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Synopsis Of

Design and Analysis of High Gain Non-Isolated DC-DC Power Converter Topologies

A Thesis

To be submitted by

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For the award of the degree

Of

DOCTOR OF PHILOSOPHY

1 Abstract

The energy demand of the world is booming, and contrary fossil fuels are depleting at a fast rate. This trend could not only lead to an energy crisis but has become a serious threat to the environment. Therefore, alternative energy resources such as photovoltaic, wind energy, and fuel cell (FC) are sustainable sources of clean and green energy for the present and future generations. To match the grid utilities from renewable sources and the required voltage of propulsion motor in fuel cell electric vehicles (FCEV), it is inexpedient to connect the photovoltaic or fuel cells in a series and parallel fashion. Henceforth, a power electronic interface (PEI) with a wide voltage conversion ratio becomes a promising solution for the aforementioned aspects. This thesis proposes and studies several boost and buck-boost converter topologies as PEI for applications like solar micro-inverter, solar power optimizers, and FCEV. The proposed converter topologies are synthesized based on a quadratic boost converter (QBC). Furthermore, the operating principle and the steady-state analysis of these proposed converter topologies in the continuous conduction mode (CCM) are discussed. In addition to the CCM analysis, a detailed discontinuous conduction mode (DCM) analysis due to the inductors is presented. Furthermore, laboratory-scaled prototypes of the proposed converter topologies are fabricated and tested to validate the theoretical analysis in CCM.

2 Objectives

Owing to the decarbonization, renewable energy finds an astounding significance and diminishes the consumption of hazardous fossil fuels Murdock *et al.* (2020). To match the grid utilities from renewable sources, it is inexpedient to connect the photovoltaic or fuel cells in a series and parallel fashion Zeng *et al.* (2020). Henceforth, the step-up dc-dc converters and captivating renewables conjunctively meet the load demand in many low power applications Qin *et al.* (2021). For the requirement of voltage gain, the conventional boost converter is broadly adopted than the buck and buck-boost converter. However, a conventional boost converter results in only ten times of voltage gain at an extreme duty ratio which is not possible practically. Based on the literature made, the research objectives related to this thesis are framed as follows:

(a) To propose a QBC with less input ripple current and rear-end capacitor voltage stress for renewable applications.

(b) To propose a set of high gain QBCs with an increase in voltage gain and reduced voltage stress across the switch.

(c) To propose a high gain continuous input current single switch buck-boost converter with reduced voltage stress and inverting output voltage.

(d) To propose a high gain continuous input current single switch buck-boost converter with reduced voltage stress and non-inverting output voltage.

(e) To develop the prototype of the proposed converters for corroborating the CCM analysis.

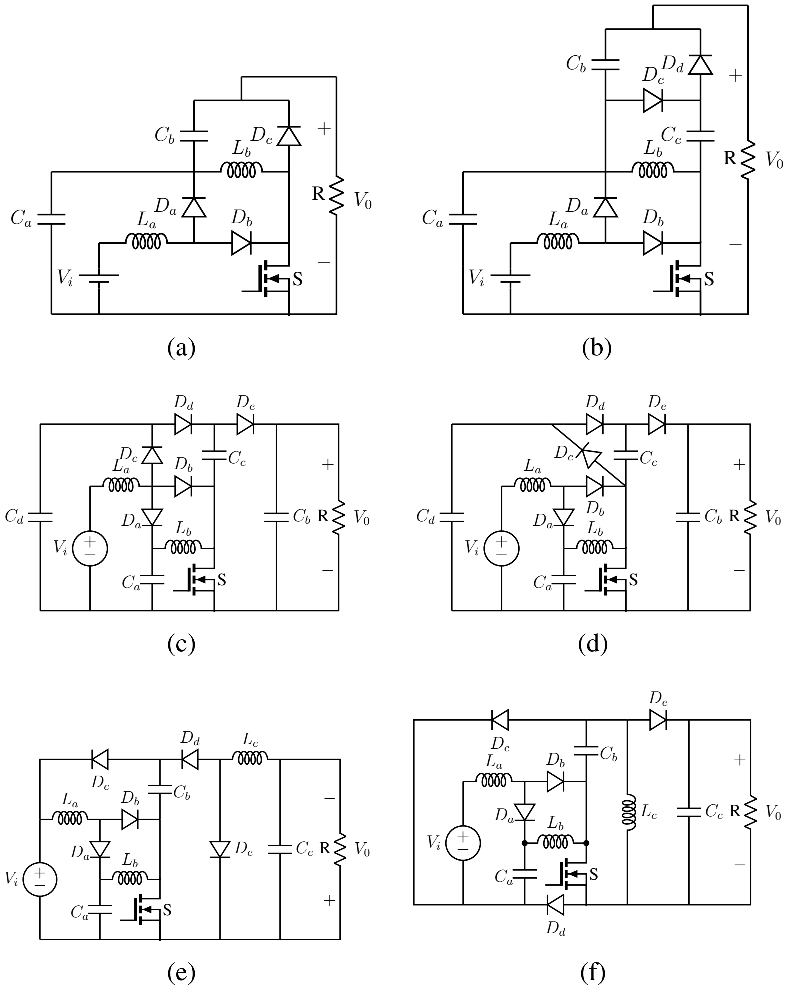


Figure 1: Proposed converters: (a) Topology-I, (b) Topology-II, (c) Topology-III, (d) Topology-IV, (e) Topology-V, (f) Topology-VI.

3 Existing Gaps Which Were Bridged

Based on the literature survey made, the following gaps are identified and bridged in this thesis:

(a) Many renewable applications require a step-up converter as a PEC to meet the DC link standards. The QBC serves as a step-up converter over the conventional boost converter due to its better voltage conversion ratio. Further, to increase the voltage gain, many QBC-based step-up converters were proposed. This thesis proposes a QBC with less input current ripple and read end capacitor voltage stress and encourages researchers to propose new converter topologies based on the proposed QBC with better features. In addition, a set of high gain step-up dc-dc converters were synthesized using QBC and a set of passive components.

(b) With the importance of the quality of continuous input current (CIC) in photovoltaic applications, several buck-boost converters were proposed in the literature. However, these converters failed to provide a wide voltage conversion ratio with required features such as CIC and minimum switch count. Hence, this thesis proposes two buck-boost converter topologies based on QBC with features like better voltage gain, a single active switch, and inverting or non-inverting output voltages.

4 Most Important Contributions

4.1 QBC With Less Input Current Ripple and Rear End Capacitor Voltage Stress

The primary contributions of this chapter are as follows:

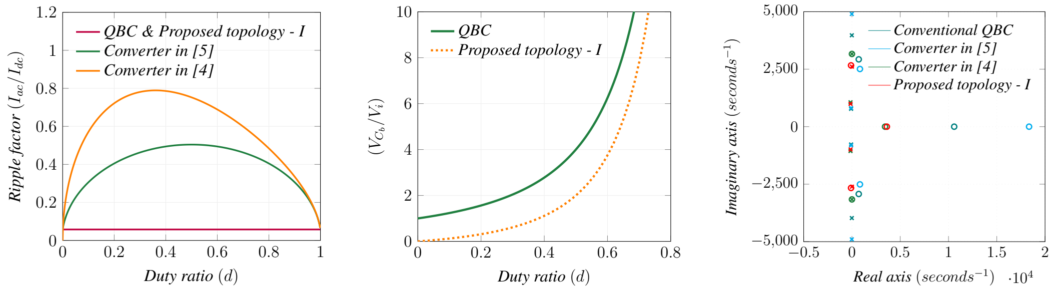
(a) A QBC with low rear end capacitor voltage stress is proposed shown in Fig. 1(a) for renewable energy applications.

(b) The proposed converter provides less ripple continuous input current in comparison with its contemporary converters in Ye and Cheng (2013) and Valdez-Resendiz *et al.* (2018) which helps to utilize a reduced size input filter capacitor.

(c) A detailed comparison analysis has been carried out with its contemporary converters in terms of ripple factor, voltage stress, efficiency, pole-zero map, and bode plot.

(d) The steady-state analysis of the proposed converter in CCM, BCM and DCMs with respect to both inductors is discussed in detail and final expressions are presented in Table 1 and Table 2.

(e) A laboratory prototype shown in Fig. 3 is developed to validate the performance of the proposed converter under steady-state conditions.



(a)	(b)	(c)

Figure 2: Comparison of converters. (a) Ripple factor vs duty ratio. (b) Rear end capacitor voltage stress. (c) Pole-Zero map comparison of the converters.

The distiction of proposed topology-I in Fig. 1(a) from its alike converters is discussed in terms of input port ripple current analysis, reduction in voltage stress across the capacitor and pole-zero map. Fig. 2(a) shows the graphical representation of variation in

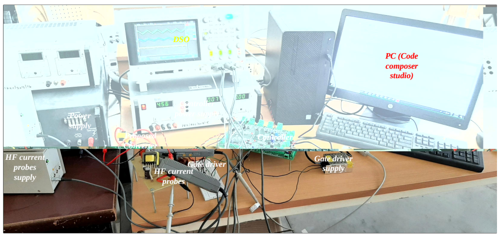


Figure 3: Hardware setup.

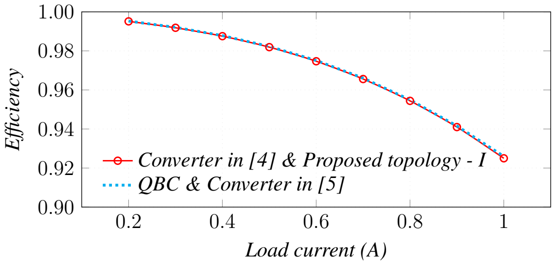
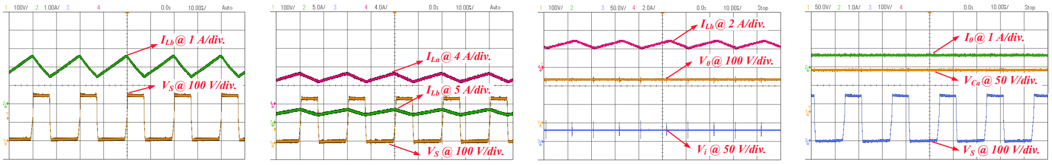


Figure 4: Efficiency comparison.

ripple factor along with the duty ratio for the converters. It can be noted that the converters in Ye and Cheng (2013) and Valdez-Resendiz *et al.* (2018) draws more ripple current as its ripple factor is high when compared with the QBC and proposed converter-I. Furhter, the proposed topology-I captivates with reduction of voltage across the capacitor C_b when compared with the conventional QBC and the converter presented in Ye and Cheng (2013) as shown in Fig. 2(b). From Fig. 2(c), it can observed that all three open-loop zeros of conventional QBC and converter in Ye and Cheng (2013) are located on the right half of the s-plane. However, the two of three open-loop zeros of the converter in Valdez-Resendiz *et al.* (2018) are shifted to the imaginary axis and in the case of the proposed converter, they are shifted towards the left half of the s-plane. Hence, the proposed converter and converter in Valdez-Resendiz *et al.* (2018) promises better stability while performing the closed-loop analysis with ease in controller design. Further, the proposed topology-I and its contemporary converters exhibit approximately similar efficiency with a small deviation as shown in Fig. 4. Finally, the steady state experimental waveforms of the proposed topology-I are shown in Fig. 5.



(a) (b) (c) (d)

Figure 5: Experimental waveforms. (a) I_{L_b} and V_S. (b) I_{L_a}, I_{L_b}, and V_S. (c) I_{L_b}, V_0, and V_i. (d) I_0, V_{C_a}, and V_S.

4.2 Single Switch High gain QBCs based on Voltage Lift Technique

The primary contributions of this chapter is encapsulated as following:

(a) A set of high gain quadratic boost converters shown in Fig. 1(b) - 1(d) are proposed as a power electronic interface for FCEV .

(b) A detailed theoretical analysis is carried out to study the steady-state operation of the proposed topology in CCM, BCM and DCMs and final expressions are presented in Table 1 and Table 2.

(c) The comparative performance analysis of the proposed converter is carried out with its alike converters with respect to the number of components, input current, common grounding, and effectiveness index.

(d) A detailed efficiency evaluation of the proposed converter is discussed.

(e) The performance of the proposed converter topology is validated with a hardware prototype.

Table 1: Summary of voltage gains.

Voltage Gain	Proposed topology-I	Proposed topology-II	Proposed topology-V	Proposed topology-VI
P_{CCM}	$\frac{1}{(1-d)^2}$	$\frac{(2-d)}{(1-d)^2}$	$\frac{d^2\,(2-d)}{(1-d)^2}$	$\frac{d}{(1-d)^3}$
P_{DCML_a}	$\frac{A_1}{2\,(1-d)}$	$\frac{(2-d)\,A_2}{2\,(1-d)}$	$\frac{d^2 A_3}{2\,(1-d)}$	$\frac{dA_4}{2\,(1-d)^2}$
P_{DCML_b}	$\frac{B_1}{2\,(1-d)}$	$\frac{B_2}{(1-d)}$	$\frac{d^2 B_3}{2\,(1-d)}$	$\frac{dB_4}{2\,(1-d)^2}$
P_{DCML_c}	-	-	-	$\frac{d}{(1-d)^2\,.\sqrt{K_c}}$

$$K_a = \frac{2L_a}{RT},\ A_1 = \left(1 + \sqrt{1 + \frac{4d^2(1-d)^2}{K_a}}\right),\ A_2 = \left(1 + \sqrt{1 + \frac{4d^2(1-d)^2}{K_a\,(2-d)^2}}\right),$$

$$A_3 = \left(1 + \sqrt{1 + \frac{4(1-d)^2}{K_a d^2}}\right),\ A_4 = \left(1 + \sqrt{1 + \frac{4(1-d)^4}{K_a}}\right),\ K_b = \frac{2L_b}{RT},$$

$$B_1 = \left(1 + \sqrt{1 + \frac{4d^2}{K_b}}\right),\ B_2 = \left(1 + \sqrt{1 + \frac{d^2}{K_b}}\right),\ B_3 = \left(1 + \sqrt{1 + \frac{4}{K_b}}\right),$$

$$B_4 = \left(1 + \sqrt{1 + \frac{4(1-d)^2}{K_b}}\right),\ \text{and}\ K_c = \frac{2L_c}{RT}.$$

4.3 Design and Analysis of High Gain Buck-Boost Converter Topology With Reduced Voltage Stress

The primary contributions of this chapter are summarized as follows:

(a) A non-isolated single switch high gain quadratic buck-boost converter shown in Fig. 1(e) is proposed with higher voltage gain over traditional quadratic buck-boost converter, reduced voltage stress across power switch and with the provision of continuous input and output currents.

(b) The operating principle and the steady-state analysis of the proposed converter topology in both CCM and DCMs are discussed and final expressions are presented in Table 1 and Table 2.

(c) A detailed efficiency evaluation of the proposed converter is discussed.

(d) The performance of the proposed converter topology is validated with simulation studies.

Table 2: Summary of condition for the boundary between CCM and DCMs.

Boundary condition	Proposed topology-I	Proposed topology-II	Proposed topology-V	Proposed topology-VI
$K_{a_{critical}}$	$d\,(1-d)^4$	$\frac{d\,(1-d)^4}{(2-d)^2}$	$\frac{(1-d)^4}{d^2\,(2-d)}$	$\frac{(1-d)^6}{d}$
$K_{b_{critical}}$	$d\,(1-d)^2$	$\frac{d\,(1-d)^2}{(2-d)}$	$\frac{(1-d)^2}{(2-d)}$	$\frac{(1-d)^4}{d}$
$K_{c_{critical}}$	-	–	–	$(1-d)^2$

4.4 A Single Switch Continuous Input Current Buck-Boost Converter With Non-Inverted Output Voltage

The predominant contributions of this chapter are abbreviated as follows:

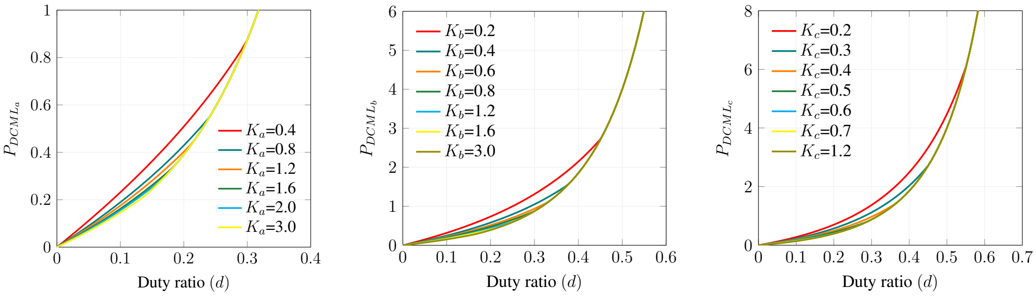
(a) A new single switch non-isolated buck-boost converter with non-inverted output voltage and wide voltage conversion ratio is presented and shown in Fig. 1(f).

(b) The steady-state analysis of the converter in both CCM and named DCM's are discussed in detail and presented with respective voltage conversion ratios in Table 1 and Table 2.

(c) A detailed comparative analysis is carried out among the proposed and its contemporary converters in voltage gain, voltage stress ratio, and effectiveness index aspects.

(d) A detailed efficiency evaluation of the proposed converter is presented.

(e) The prototype of the proposed buck-boost converter is fabricated and tested in the laboratory for both buck and boost modes of operation.



(a) (b) (c)

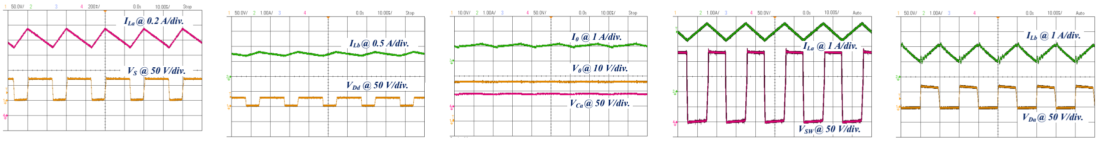
Figure 6: Voltage gains, (a) $DCML_a$. (b) $DCML_b$. (c) $DCML_c$.

A comprehensive comparative investigation of presented converters V and VI among other converters is facilitated in Table 3 to demonstrate its performance in CCM. The investigation consider various parameters like voltage gain, components count, voltage stress across switch, output voltage polarity, and input current nature. The proposed topology-V delivers better voltagin gain with reduced voltage stress across when compared with the converter in Zhang *et al.* (2017). The proposed topology-VI exhibits

Table 3: Comparison between proposed converter and other converters.

Converter in	Voltage gain	Component count					Switch voltage stress	O/P voltage polarity	CIC	d for $P_{CCM} = 1$
		S	L	C	D	T				
Banaei and Sani (2018)	$\frac{3d}{1-d}$	1	6	3	4	14	$\frac{V_0}{3d}$	Non-inverted	Yes	0.25
Zhang *et al.* (2017)	$\frac{d^2}{(1-d)^2}$	1	3	5	3	12	$\frac{V_0}{d^2}$	Inverted	Yes	0.5
Proposed topology -V	$\frac{d^2(2-d)}{(1-d)^2}$	1	3	5	3	12	$\frac{V_0}{d^2(2-d)}$	Inverted	Yes	0.445
Proposed topology -VI	$\frac{d}{(1-d)^3}$	1	3	5	3	12	$\frac{V_0}{d}$	Non-inverted	Yes	0.3178

S - Switches ; L - Inductors ; C - Capacitors ; D - Diodes ; T- Total number of components



(a) (b) (c) (d) (e)

Figure 7: Experimental results, Buck mode - (a) $I_{L_a}\&V_S$. (b) $I_{L_b}\&V_{D_d}$. (c) $I_0, V_0\&V_{C_a}$. Boost mode- (d) $I_{L_a}\&V_{SW}$. (e) $I_{L_b}, \&V_{D_a}$.

required non-inverted output voltage polarity with less component count when compared with the converters in Banaei and Sani (2018) and Zhang *et al.* (2017). Finally, the DCM voltage gains of the proposed topology-VI are presented graphically in Fig. 6 along with some key experimental resutls in Fig. 7.

5 Conclusions

This thesis proposes several single switch non-isolated DC-DC converter topologies for renewable applications. The proposed converter topologies are synthesized with the help of QBC and several passive elements. Further, these converter topologies exhibit the necessary features like CIC, wide voltage conversion ratio, utilization of a single power switch, and reduced voltage stress. The aforementioned features make the proposed converters as a suitable candidate for various renewable energy applications, such as PV, FCEV, and wind energy. Furthermore, the steady-state analysis of the proposed converters is carried out in both CCM and possible DCMs with appropriate voltage transfer ratios. In addition, a detailed comparative analysis is done among the proposed converters and their contemporary converters in voltage gain, voltage stress ratio, and effectiveness index aspects. From the comparison, it can be inferred that the proposed converters result in better voltage gain with optimum component count as well as lower voltage stress. Furthermore, the effectiveness index comparison confirms the prominence of the proposed converters over its contemporary converters. Further, the prototype of the proposed converters is fabricated to validate the theoretical analysis of CCM. From experimental analysis, it can be noted that the converter achieves the required voltage gain with the reduction in voltage stress and promises the validation of the converter theoretical analysis in CCM.

6 Organization of the Thesis

The proposed outline of the thesis is as follows:

(a) Chapter 1: Introduction.

(b) Chapter 2: Literature Review.

(c) Chapter 3: Quadratic Boost Converter with Less Input Current Ripple and Rear End Capacitor Voltage Stress.

(d) Chapter 4: Single Switch High gain Quadratic Boost Converters based on Voltage Lift Technique.

(e) Chapter 5: Design and Analysis of High Gain Buck-Boost Converter Topology with Reduced Voltage Stress.

(f) Chapter 6: A Single Switch Continuous Input Current Buck-Boost Converter With Non-Inverted Output Voltage.

(g) Chapter 7: Conclusion and Future Scope.

7 List of Publications

I. REFEREED JOURNALS BASED ON THE THESIS

1. Mukkapati Ashok Bhupathi Kumar and Vijayakumar Krishnasamy, "A Single Switch Continuous Input Current Buck-Boost Converter With Noninverted Output Voltage," *IEEE Transactions on Power Electronics*, vol. 38, no. 2, pp. 2181-2190, 2023, (IF: 5.967).
2. Mukkapati Ashok Bhupathi Kumar and Vijayakumar Krishnasamy, "Quadratic Boost Converter With Less Input Current Ripple and Rear-End Capacitor Voltage Stress for Renewable Energy Applications," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 10, no. 2, pp. 2265-2275, 2022, (IF: 5.462).
3. Mukkapati Ashok Bhupathi Kumar and Vijayakumar Krishnasamy, "Enhanced Quadratic Boost Converter Based on Voltage Lift Technique for Fuel Cell Vehicle," *Computers & Electrical Engineering*, vol. 102, pp. 108256, 2022, (IF: 4.512).
4. Mukkapati Ashok Bhupathi Kumar and Vijayakumar Krishnasamy, "A Single Switch High Gain Transformer-Less Quadratic Boost Converter with Reduced Voltage Stress," *IEEE Transactions on Vehicular Technology*, March 2023, (IF: 6.239, Under revision).

II. REFEREED JOURNALS (Others)

1. Mukkapati Ashok Bhupathi Kumar, Vijayakumar Krishnasamy, and Rajvir Kaur "Genetic algorithm assisted fixed frequency sliding mode controller for quadratic boost converter in fuel cell vehicle," *IET Electrical Systems in Transportation*, vol. 10, no. 1, pp. 81-88, 2020, (IF: 2.387).
2. Saurabh Kumar, Mukkapati Ashok Bhupathi Kumar, Vijayakumar Krishnasamy, Rajvir Kaur, and B. Chitti Babu "Improved control strategy for Cuk converter assisted wind-driven SEIG for DC nanogrid," *IET Electric Power Applications*, vol. 14, no. 10, pp. 1906-1917, 2020 (IF: 1.737).

III. PRESENTATIONS/PUBLICATIONS IN CONFERENCES BASED ON THE THESIS

1. Mukkapati Ashok Bhupathi Kumar and Vijayakumar Krishnasamy, "Analysis of Discontinuous Conduction Modes in the High Gain Buck-Boost Converter," *2021 National Power Electronics Conference (NPEC)*, pp. 1-6, (2021).
2. Mukkapati Ashok Bhupathi Kumar and Vijayakumar Krishnasamy, "Design and Analysis of High Gain Buck-Boost Converter Topology With Reduced Voltage Stress," *2019 National Power Electronics Conference (NPEC)*, pp. 1-6, (2019).

IV. PRESENTATIONS/PUBLICATIONS IN CONFERENCES (Others)

1. Mukkapati Ashok Bhupathi Kumar, Vijayakumar Krishnasamy, and Nalavath Saikumar, "A Coupled Inductor Based LCD Network Integrated High Gain Quadratic Converter For Renewable Applications," *2020 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES)*, pp. 1-6, (2020).
2. Saurabh Kumar, Mukkapati Ashok Bhupati Kumar, Vijayakumar Krishnasamy, and Rajvir Kaur, "AISMC for Islanded Operation of Wind Driven SEIG Based DC Nanogrid," *2019 National Power Electronics Conference (NPEC)*, pp. 1-6, (2019).

References

1. **Banaei, M. R.** and **S. G. Sani** (2018). Analysis and implementation of a new sepic-based single-switch buck–boost dc–dc converter with continuous input current. *IEEE transactions on power electronics*, **33**(12), 10317–10325.

2. **Murdock, H. E.**, **D. Gibb**, **T. André**, **J. L. Sawin**, **A. Brown**, **F. Appavou**, **G. Ellis**, **B. Epp**, **F. Guerra**, **F. Joubert**, *et al.* (2020). Renewables 2020-global status report.

3. **Qin, L.**, **L. Zhou**, **W. Hassan**, **J. L. Soon**, **M. Tian**, and **J. Shen** (2021). A family of transformer-less single-switch dual-inductor high voltage gain boost converters with reduced voltage and current stresses. *IEEE Transactions on Power Electronics*, **36**(5), 5674–5685.

4. **Valdez-Resendiz, J. E.**, **J. C. Rosas-Caro**, **J. C. Mayo-Maldonado**, and **A. Llamas-Terres** (2018). Quadratic boost converter based on stackable switching stages. *IET Power Electronics*, **11**(8), 1373–1381.

5. **Ye, Y.-m.** and **K. W. E. Cheng** (2013). Quadratic boost converter with low buffer capacitor stress. *IET Power Electronics*, **7**(5), 1162–1170.

6. **Zeng, Y.**, **H. Li**, **W. Wang**, **B. Zhang**, and **T. Q. Zheng** (2020). High-efficient high-voltage-gain capacitor clamped dc–dc converters and their construction method. *IEEE Transactions on Industrial Electronics*, **68**(5), 3992–4003.

7. **Zhang, N.**, **G. Zhang**, **K. W. See**, and **B. Zhang** (2017). A single-switch quadratic buck–boost converter with continuous input port current and continuous output port current. *IEEE Transactions on Power Electronics*, **33**(5), 4157–4166.