

# Contents

<b>Abstract</b>	xiii
<b>List of Tables</b>	xix
<b>List of Figures</b>	xxi
<b>Nomenclature</b>	xxvii
<b>1 Introduction</b>	1
1.1 Motivation . . . . .	1
1.2 Solar Power Generation . . . . .	4
1.3 Wind Energy Conversion System . . . . .	6
1.4 Hybrid Energy Conversion System . . . . .	8
1.5 Literature Review . . . . .	9
1.5.1 Converters for photovoltaic generation systems . . . . .	9
1.5.2 Converters for three-phase AC to DC and WECS . . . . .	13
1.6 Organization of the Thesis . . . . .	15
<b>2 A High Gain Boost Converter for Solar Power Generation</b>	19
2.1 Introduction . . . . .	19
2.2 Circuit Description and Converter Operation . . . . .	21
2.2.1 Mode-1 . . . . .	21
2.2.2 Mode-2 . . . . .	21
2.2.3 Mode-3 . . . . .	21
2.2.4 Mode-4 . . . . .	22
2.2.5 Mode-5 . . . . .	22
2.2.6 Mode-6 . . . . .	22

2.3	Converter Design . . . . .	26
2.4	Results and Discussion . . . . .	29
2.5	Summary . . . . .	36
<b>3</b>	<b>A Quadratic Boost Converter with Ripple-Free Input Current for PV Application</b>	<b>37</b>
3.1	Introduction . . . . .	37
3.2	Circuit Description and Converter Operation . . . . .	38
3.2.1	Mode-1 . . . . .	39
3.2.2	Mode-2 . . . . .	39
3.2.3	Mode-3 . . . . .	40
3.2.4	Mode-4 . . . . .	40
3.3	Converter Design and Small Signal Analysis . . . . .	43
3.3.1	Selection of duty D . . . . .	43
3.3.2	Selection of inductors . . . . .	43
3.3.3	selection of capacitors . . . . .	44
3.3.4	Small signal analysis . . . . .	45
3.4	Results and Discussion . . . . .	47
3.5	Summary . . . . .	55
<b>4</b>	<b>A New Three-Phase AC-DC Single-Stage WECS</b>	<b>57</b>
4.1	Introduction . . . . .	57
4.2	Three-Phase Bridgeless Cuk Converter . . . . .	58
4.2.1	Circuit description . . . . .	58
4.2.2	Circuit operation . . . . .	59
4.2.3	Converter design . . . . .	62
4.2.4	Converter analysis . . . . .	64
4.3	Wind Turbine Emulation . . . . .	66
4.3.1	MPPT and control . . . . .	66
4.4	Simulation and Discussion . . . . .	67
4.5	Hardware Results and Discussion . . . . .	73
4.6	Summary . . . . .	77

<b>5 Single-Stage Integration of PMSG Based WECS in DC Microgrid</b>	<b>79</b>
5.1 Introduction . . . . .	79
5.2 Bridgeless Cuk Converter . . . . .	81
5.2.1 Circuit description . . . . .	81
5.2.2 Converter operation . . . . .	81
5.2.3 Small signal analysis . . . . .	84
5.3 WECS Description and Converter Design . . . . .	86
5.3.1 MOD-2 turbine model . . . . .	86
5.3.2 SCIM control . . . . .	87
5.3.3 Converter design . . . . .	89
5.3.4 MPPT and system description . . . . .	90
5.4 Simulation Results . . . . .	92
5.5 Hardware Results . . . . .	96
5.6 Summary . . . . .	102
<b>6 Development of a Photovoltaic-Wind Hybrid Energy Conversion System</b>	<b>103</b>
6.1 Introduction . . . . .	103
6.2 HECS Feeding a DC Microgrid with BESS . . . . .	104
6.2.1 PV generation . . . . .	104
6.2.2 Wind energy conversion system . . . . .	106
6.2.3 DC microgrid control with BESS . . . . .	108
6.3 HECS Feeding DC Microgrid with Single-Phase AC Grid . . . . .	109
6.4 Summary . . . . .	114
<b>7 Conclusion and Future Scope</b>	<b>115</b>
7.1 Conclusion . . . . .	115
7.2 Future Scope . . . . .	116
<b>A List of Publications</b>	<b>117</b>
A.1 Published: . . . . .	117
A.2 Revision Submitted: . . . . .	117



# List of Tables

1.1	COMPARISON BETWEEN DIFFERENT INTERLEAVED CONVERTERS	12
2.1	DESIGN PARAMETERS	28
2.2	REACTIVE COMPONENTS	28
2.3	DEVICE SPECIFICATIONS	29
3.1	DESIGN PARAMETERS	44
3.2	REACTIVE COMPONENTS	44
3.3	DEVICE SPECIFICATIONS	47
3.4	COMPARISON WITH CONVENTIONAL CONVERTERS	51
4.1	DESIGN PARAMETERS	62
4.2	DESIGNED CONVERTER PARAMETERS	64
4.3	TURBINE PARAMETERS	67
4.4	COMPONENT SPECIFICATION	74
5.1	PMSG PARAMETERS	87
5.2	WIND TURBINE PARAMETERS	87
5.3	MOTOR PARAMETERS	89
5.4	DESIGN PARAMETERS	90
5.5	CONVERTER PARAMETERS	92
5.6	COMPONENT DESCRIPTION	97
5.7	SYSTEM PERFORMANCE	101



# List of Figures

1.1	Projection of energy consumption based on source type. . . . .	2
1.2	Typical daily distribution of solar, wind and hybrid power generation. . . . .	3
1.3	Typical annual distribution of solar, wind and hybrid power generation. . . . .	3
1.4	The derivation of the I-V characteristics of PV cell . . . . .	4
1.5	MPP oscillation owing to ripple in the output current of the solar panel . .	5
1.6	Schematic diagram of a PMSG based WECS. . . . .	7
1.7	Typical WECS with front-end DBR . . . . .	7
1.8	The topography of DC microgrid with hybrid sources . . . . .	8
1.9	Topology of a ultra-high voltage gain converter [5]. . . . .	10
1.10	Topology of the Z-converter based high gain converter [6] . . . . .	11
1.11	Topologies of recently proposed high gain DC-DC converters (a)- [2], (b)- [1], (c)- [3], (d)- [4] . . . . .	11
1.12	Topology of a input-current-ripple elimination converter [7]. . . . .	13
1.13	Proposed converter in [8] for WECS. . . . .	14
1.14	Topology of converter presented in [9] for WECS. . . . .	15
2.1	(a)-Topology of the proposed converter. (b)-Two-phase interleaved con- verter topology. . . . .	20
2.2	Graphical depiction of different modes of operation of the converter. . . . .	23
2.3	Key waveform of proposed converter. . . . .	24
2.4	Simulated results showing the voltage stresses across switches and output voltage at 120 V input voltage and 50 % duty cycle. . . . .	29
2.5	Simulated voltage stress of diodes $D_1$ and $D_{11}$ with voltage across capacitor $C_1$ and $C_o$ at 120 V input voltage and 50 % duty cycle. . . . .	30
2.6	Simulated inductor currents of both the phases. . . . .	30

2.7	Experimental setup. . . . .	31
2.8	Voltage stresses across switches. . . . .	32
2.9	Voltage stresses across diodes. . . . .	32
2.10	Output voltage (channel-1), input voltage (channel-2), current in $L_1$ (channel-3), current in $L_2$ (channel-4), input current (channel-MATH). . . . .	33
2.11	Output voltage, input voltage, and current in coupled inductors. . . . .	33
2.12	Maximum power point tracking (INC MPPT) –output voltage (channel-1), input voltage (channel-2), voltage across $C_1$ (channel-3), input current (channel-4). . . . .	34
2.13	MPPT performance of the proposed system. . . . .	35
2.14	Converter efficiency at different input voltage and output power. . . . .	36
3.1	Topology of the proposed converter . . . . .	38
3.2	Interleaved topology of the proposed converter . . . . .	39
3.3	Different modes of converter operation. . . . .	41
3.4	Key waveforms of proposed converter. . . . .	41
3.5	Converter parameters for small signal analysis. . . . .	46
3.6	Simulated results showing the input inductor currents with voltage stresses on the switches $Q_1$ & $Q_{11}$ . . . . .	48
3.7	Simulated voltage stress on diodes $D_1$ & $D_{11}$ with inductor currents of $L_1$ & $L_{11}$ . . . . .	48
3.8	Simulated inductor currents of $L_1$ & $L_2$ with input and output voltages. . . . .	49
3.9	Simulation result showing voltage stresses on switches and relation between output DC microgrid voltage and voltage of capacitor $C_1$ . . . . .	49
3.10	Experimental setup. . . . .	50
3.11	Inductor current of $L_1$ , $L_2$ , capacitor voltage, output voltage. . . . .	50
3.12	Voltage stress on $Q_1$ , $Q_{11}$ , inductor currents of $L_1$ and $L_{11}$ . . . . .	51
3.13	Input source current, current of inductor $L_1$ , $L_2$ , output voltage. . . . .	52
3.14	Voltage stress on switch $Q_2$ , $Q_{22}$ , current of inductor $L_2$ , $L_{22}$ . . . . .	52
3.15	Voltage stress on diode $D_1$ on channel-1, voltage stress on diodes $D_2$ on channel-2, input voltage on channel-3, output voltage on channel-4. . . . .	53

3.16	Transient response of the converter states; input voltage on channel-1, input current on channel-2, capacitor voltage on channel-3, output voltage on channel-4. . . . .	53
3.17	MPPT response. . . . .	54
3.18	Efficiency curve with output power and input voltage. . . . .	54
4.1	Circuit topology of the proposed converter . . . . .	58
4.2	Current directions with switches in 'ON' state(Mode-1) . . . . .	59
4.3	Current directions with switches in 'OFF' state and input inductors energized (Mode-2) . . . . .	60
4.4	Current directions with Switches in 'OFF' state with input inductors de-energized (Mode-3) . . . . .	60
4.5	Key waveforms of the proposed converter . . . . .	61
4.6	The schematic diagram of wind energy emulation and conversion system .	64
4.7	Flowchart of MPPT technique . . . . .	68
4.8	Input current and voltage waveform . . . . .	69
4.9	Voltage and current waveform from source . . . . .	69
4.10	Calculated voltage and current maxima . . . . .	70
4.11	Current waveform of input and output inductors . . . . .	70
4.12	MPPT characteristics . . . . .	71
4.13	Wind turbine emulator response . . . . .	72
4.14	Experimental setup . . . . .	73
4.15	Input inductor current waveform ( $I_{peak}=15$ A). Current in R phase(channel-3 at 5 A/div), Y phase(channel-1 at 5 A/div), B phase(channel-2 at 5 A/div)	74
4.16	Current waveforms at 10 percent duty, current in R phase (channel-3 at 2A/div), Y phase (channel-1 at 2 A/div), B phase (channel-2 at 2A/div) and output voltage on channel 4 at 20 V/div . . . . .	75
4.17	Voltage of R phase (channel-3 at 50 V/div) and input current (channel-2 10 A/div) and output voltage of the converter (channel-1 at 20 V/div) . .	75
4.18	Generator voltage (channel-1 at 50 V/div) and current (channel-2 at 2 A/div) with output voltage of converter (channel-4 at 20 V/div) . . . . .	76
4.19	Transient filter voltage (channel-1 at 50 V/div) and current (channel-2 at 500 mA/div) waveforms and output voltage(channel-4 at 20 V/div) . . . . .	76

4.20 SEIG voltage buildup (channel-1 at 50 V/div), generator current(channel-2 at 2 A/div), speed of SEIG(channel-3 at 200 RPM/div) and output voltage(channel-4 at 100 V/div) . . . . .	77
5.1 Topology of the bridgeless cuk converter. . . . .	80
5.2 Mode-1 of converter operation. . . . .	82
5.3 Mode-2 of converter operation. . . . .	82
5.4 Mode-3 of converter operation. . . . .	82
5.5 Key waveforms of converter operation. . . . .	83
5.6 Equivalent circuit for small signal analysis. . . . .	84
5.7 The schematic diagram of wind energy emulation and conversion system. .	88
5.8 System description for wind turbine emulation. . . . .	91
5.9 Voltage across switches and input current. . . . .	93
5.10 Input current, output current and capacitor voltages. . . . .	94
5.11 Voltage stress across diode and switch of phase R. . . . .	94
5.12 Input current, output currents and capacitor voltage of phase R. . . . .	95
5.13 Comparative efficiency plot of proposed converter with DBR and conventional converter. . . . .	95
5.14 Laboratory setup. . . . .	96
5.15 Voltage of DC microgrid (channel-1) and three-phase input current (channel-2,3,4). . . . .	98
5.16 Voltage of DC microgrid (channel-1), three-phase output inductor currents (channel-2,3,4). . . . .	98
5.17 DC microgrid voltage (channel-1), input inductor current of phase-R (channel-2), output inductor current of phase-R (channal-3), voltage stress on switch of phase R (channel-4). . . . .	99
5.18 Zoomed view of the output inductor current (channel-2), input inductor current (channel-3), and voltage stress on switch (channel-4), DC microgrid (channel-1). . . . .	99
5.19 Zoomed view of the output inductor current (channel-2), input inductor current (channel-3), and voltage stress on diode (channel-4), DC microgrid (channel-1). . . . .	100

5.20	Voltage of microgrid (channel-1), output inductor current (channel-2), input inductor current (channel-3), capacitor voltage (channel-4). . . . .	102
6.1	Schematic of the system with battery. . . . .	104
6.2	Topology of the quadratic gain bi-directional converter. . . . .	105
6.3	PV output with change in irradiance from (800 to 1000 W/m <sup>2</sup> ) voltage and current. . . . .	105
6.4	Performance of wind turbine emulator and TSR following MPPT. . . . .	106
6.5	PMSG characteristics and the input current of the AC to DC converter. . .	107
6.6	The battery states and formation control of the DC microgrid . . . . .	108
6.7	Schematic of the system with grid. . . . .	109
6.8	Schematics of the control logic of the single-phase inverter. . . . .	110
6.9	Control technique for grid connection and current control. . . . .	110
6.10	The following of the d-axis current with solar irradaince change at t= 0.5 s and wind speed change at t=0.9 s. . . . .	112
6.11	Tracking of the grid voltage and change in the grid current. . . . .	113
6.12	DC microgrid voltage regulation. . . . .	113