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This is to certify that the thesis entitled ***"Switched Impedance Source Based Series Parallel Topologies with Multiple AC and Single DC Outputs"*** which is being submitted by ***"Shri Prakash Sonkar"*** has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

It is further certified that the student has fulfilled all the requirements of Comprehensive Examination, Candidacy and SOTA for the award of Ph.D. Degree.

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I, ***Shri Prakash Sonkar***, certify that the work embodied in this thesis is my own bonafide work and carried out by me under the supervision of ***"Dr. Vivek Nandan Lal"*** and ***"Dr. Rajeev Kumar Singh"*** at the ***"Department of Electrical Engineering"*** Indian Institute of Technology (BHU), Varanasi. The matter embodied in this thesis has not been submitted for the award of any other degree/diploma. I declare that I have faithfully acknowledged and given credits to the research workers wherever their works have been cited in my work in this thesis. I further declare that I have not willfully copied any other's work, paragraphs, text, data, results, etc., reported in journals, books, magazines, reports dissertation, thesis, etc., or available at websites and have not included them in this thesis and have not cited as my own work.

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DEDICATION AND ACKNOWLEDGMENT

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(Shri Prakash Sonkar)

Dedicated to my parents and wife Sadhana.

ABSTRACT

In the last few decades, the energy demand of an exploding population and a growing global economy has skyrocketed. Therefore, conventional and non-conventional energy resources are used to fulfil the increased energy demand. Conventional energy resources or fossil fuels include coal, oil, gas and nuclear energy and these are the basic source of electricity. The national electric grid in India has a total installed capacity of 384.12 GW out of 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%) by non-renewable energy resources. Due to the good availability of coal in India, the major portion of non-renewable energy (62.7%) is contributed 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 (RESs), which are freely available.

Therefore, using renewable energy resources (RESs), the above-mentioned problem can be easily coped up. The RESs include sunlight, wind, rain, tides and geothermal. Due to more contribution of power, less installation and low cost, and pollution-free, solar PV is best suited for residential and commercial AC power distribution. However, it is unable to match the required DC/DC or DC/AC outputs bus voltage alone. It is also unable to fulfill the load demand by the distribution systems as they have low voltage at the output. Therefore, to match and fulfill the demands an intermediate converter is needed which can operate at a higher duty cycle. However, operating the converter at a higher duty cycle will lead to poor performance

due to more losses. The other option to achieve the high gain or desired voltage is to increase the number of stages of the converter. This will reduce stresses on the components and improve the performance of the converters however, due to more number of stages, efficiency will reduce and result in lower power density. To get multiple outputs various converters are needed, which results in more weight, volume and cost. This will also lead to lower power density and more losses consequently the decreased overall efficiency.

The z source inverter (ZSI) has the capability to boost the voltage and perform the operation of DC-AC power conversion in a single stage. However, it has a discontinuous input current, which requires an input filter. Using input filter results in lower power density, more weight, volume and cost which make the system more bulky and costly.

Therefore, to overcome the above disadvantages multi-output converters (MOCs) are have become potential options due to the following advantages:

1. A multi-output converter should have a continuous input current so that the requirement of an input filter can be eliminated.
2. The number of passive components should be less.
3. A multi-output converter should be a single-stage converter.
4. Similar to quasi Z source inverters, MOCs should have a good EMI noise immunity.
5. Because renewable energy sources such as solar PV provide less voltage, the converter should have a strong boost inversion capability.
6. For good reliability, MOCs should have inherent shoot-through protection capability and higher power density.
7. MOCs should be capable of buck-boost operations.
8. To avoid losses, total harmonic distortion and achieve high voltage gain in MOCs, converters should not operate at an extreme shoot-through duty cycle.

9. 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.

The series parallel converters proposed in the thesis have all the properties of multi output converters. They are capable of providing multiple regulated AC and single DC outputs simultaneously. There are four types of the series-parallel converters with multiple outputs, which is given as follows:

(2) Single-phase series-parallel converters with regulated multiple AC outputs.

(3) Three-phase quasi-Z source inverters with regulated multiple AC outputs for the application of microgrids and three-phase residential loads.

(4) Single-phase series-parallel converters with regulated multiple AC and single DC outputs.

(5) Diode-assisted switched LC qZSI network-based multi-output series-parallel topologies for microgrid applications.

The design and implementation of the above-proposed converters and their application are presented 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.

In general, the overall contribution of the thesis is summarised as follows:

1. The first proposed converter is a single-phase series-parallel converter with multiple regulated AC output. The proposed converter can supply multiple regulated AC outputs simultaneously. It has two variants, i.e., series and parallel. It is capable of supplying multiple AC outputs with constant voltage and variable current with parallel version of the proposed converter. Similarly, series version is capable of supplying multiple AC

outputs with constant current and variable voltage. 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. The proposed converters are verified for two single-phase inverter units. The detailed steady-state analysis, mathematical modelling and simulation 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, misgating of switches and buck-boost output capability because they are based on quasi 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 of 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 demands at a time. It can operate with different voltages and frequencies (50 and 60

Hz). The detailed steady-state analysis, mathematical modelling and simulation are presented to validate the proposed converters.

4. The fourth converter with *n* number regulated three-phase AC along with single DC outputs 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 outputs 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 converters, the DC output voltage 380 V has been used. This is relatively high voltage and hence highly effective grounding and protection are required. Similarly, in series mode converters the DC output voltage is 325 V which is equal to the peak of the AC phase voltage. The dc-link voltage of standard single-phase power supply with diode bridge input is 325 V. As a result, existing supplies will work with this dc voltage level. Hybrid pulse width modulation (PWM) with the constant frequency shoot-through technique is used to control the proposed topologies. The PWM signals are generated by a 32 bit TMS320F28335 DSP operating with a clock frequency of 150 MHz. All the converters are simulated using MATLAB 2017b software. The hardware system consists of an impedance network, DC network, two three-phase inverters, LC filter and a DSP kit. The three-phase AC outputs are loaded with six 20 Ω loads in a Y- connection and DC output is loaded with a 100 Ω. Finally, 2.18 kW and 2.02 kW prototypes for parallel and series versions are developed in the laboratory to validate the performance for two AC and one DC outputs. The measured efficiency of the parallel and series version of the proposed topology is 90.01% and 89.95% respectively.

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Nomenclature

Symbols	Definition
AC	Alternating current
DC	Direct current
HMGS	Hybrid microgrid systems
MOCs	Multi output converters
qZSI	Quasi-Z-source inverter
VSI	Voltage source inverter
EMI	Electromagnetic interference
PWM	Sinusoidal Pulse width modulation
ST	Shoot-through
NST	Non shoot-through
PV	Photo voltaic
M, m	Modulation index
D, D_{st}, d	Shoot-through duty cycle
G, G_{AC}	AC gain
G_{DC}	DC gain
L	Inductor
C	Capacitor
L_f	Filter inductor
C_f	Filter capacitor
f_{SW}	Switching frequency
Hz	Frequency
V_{PN}, V_{pn}	Switch node, DC-link voltage
V_{in}	Input voltage
I_{in}, i_{in}	Input current
I_{PN}, i_{pn}	Switch node current