in India has a total installed capacity of 384.12 GW. In which about 147.28 GW (i.e. 37.3%) power is contributed by renewable energy resources (i.e. wind, solar, biogas and small hydropower) and 240.84 GW (i.e. 62.7%) is non-renewable energy resources. Due to good availability of coal in India, the major portion

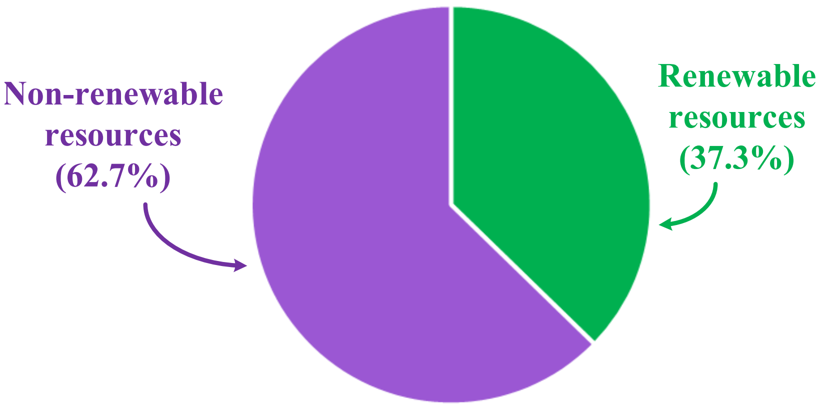

Figure 1.1: Percentage contribution of renewable and non-renewable energy resources in power generation.

of non-renewable energy (62.7%) is used by the National thermal power plant (NTPC). Instead of NTPC, the steel industry also uses a significant amount of coal. While coal has the potential to be a fantastic source of energy, it also has several disadvantages. The most significant disadvantage of coal is its poor environmental impact. Coal-fired power stations contribute significantly to air pollution and greenhouse gas emissions. Coal combustion emits sulphur dioxide, a hazardous chemical connected to acid rain, in addition to carbon monoxide and heavy metals like mercury. Due to these disadvantages, most of the industry moving towards renewable energy resources, which are freely available.

Figure 1.2 shows the percentage of contribution energy by the different renewable energy resources (i.e. wind, solar, biogas and small hydropower) in power generation. The total installed capacity of renewable energy resources in India is 96.9 GW of which 44% of energy is contributed by solar power, 41% by wind, 10% by biogas power and 5% by small hydro. From Figure 1.2, the percentage contribution of energy in total generation by the solar is more

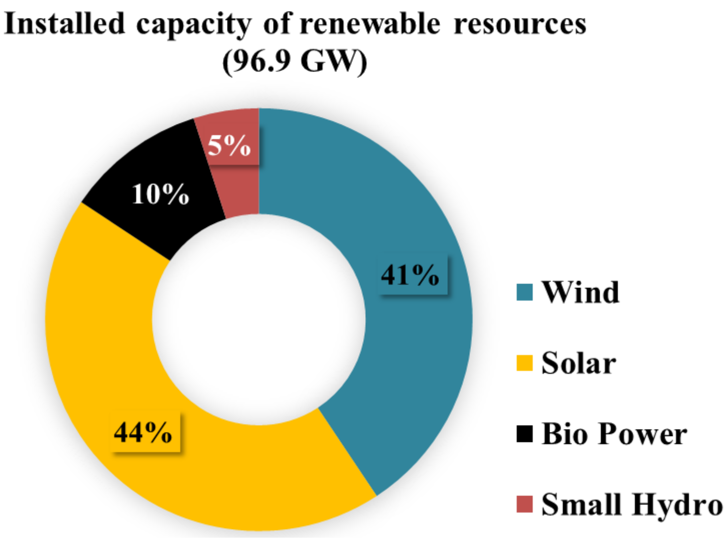

Figure 1.2: Percentage contribution of renewable energy resources in power generation.

in comparison to the other three renewable energy resources because the sun is available everywhere except some places. However, instead of more contributions and numerous advantages, these renewable energy resources have many disadvantages.

1.1.2 Pros and Cons of the Renewable Energy Resources

The pros and cons of different renewable energy resources are shown in Table 1.1.

TABLE 1.1

PROS AND CONS OF DIFFERENT RENEWABLE ENERGY RESOURCES

Renewable resources	Pros	Cons
Solar power	1. It reduces the cost of the energy bill. 2. Eco-friendly. 3. Low maintenance cost. 4. It creates jobs. 5. The excess power can be sold. 6. Reduced dependence on oil and fossil fuels	1. High initial cost. 2. Expensive electric storage. 3. Weather dependent. 4. Power converter cost is more. 5. Depending on geographical location.
Wind power	1. No pollution. 2. Low price. 3. Does not produce GHG. 4. It is a clean fuel source.	1. Require more space. 2. Loud noise. 3. Accident of birds.

Biogas power	1. A good alternative for electricity and cooking in the rural area. 2. Utilization of waste.	1. It is weather-dependent. 2. A foul odor emitted from it. 3. It contains impurities.
Small Hydropower	1. Efficient energy source. 2. Reliable electricity source. 3. Clean source of energy.	1. Affect fish population. 2. Low power in summer. 3. Energy expansion is not possible.

Among all the four renewable energy sources, solar PV-based microgrids have more advantages. It can easily install at the buildings, rooftop of the building and on useless land etc.

1.1.3 Microgrids

Microgrids are a group of local energy sources that is connected to the grid but can disconnect and operate independently, usually in the event of an electrical outage. It includes a variety of components like as controlled and uncontrolled loads, DC-DC, DC-AC power converters and storage devices that work in concert with regulated power electronic devices. It is gaining popularity because it allows for more flexible power transfer and integration of renewable energy sources, which has a lot of potential for use in rural areas or on islands. Renewable energy sources, power electronic interfaces and electrically connected loads are common components of microgrids. Batteries, super capacitors, power converters and flywheels are essential components for renewable-energy-based microgrids because they can handle power variations produced by renewable energy resources intermittent and stochastic nature. In addition, the use of renewable energy sources, power converters and microgrids are required to improve power quality and meet various demand-side management functions such as valley filling, peak shaving, black start, and voltage support [5]-[10].

1.1.4 AC, DC and Hybrid Microgrids

AC, DC and hybrid microgrids are the three types of microgrids available. AC microgrids provide the advantage of connecting all units using an AC bus connection. A DC-AC inverter or an AC-DC rectifier were required to connect DC equipment to the AC bus line.

An AC microgrid typically has high power output. There could be multiple AC sub-lines; for example, the grid is AC 38kV, and transformers connect various 10kV AC lines. A shared DC bus line, which feeds DC units attached to it, is a component of DC microgrids as well. Typically, DC loads or generators have a low power rating. By controlling the DC bus voltage, DC microgrids can be easily controlled. A hybrid microgrid system is created when a DC bus line and an AC bus line coexist in a microgrid system. The DC and AC bus contains many DC and AC loads connected to it. The example of DC and AC loads are electric vehicle charging station, DC and AC motor, small-scale industry [11]-[14].

Figure 1.3 shows the single line diagram of the conventional microgrids which includes renewable energy sources (solar and wind), DC-DC, DC-AC and bidirectional power converters with DC, AC loads and storage systems. The output voltages of the renewable energy sources (solar and wind) are of very low magnitude hence to match the grid voltage or to fulfill the load demand it is necessary to boost voltage using a DC-DC converter. The boosted DC output voltage is fed to the DC bus and used for different DC loads like electric vehicle charging and DC motor. The DC outputs can be stored by using a bidirectional DC-DC converter and can be used during an electric outage. Further, to fulfill the AC load demand, a

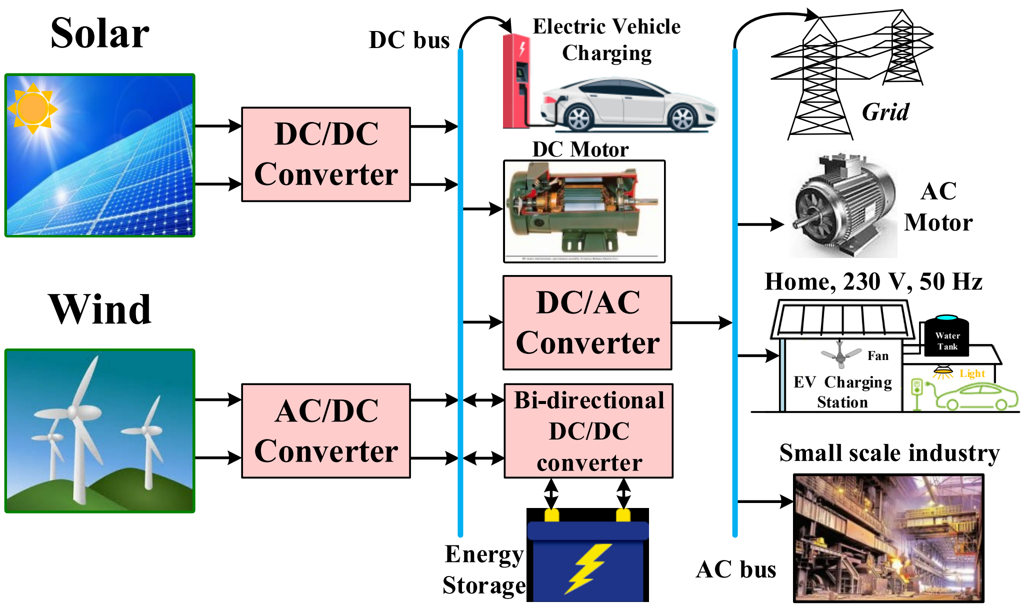

Figure 1.3: Single line diagram of a microgrid.

DC-AC converter is used to convert the DC into AC voltage and the converted AC voltage fed to AC microgrid, which is connected to many AC loads. Microgrid uses renewable energy resources, which has zero fuel cost. In this way, it has many advantages, which are given below.

1. It provides efficient, low-cost and clean energy.
2. It improves the operation and stability of the regional electric grid.
3. The regional electric grid's operation and stability are improved.
4. Reliable and resilient critical infrastructure.
5. It lowers "congestion" on the grid and cuts peak loads.
6. It enables high-efficiency (combined heat and power) CHP, which reduces the use of fuel, line losses and carbon emissions.
7. It integrates renewables, thermal, electric storage, advanced system and building controls.
8. It boosts competition in regional transmission organization (RTO) marketplaces.
9. It provides energy, capacity, and ancillary services to the grid.
10. Assist refugee centers and first responders in area emergencies.
11. It makes use of local energy sources and creates jobs in the area.
12. Rather than concentrated risk, diversify your risk.

1.1.4.1 Need of Multi Outputs Converters in Microgrids

There are many drawbacks to using conventional converters in microgrids. Therefore, it is necessary to use multi-outputs converter in microgrids. Figure 1.4 shows the block diagram representation of the conventional hybrid multi-output converters, which is able to produce multiple hybrid outputs using traditional hybrid converters. However, traditional hybrid converter uses more number stages to get the multiple output, which leads to more losses. Some useful points are given below which describe the need for multi-output converters.

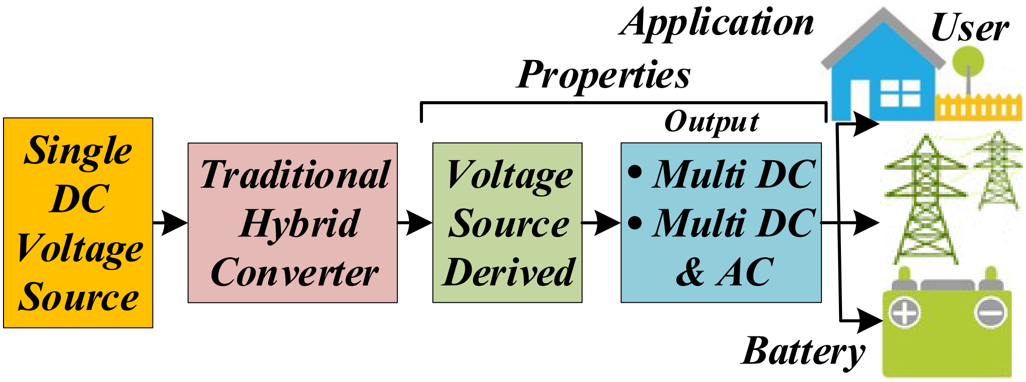

Figure 1.4: Block diagram representation of conventional hybrid multi-output converters.

1. Solar PV-based renewable energy resources have to match the required DC/DC or DC/AC output voltage bus or as demanded by the distribution system which uses more converters.
2. The conventional converters are unable to produce multiple AC and DC outputs simultaneously.
3. They are unable to meet more than one load demand at a time.
4. To achieve desired output voltage cascaded or step-up transformer after inverter terminals are used which leads to more number of conversion stages.
5. They have lower power density.
6. To achieve high voltage gain, the converter needs to operate at an extreme duty cycle.
7. Operating at an extreme duty cycle leads to severe reverse recovery of the diodes, increased EMI, losses and this leads to decrease the efficiency.
8. For futuristic households with AC/DC loads multi-output converter will be the mandatory requirement.

1.1.4.2 Desired characteristics for Multi-Output Converters

This section identifies and summarizes several desirable properties for multi-output converters:

10. A multi-output converter should have a continuous input current so that the requirement of an input filter can be eliminated.
11. The number of the passive component should be less.
12. A multi-output converter should be a single-stage converter.
13. Similar to quasi-Z-source inverters, MOCs should have a good EMI noise immunity system.
14. Because renewable energy sources such as solar PV provide less voltage, the converter should have a strong boost inversion capability.
15. For good reliability, MOCs should have inherent shoot-through protection capability and higher power density.
16. MOCs should be capable of buck-boost operations.
17. To avoid the waveform distortion in DC-AC conversion, the converter should not require a dead band for switching.
18. To avoid losses, total harmonic distortion and achieve high voltage gain, MOCs, should not operate at an extreme shoot-through duty cycle.
19. Transformer-based topologies consist of magnetic cores which results in more weight, volume and cost of the converter. It has lower efficiency due to leakage inductance. Therefore, non-isolated converters are more suitable for microgrid applications.

1.2 Literature Review

In recent times the idea of the AC/DC hybrid microgrid systems (HMGS), containing many electronically controlled strategies of parallel-connected distributed resources that are capable of functioning in both islanded and grid-connected modes evolved rapidly. It is a systemic approach to interconnect various converter outputs, renewable energy sources, energy storage systems, and local loads within certain areas. The HMGS also provides reliable, low-cost, renewable energy, improves local resilience, and improves the regional electric grid's operation and stability [15]-[16]. Moreover, the required prerequisite for futuristic houses with AC/DC loads is a hybrid microgrid. For modern electrical applications such as hybrid microgrids, hybrid electric vehicles, standby power supplies, etc., conventional single output converters cannot fully meet the simultaneous requirements of different types of voltage outputs [17]-[23]. As a result, increasing hybrid microgrid applications and other residential loads need power converters that provide multiple outputs simultaneously. Hybrid multi-output converters (MOCs) are becoming prominent to achieve these requirements due to their ability to generate multiple AC and DC outputs simultaneously. Besides, MOCs are a cost-effective alternative to solve the power supply issue in remote areas far from the grid. There are several advantages of these converters, such as higher power density, compact size, lower costs, and better reliability [24].

Many studies are ongoing due to the demand and benefits of hybrid MOCs and the literature lists different hybrid MOCs. The MOCs discussed in [25]-[28] are primarily DC/DC converters able to supply dual DC output using single or dual DC input. However, it does not have any AC at the output. Literatures [29]-[30] deliberate dual output DC/DC converters having buck/boost capabilities simultaneously. However, these converters also do not have any AC at the output. Topology [31]-[36] presents a DC-DC converter with a single input and multiple DC outputs having buck-boost capability with reduced switching losses, but no AC at the output. A high-efficiency coupled inductor-based DC-DC converter with single DC input multiple DC outputs is proposed in [37]. However, it does not have any AC at the output. Paper [38]-[43] proposed a novel non-isolated single-input dual-output three-level DC-DC converter for medium and high voltage applications. Their output voltages are regulated simultaneously with no AC at the output. Literatures [44], Figure 1.5 discuss converter that can give high gain, buck, boost DC outputs using a single inductor for hybrid renewable energy applications and

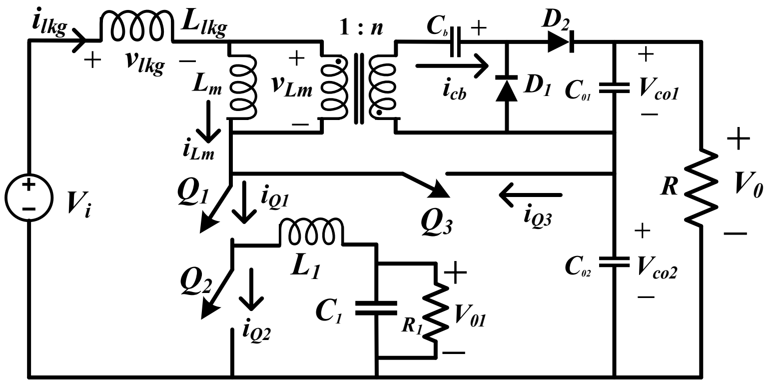

Figure 1.5: Equivalent circuit of single input dual DC/DC converter.

can perform buck-boost operation simultaneously. All the outputs can be independently regulated. However, high gain achieved at high duty cycle which results in more power losses. In addition, it is unable to produce multiple AC. Article [45]-[46] are single inductor multi input multi outputs high gain DC-DC converter with simple control technique. However, these converters unable to produce multiple AC at the output. Papers [47]-[48] proposes DC-DC converter that is non-isolated and can produce multiple high step-up DC outputs using a single input. However, they also do not have any provision of AC output. In this paper, single-stage dual-input single-output high-gain three-phase inverters able to give only single three-phase AC output is proposed. However, it is unable to produce multiple AC at the output [49]. This article proposes a single-stage non-isolated bidirectional multiport DC-DC converter able to produce only DC output however; it is unable to produce multiple AC at the output [50]. This paper proposes a high peak output power and high power conversion efficiency single inductor multi-input multi-output converter for energy harvesting systems. However, it uses multiple inputs to produce multiple outputs. It is for low power application and is unable to produce multiple three-phase AC outputs [51]. Article [52] is a multicell multi-input multi-output reconfigurable converter that is unable to produce multiple AC at the output. In [53] a single-phase single-stage single inductor multi-output DC-AC buck hybrid converter for battery charging application. It is can perform only buck operations at low power. It is unable to produce multiple three-phase AC at the output. Topology discussed in [54], is three-phase MOCs able to produce unregulated three-phase multiple AC outputs with no DC at the output. Hybrid MOCs discussed in [55] can produce a single DC and three-phase AC output simultaneously from a single DC input. Both the DC and three-phase AC outputs can be independently regulated. However, it is unable to produce multiple AC at the output. MOCs presented in [56]-[58] can supply single-phase regulated AC along with one DC output but not multiple AC. Paper [59] proposed a boost-derived converter that gives unregulated DC and AC outputs but not multiple AC. The topology proposed in [60], Figure 1.6 is boost-derived dual output hybrid converter able to supply one single-phase AC and DC simultaneously but not

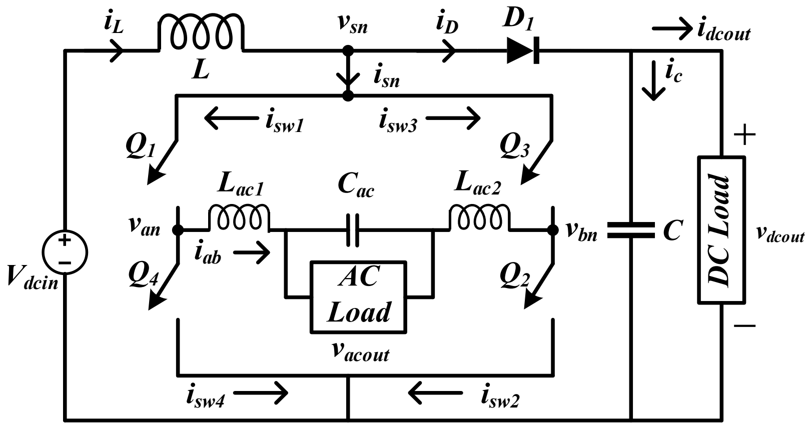

Figure 1.6: Boost-derived dual output hybrid converter.

multiple AC. Its outputs are more suitable for low power application like home appliances and single-phase motor. Paper discussed in [61]-[63] are high gain DC-DC converter able to give two DC outputs that can perform buck-boost operation simultaneously. Article [64] presents a an interleaved high gain converter that can produce single-phase AC and DC outputs simultaneously. However, it is not equipped to offer multiple AC at the output. In [65]-[66], minimum-phase dual output hybrid converters with simultaneously regulated AC and DC outputs are presented. Figure 1.7 shows the circuit diagram of the proposed minimum phase converters, which uses a damping network to remove the effect of right half plane zero.

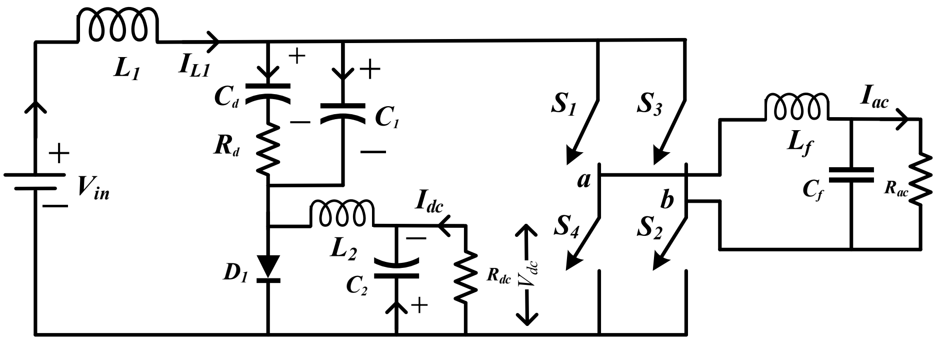

Figure 1.7: Minimum phase dual output hybrid converter.

However, use of damping network results in more losses due to which efficiency will be poor. It is not equipped to offer multi AC outputs and not suitable for high power application. Article [67]-[68], are transformer less hybrid converters able to give single AC and DC outputs simultaneously, which is for low power application. In addition to this, it uses more number of switches and unable to produce multiple three-phase AC at the outputs. A quadratic boost derived hybrid multi output converter is elaborated in [69], capable of supplying multiple single-phase AC along with one DC output. However, it is low power application and suffering from shoot-through problem. Hybrid converter deliberated in [70] and shown in Figure 1.8 is a qZSI-based buck-boost MOC with dual DC and single AC outputs. With only one AC, it can supply two DC outputs in a wide range of output voltages. However, it is for low power application and unable to produce multiple AC at the outputs.

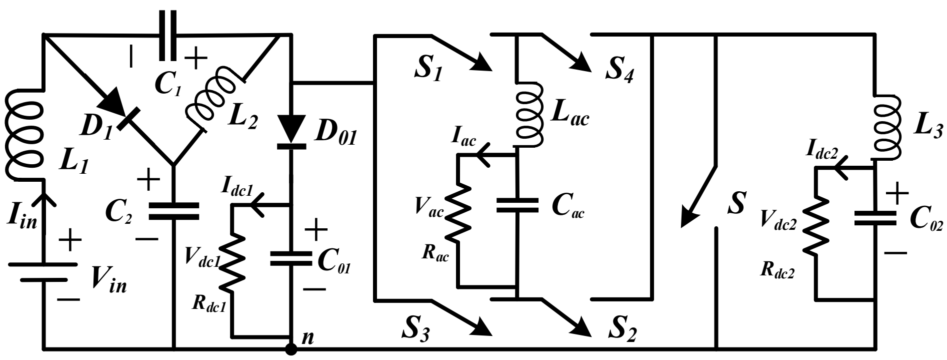

Figure 1.8: QZSI Based Buck-boost hybrid converter with dual DC and single AC outputs.

1.3 Research Gap with Existing Multi Outputs Converters

In general, existing MOCs discussed in section 1.2 have various limitations such as

1. Some can produce only multi-DC outputs and cannot produce AC output.
2. Some MOCs are unable to perform the buck-boost operation.
3. Some of them can produce both AC and DC having single DC or multiple DC with one AC output and cannot supply multiple AC outputs.
4. Some hybrid converters use more number stages to get multiple outputs.
5. The existing hybrid MOCs are having only one AC output, that is single-phase and thus, they are suitable only for low power applications.
6. Some of them have the problem of misgating and electromagnetic interference (EMI).
7. Some hybrid converters have more passive components.
8. Their weight, volume and cost is more,
9. They have lower power density.
10. Some of them can perform the buck-boost operation and can produce AC and DC; however, they have low efficiency.
11. Some MOCs have discontinuous input current, which requires an input filter.
12. No MOC provides multi three-phase outputs and thus, they are not suitable for high power applications.

1.4 Objective of the Thesis

The main purpose of this thesis is to design and build a proof concept for a hybrid multi-output converter for the application of a hybrid microgrid. The design of the quasi-Z-source network, DC network, AC network, constant frequency shoot-through (CFST) hybrid PWM signal (HPWM) based on the simple boost control (SBC) and digital signal processor (DSP) are all part of the multi-outputs system implementation. The scope of this study is limited to the topology's design and implementation.

To overcome the problem associated with conventional multi-output converters and satisfy the desired characteristics of the multi-output converter, various multi-output converters with multiple AC and DC outputs are proposed in this thesis. The proposed converters are suitable for various DC-DC and DC-AC power conversion in a single stage with the buck-boost operation for the application of microgrids. The overall contribution of the thesis are summarised as follows:

1. The first proposed converters are a single-phase series-parallel converters with multiple regulated AC output. The proposed converters can supply multiple regulated AC outputs simultaneously. It has two modes i.e. series and parallel. It is capable of supplying multiple AC outputs with constant voltage and variable current during parallel mode operation and vice-versa in series mode. Since it is a single-stage power conversion converter, hence it has a higher power density with reduced passive component counts. It can supply more than one load demand at a time using its multiple output features. It can be used for homes, single-phase motors up to 5 horsepower and businesses simultaneously. The proposed converters are simulated for two single-phase inverter units. The detailed steady-state analysis, mathematical modelling and simulation results are presented to validate the proposed concept.
2. The second proposed converter is a three-phase quasi-Z-source inverter with regulated multiple AC outputs for microgrid and three-phase residential load application. It is developed by replacing the main switch of the quasi-Z-source inverter with *n* number of series parallel connected three-phase inverters. It can supply *n* number of three-phase AC outputs simultaneously. The suggested inverters inherit advantages such as inherent shoot-through protection and buck-boost output capability because they are based on impedance source inverters. These inverters' output power can be supplied into the microgrid three-phase residential loads and industry simultaneously. To bring out the

features of the suggested inverters, detailed mathematical modelling, steady-state and dynamic evaluations are carried out.

3. To supply *n* number AC along with single DC outputs simultaneously, a third converter with title single-phase series-parallel converters with multiple AC and single DC outputs are presented. The proposed converters are formed by connecting *n* number of single-phase inverters in series and parallel mode to the main switch of the single-phase quasi-Z source inverter. Since it is derived from a quasi-Z source inverter, therefore, it inherits all the properties of the quasi-Z source inverters. Its outputs can be used for the domestic and home appliances simultaneously without using any extra adopter or regulator. The proposed converter can fulfill two AC and single DC load demand at a time. It can operate with different voltages and frequencies (50 and 60 Hz). It can perform buck-boost operations.
4. The fourth converter with *n* number regulated three-phase AC outputs along with single DC output with buck-boost capability for the application of modern futuristic houses, three-phase residential load, and microgrid are presented. It can supply two three-phase regulated AC along with one DC output simultaneously for the application of microgrid and DC power distribution. A single-stage power conversion converter results in less weight, volume and cost. Since it is a single-stage converter, it uses a lesser number of passive components. Being a single-stage converter, it has a compact size and hence higher power density. In the parallel mode converters, the DC output voltage 380 V has been used in DC datacentres. This is relatively high voltage and hence highly effective grounding and protection are required. Similarly, in series mode converters the DC, output voltage 325 V is equal to the peak of the AC phase voltage.

1.5 Organization of the Thesis

- Chapter 1 discusses about the AC, DC and hybrid microgrid, structure of the microgrid, advantage and disadvantages of renewable energy based microgird, need of multi-output converter in microgrid, detailed review of multi-output converter, desires characteristics of the multi output converter and contribution of the thesis.
- The quasi-Z-source series-parallel multi-output inverters are discussed in detail in Chapter 2. It includes a full description of operation, AC power expression, passive component stresses, component design, control method, and simulation results.
- Chapter 3 introduces quasi-Z-source series-parallel multi-outputs inverters topologies for three-phase microgrid applications. A detailed modelling, mathematical analysis, controller design, pulse width modulation (PWM) technique and experimental results with efficiency are presented in this chapter.
- Chapter 4 proposes a diode assisted switched LC quasi-Z-source series-parallel hybrid converter with multi AC and single DC outputs. Design of passive components, DC and AC network, mathematical modelling, AC and DC power expression, control technique and simulation results with different voltages and frequencies has been presented in this chapter.
- Chapter 5 suggests three-phase multi AC quasi-Z-source series-parallel hybrid converter topologies for microgrid application. The operation, steady-state analysis, mathematical modelling, AC and DC power expression, control logic, controller design, hybrid PWM technique, steady-state and dynamic hardware results with efficiency and power loss analysis of the proposed topologies has been elaborated in this chapter.
- Chapter 6 summarises the main point of the thesis and suggests some point for future work.