IODUS - Politehnica University Timişoara
Doctoral School of Engineering Studies

DEVELOPMENT OF NEW DC-DC CONVERTER ARCHITECTURES. MODELING, CONTROL AND APPLICATIONS

PhD Thesis – Summary

for getting the scientific title of “doctor” from

Politehnica University Timişoara

in the field of Electronics, Telecommunications and Informational Technologies Engineering

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1. Introduction

The PhD thesis focuses on new dc-dc converters, modelling, control, and applications in the field of Electronics, Telecommunications, and Information Technologies Engineering. It introduces new converter topologies and controller designs. Various quadratic dc-dc converters are analysed, along with stacked topologies. The research emphasises the importance of innovation in power electronics to meet the demands for regulated voltage sources and energy harvesting systems.

1.1. Overview of the Importance of DC-DC Converters in Power Electronics

DC-DC converters play a crucial role in modern power electronics by enabling efficient voltage regulation and power management in various applications. They facilitate the conversion of direct current (dc) from one voltage level to another, which is essential for integrating renewable energy sources, such as solar panels and fuel cells, into the power grid. Additionally, with the boom of electric vehicles (EVs) and hybrid electric vehicles (HEVs), dc-dc converters are vital for optimizing energy usage, enhancing battery performance, and ensuring reliable operation of electronic devices across different sectors, including consumer electronics, telecommunications, and industrial automation.

1.2. Objectives of the Thesis

The primary objective of this thesis is to propose innovative dc-dc converter topologies that offer advantages over traditional converters, particularly in terms of static conversion ratios, efficiency, and reduced semiconductor stress. The research contributes to the field of power electronics by introducing four new buck converters, one new boost converter, and three new buck-boost converters, all designed to enhance performance in various applications. Additionally, the thesis includes the development of small-signal models and controller design strategies, providing a comprehensive framework for future research and practical implementation in energy harvesting and power supply systems.

The thesis aims to achieve the following specific goals:

- *Development of new converter topologies*: To propose and analyse several innovative dc-dc converter topologies, including four new buck converters, one new boost converter, and three new buck-boost converters, that brings improvements upon existing designs in terms of efficiency and performance.

- *Optimisation of performance metrics*: To enhance the static conversion ratio and reduce semiconductor stresses using the proposed converter topologies, thereby increasing equipment reliability and operational efficiency in various applications.
- *Modelling and control techniques*: To develop small-signal models and advanced control strategies for the new converter architectures, thus facilitating better performance in real-world applications, particularly in energy harvesting and power management systems.

2. Methodology

The research methodology employed in this thesis includes the following key steps.

- *Problem identification:* The initial phase involves identifying the specific challenges and limitations in existing dc-dc converter technologies, guiding the focus of the research. Also, some existing power converters are selected as a starting point of the research. They are candidates to converter cell rotation methodology.
- *Mathematical modelling*: The next step entails developing theoretical models for the proposed converter topologies, allowing for analysis of their performance features and operational behaviour. The studies are carried out for the dc model and also for the small-signal model. A design algorithm is also provided.
- *Design and simulation*: The converters are designed using computation and simulation software packages, such as MATLAB™ and CASPOC. These software tools are also used to validate converters functionality and performance under various conditions.
- *Experimental validation*: Physical prototypes of the converters are constructed and tested in laboratory settings to compare the experimental results with simulation data, confirming the practical applicability of the proposed converters designs.
- *Optimisation*: Finally, with a specific design, the parameters of the converters may be optimized based on the findings from simulations and experiments, focusing on enhancing efficiency, reducing component stresses, and improving overall performance. Their target application is identified also from these findings. The design algorithms can lead to a specific design based on certain requirements.

The thesis employs several modelling and simulation techniques to analyse and validate the proposed dc-dc converter topologies.

- *State-Space modelling*: This technique is used to derive mathematical representations of the converters, capturing their dynamic behaviour through state-space equations. It facilitates the dc analysis and response characteristics.
- *Small-Signal modelling*: Small-signal models are developed to study the converters' behaviour under small perturbations around an operating point. This approach allows the computing of transfer functions from the state-space model, which are essential for control design and stability analysis.
- *MATLAB™ simulations*: The converters are simulated using MATLAB™. This enables the evaluation of performance metrics such as efficiency, transient

response, and steady-state behaviour under various operating conditions. The design procedure is implemented in a MATLAB™ script, too. E. g., the control to output transfer function of ZL1-Buck converter was calculated from state space model in both ideal and conduction losses case. The results for magnitude are depicted in Figure 1, together with the experimental results. All computation and the data plot were implemented using MATLAB™.

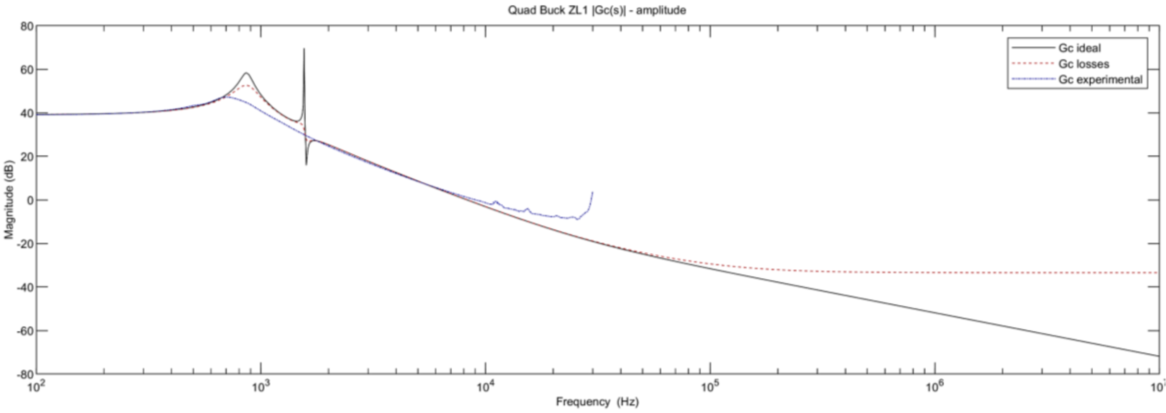
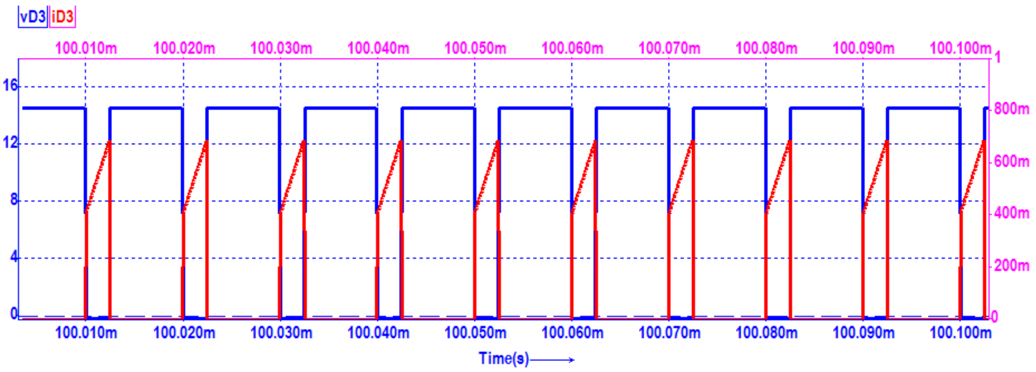


Figure 1. The theoretical and experimental control to output transfer function of ZL1-Buck, the magnitude Bode representation [original].

- *CASPOC simulations*: Circuit-level simulations are performed to analyse the electrical characteristics of the converters in detail. This includes assessing the impact of parasitic elements and validating the theoretical models against practical scenarios. E.g., the schematic of ZL1-Buck converter was reproduced in CASPOC and the conduction losses of components were included, in Figure 2 being depicted the voltage across diode D_3 and the current through the same diode. The shapes confirms that the converter operates in continuous conduction mode (CCM) with respect of this diode.



Trace	t	y	MinX	MaxX	MinY	MaxY	Mean	RMS	Peak-Peak	Abs Mean	RMS ac	Integral	Ripple
1 - vD3			100.003m	100.103m	-220m	14.684	10.938	12.690	14.904	11.048	6.434	1.093m	1.160
2 - iD3			100.003m	100.103m	-1.468u	689.678m	137.148m	277.431m	689.680m	137.150m	241.160m	13.715u	2.023

Figure 2. Voltage and current related to the 3rd diode from ZL1-Buck, conduction losses included [original].

- *Experimental testing:* Prototypes of the converters are built and tested in a laboratory environment, allowing for real-world validation. This step ensures that the models accurately reflect the performance of the converters in practical applications. In Figure 3 the solar energy harvesting prototype of ZL3-Buck switching converter is enfaced.

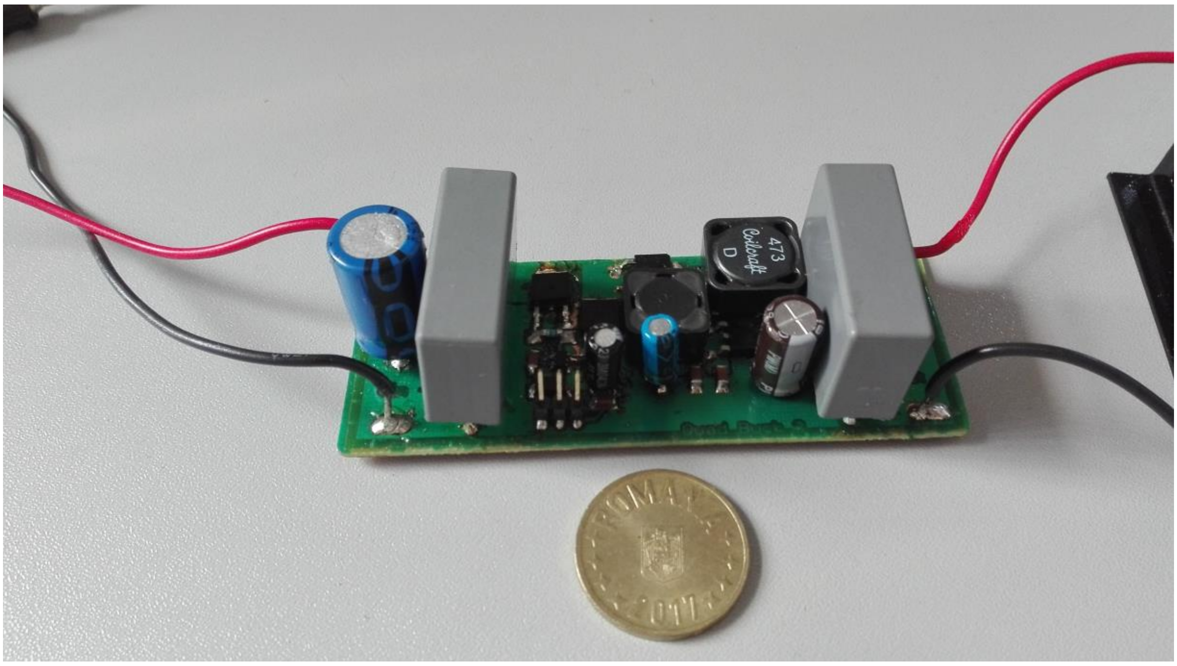


Figure 3. The assembled PCB of the ZL3-Buck solar prototype [original]

3. New DC-DC Converter Architectures

3.1. Detailed Description of the Proposed Converter Topologies

The thesis proposes several new dc-dc converter topologies, focussing on enhancing efficiency and performance.

The ***ZL1-Buck converter***, shown in Figure 4, employs a single active switch and is designed to efficiently reduce the input voltage while increasing the output current. It features a simple structure, making it cost-effective for applications requiring voltage regulation when the difference between the input and the output voltages is small.

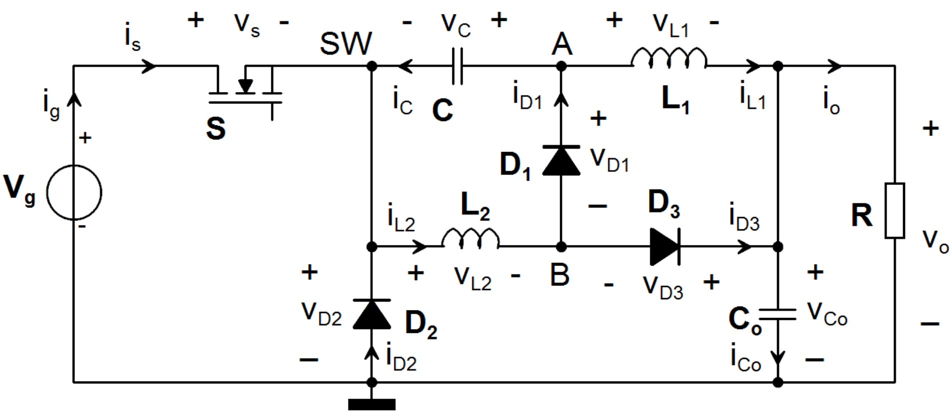


Figure 4. The new proposed Quad ZL1-Buck converter [original]

The ***ZL1-Buck-Boost converter*** is analysed when it operates in CCM and is characterised by its ability to step-down or especially step-up voltage. This flexibility is crucial for applications where the input voltage may significantly vary, such as in photovoltaic (PV) systems. The converter design incorporates two inductors, two capacitors, one transistor, and three diodes, as depicted in Figure 5, which work together to achieve the desired voltage conversion.

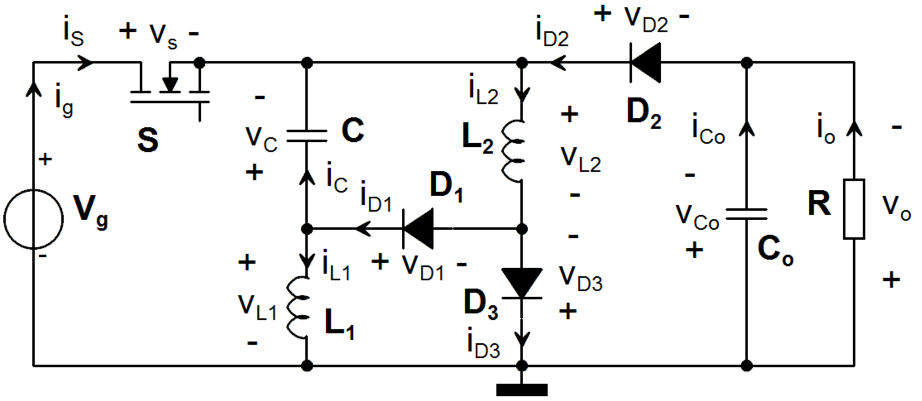


Figure 5. The new proposed Quad ZL1-Buck-Boost converter [original]

The ZL2 and ZL3 families each consist of a quadratic buck and a quadratic buck-boost converter. Their main features are an improved static conversion ratios and reduced semiconductor stresses, thus recommending them as ideal candidates for specific applications.

The study delves into various elements and waveforms associated with the quadratic ZL3-Buck converter which is shown in Figure 6.

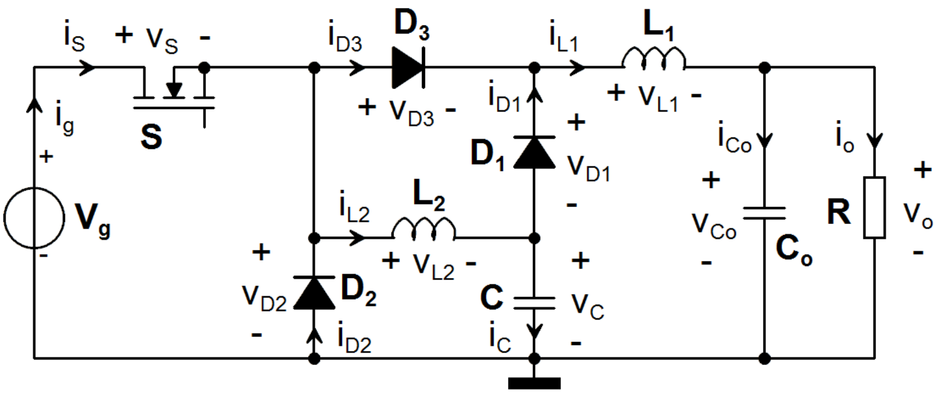


Figure 6. The proposed Quadratic ZL3-Buck converter [original]

It explores the simulation and experimental results and performance metrics for using with PV modules under varying conditions. Additionally, it details the design, simulation waveforms and efficiency analyses of the proposed quad ZL3-Buck converter prototypes, highlighting their operational characteristics and thermal evaluations during testing. Applications in PV systems demonstrate the utility of the ZL3-Buck converter. Measurements obtained with the solar test bench are reproduced in Figure 7. For an optimal design and for the extraction of the demanded requirements, the PV panels are simulated, because of the sparse characteristics in the datasheet. Simulated PV characteristics are enfaced in Figure 8.

The ***Stacked Buck*** and ***Boost converters*** are multi-stage step-up or step-down converters. These topologies are designed to achieve alleviated voltage conversion ratios by stacking multiple stages of traditional buck and boost converters. This stacked configuration allows for better efficiency and performance in applications that require significant or specific voltage changes. Theoretical waveforms related to passive and active elements of the converters are studied. Static conversion ratios and efficiency equations are evaluated, with particular attention to lossy models. This chapter also discusses theoretical formulations, simulation waveforms, and experimental validations for stacked buck and boost converters with different number of stages, emphasising their conversion ratios and efficiency outcomes.

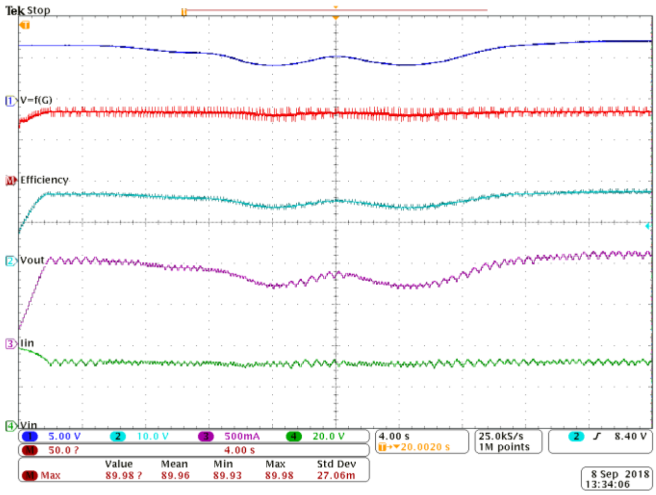


Figure 7. Oscilloscope capture with variable irradiation: the voltage from the pyranometer (V=f(G) – navy blue), the output voltage (Vout – cyan), the instantaneous efficiency (Efficiency – red), the input current (Iin – magenta), the input voltage (Vin – green) [original]

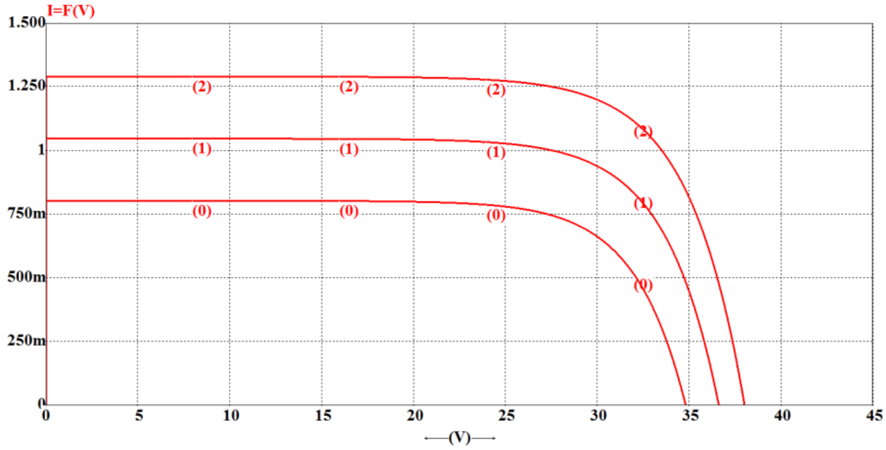


Figure 8. Current-voltage characteristics of the PV modules in series: (0) → 600W/m², (1) → 800 W/m², and (2) → 1000 W/m²

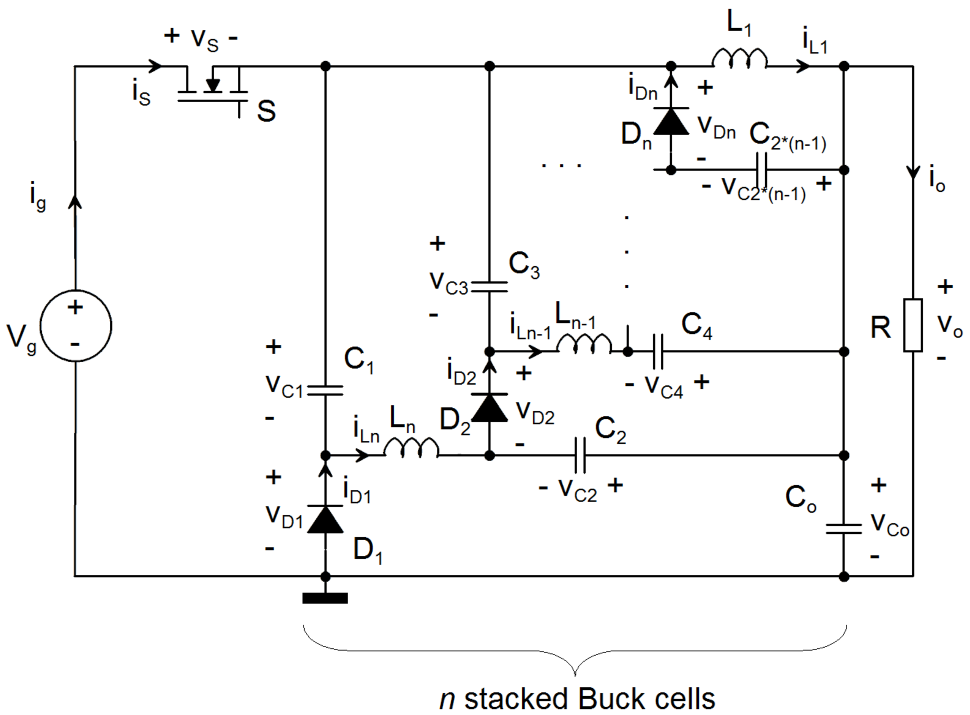


Figure 9. The generalisation of the Stacked Buck Converter [original]

Furthermore, the research extends to the development of new generalised dc-dc converter architectures, focussing on modelling, simulations, and application prospects. The stacked buck converter for any number of stages is shown in Figure 9.

Each proposed topology is analysed for its operational characteristics, efficiency, and suitability for specific applications, demonstrating their potential advantages over traditional and other reported designs. Comparisons with similar topologies show the advantages of the proposed converters.

The investigation also involves the integration of control mechanisms, for example, using operational amplifiers, to regulate output voltages and manage load variations, showcasing the versatility and adaptability of the proposed converter designs.

3.2. Advantages over other converters

The proposed converter topologies are compared to existing technologies to highlight their advantages. They offer several advantages compared to traditional converters:

- *High efficiency*: The new topologies exhibit small energy losses, resulting in an overall efficiency compared to that of classical converters such as buck, boost and buck-boost converters. The new topologies, such as the ZL1-Buck and ZL1-Buck-Boost converters, demonstrate efficiencies exceeding 90%. The experimental efficiency and the one computed from the state-space model with conduction losses included may be noticed in Figure 10 for ZL3-Buck topology.

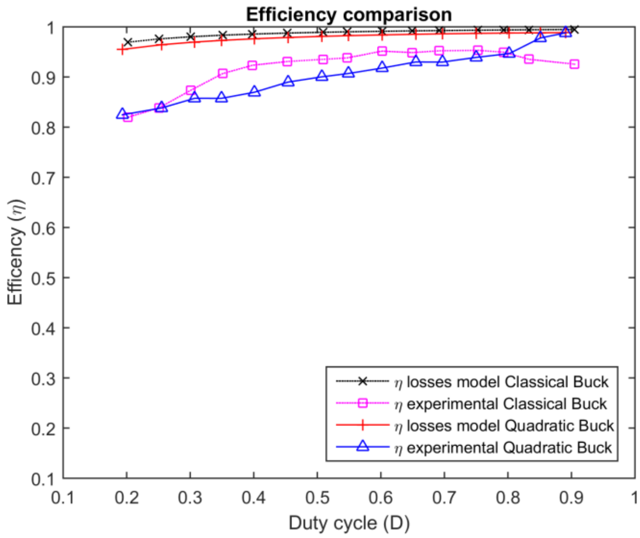


Figure 10. Theoretical efficiency in comparison with measured efficiency for the classical Buck converter and the proposed ZL3-Buck converter [original]

- *Improved static conversion ratios*: The proposed converters exhibit enhanced static conversion ratios, allowing for better duty cycle usage and adaptability in applications where input and output voltages are close to each other, or a high voltage gain is required. For instance, the ZL1, ZL2, and ZL3 families provide better performance in both step-up and step-down applications, allowing for more versatile use in various power management scenarios. A comparison of the duty cycle curves is shown in Figure 11. E.g, in the case of ZL3-Buck, for an elevated static conversion ratio of M = 0.9, the traditional converter must be operated near D = 0.9, while the proposed converter will have a more relaxed duty cycle near D = 0.7.

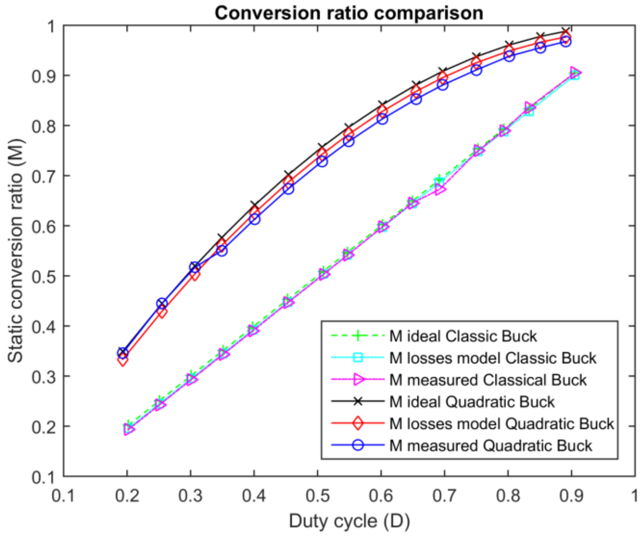


Figure 11. Theoretical dc conversion ratio in comparison with the losses model, and measurements for the classical Buck converter and the proposed ZL3-Buck converter [original]

- *Reduced component stresses*: When the design and operation of the converters are optimised, the proposed topologies reduce the current and voltage stresses of the semiconductors and other components, leading to increased reliability and longer operational life.
- *Cost-effectiveness*: The proposed topologies are designed with a low count of components.
- *Versatility*: The ability to operate at moderate duty cycle in extreme cases such as low step-down or high step-up.

These advantages position the proposed converter topologies as better alternatives for various applications in power electronics. In general, the proposed converter topologies demonstrate superior performance, efficiency, and cost-effectiveness compared to other dc-dc converter topologies, making them suitable for modern applications in renewable energies and power supplies.

4. Performance Analysis

The thesis presents comprehensive results from both simulations and experimental validations of the proposed converter topologies. Here are some examples.

4.1. ZL1-Buck Converter

Simulation results: The output voltage was calculated as 21.887V using the theoretical state-space model, while the simulation yielded 21.905V, demonstrating close alignment with the theoretical predictions.

Experimental results: The practical prototype confirmed the simulation results, with minor discrepancies attributed to tolerances of the real-world components.

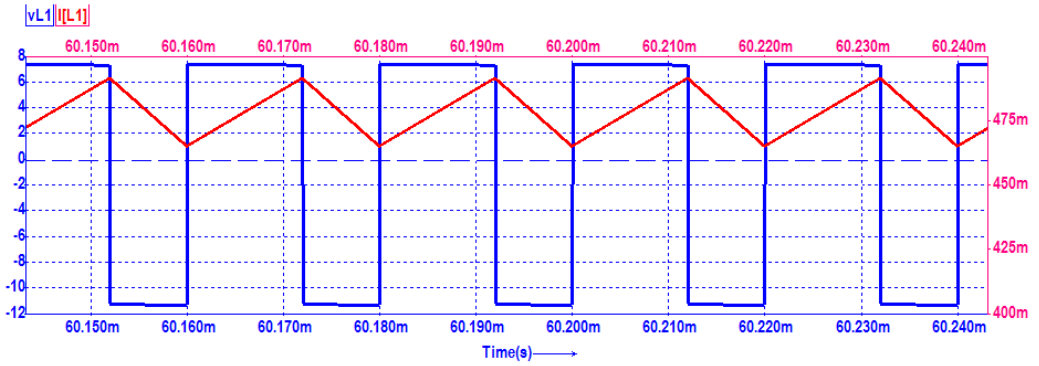
4.2. ZL1-Buck-Boost Converter

Simulation results: The output voltage was predicted to be 25.6434V, and the simulation achieved 25.644V, indicating a high accuracy in the modelling.

Experimental results: Testing showed that the converter maintained the good performance under varying operational duty cycles, validating the effectiveness of the design in practical applications.

5. Waveform Analysis

Simulation results: The waveforms of the simulations exhibited the expected theoretical shapes, with minor variations in levels, indicating good model fidelity. The signals related to coil L_1 from the two stages stacked buck converter are depicted in Figure 12.



Trace	t	y	MinX	MaxX	MinY	MaxY	Mean	RMS	Peak-Peak	Abs Mean	RMS ac	Integral	Ripple
1 - vL1			60.143m	60.243m	-11.264	7.528	1.374m	9.180	18.791	8.996	9.180	-50.436n	6.684k
2 - I(L1)			60.143m	60.243m	465.400m	491.864m	478.767m	478.768m	26.464m	478.767m	1.025m	47.865u	1

Figure 12. Simulation results for stacked-buck converter with n=2: the voltage across the first inductor and the current through the same inductor [original]

Experimental results: The waveforms captured during testing closely matched with the simulated results, confirming the operational integrity of the converters. The acquired signals for the same converter, staked buck with n = 2 stages, are reproduced in Figure 13.

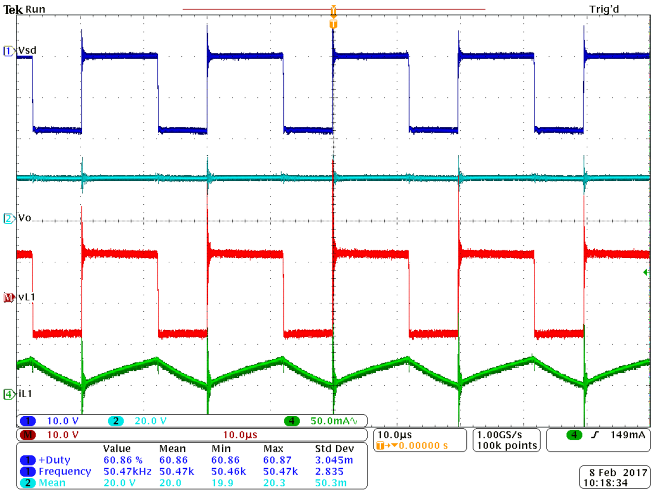


Figure 13. Oscilloscope capture (stacked buck n=2): voltage across the transistor, source to drain (Vsd – dark blue), output voltage (Vo – cyan), voltage across L_1 (vL1 – red), current through L_1 (iL1 – green) [original]

Overall, the results of both simulations and experiments validated the proposed converters designs, showcasing their potential for high efficiency and reliable performance in various applications.

6. Applications

6.1. Potential Applications of the New Converters

The proposed dc-dc converter topologies have a wide range of potential applications, including:

- *Renewable energy systems*: The ZL-Buck and ZL-Buck-Boost converters are particularly suitable for integration in PV energy harvesting systems, where they can efficiently manage the varying input voltages of solar panels to optimise energy conversion and storage.
- *Electric vehicles*: The new converter designs can be utilised in EV power management systems, providing efficient current and voltage regulation for battery charging and power distribution, enhancing overall vehicle performance and range.
- *Portable electronics*: The compact and efficient nature of the proposed converters makes them ideal for use in portable electronic devices, such as smartphones and laptops, where space and energy efficiency are critical.
- *Industrial power supplies*: These converters can be used in industrial applications to power machinery and equipment, where reliable and efficient voltage conversion is essential for operational efficiency and cost savings.
- *Energy storage systems*: The converters can be integrated into energy storage solutions, such as battery management systems, to optimise the charging and discharging processes, improving the life and performance of energy storage devices.

In conclusion, the versatility and efficiency of the new converters pose them well for a variety of applications in different sectors, particularly in renewable energy and advanced electronic systems.

6.2. Discussion on energy harvesting and efficiency improvements.

Energy harvesting refers to the process of capturing and storing energy from various renewable sources, such as solar, wind, and thermal energy, for later use. The integration of dc-dc converters in renewable energy systems, particularly solar energy, is a growing area of interest. The proposed dc-dc converter topologies could play an important role in enhancing the efficiency of energy harvesting systems.

- *Optimised conversion:* The new converter topologies, such as the ZL-Buck and ZL-Buck-Boost converters, are engineered to achieve high efficiency in converting harvested energy into usable electrical power. Their ability to maintain high efficiency under varying input conditions is essential for maximising energy capture from fluctuating renewable sources.
- *Static conversion ratio*: The converters improved static conversion ratios allow for effective voltage regulation, ensuring that the output voltage remains stable even when the input from the energy sources varies significantly. The efficiency remains high in various scenarios. This is vital for applications like solar energy systems, where solar irradiance can change rapidly.
- *Reduced losses*: By minimising semiconductor stresses and optimising component selection, the proposed topologies reduce energy losses during conversion. This leads to higher overall system efficiency, which is critical for

applications where energy resources are limited and need to be effectively utilised.

- *Integration with advanced control strategies*: Future work on implementing current mode control and one-cycle control strategies with these converters can supplementarily enhance their performance. These control techniques can improve response times and stability, leading to better energy management and utilisation in harvesting systems, also for the consistency of the dc bus. In this thesis classical control strategies such as perturb & observe (P&O) or PID are employed.

In summary, the proposed dc-dc converter topologies significantly contribute to energy harvesting efforts by improving conversion efficiency, reducing losses, and providing stable output, thus maximising the potential of renewable energy sources.

7. Controller Design

The controller design presented in this thesis is a critical aspect of ensuring the effective closed loop operation of the proposed dc-dc converter topologies.

7.1. Approach to High-Order Systems

The thesis addresses the challenges associated with designing controllers for high-order converters, specifically the 4th order ZL3 Buck-Boost converter. It employs a method of reducing the control-to-output transfer function from fourth order to 2nd order, making the design process more manageable and applicable to classical control techniques. The estimated control to output transfer function for the ZL3-Buck-Boost dc-dc converter is illustrated in Figure 14, together with the original, 4th order one. As a remark about the phase representation, one may state that since the trigonometric functions are periodic with period 360°, it results that all phase plots are practically over-imposed.

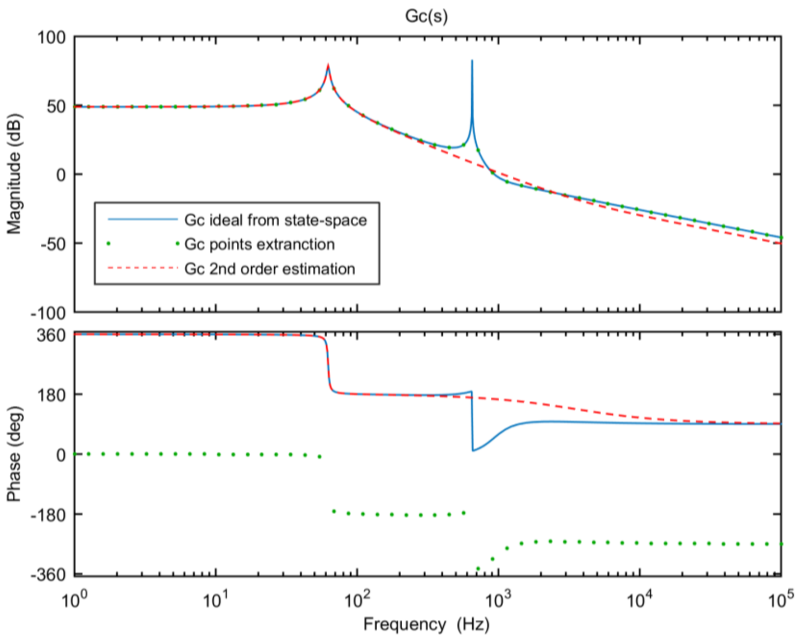


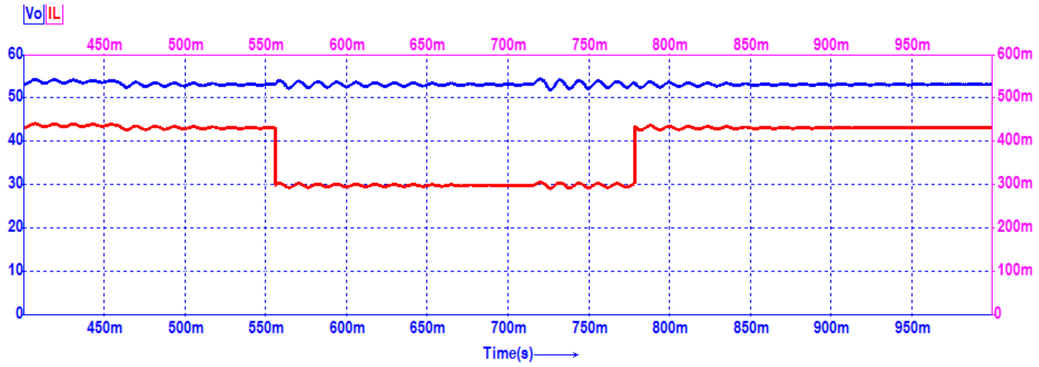
Figure 14. The Bode representations for the ZL3-Buck-Boost converter control to output transfer function, the extracted points and the estimated order reduction transfer function [original]

7.2. Classical Control Techniques

The controller design is based on well-established methods such as pole-zero placement and the K-factor method, which are effective for 2nd order systems. This approach allows for the systematic tuning of controller parameters to achieve desired performance metrics, such as stability, time response, overshoot, etc.

7.3. Simulation and Validation

The controller design is validated through simulations, demonstrating its effectiveness in maintaining stable output voltage and regulation under varying load conditions. The results indicate that the controller can adapt to system changes, ensuring reliable performance in practical applications. If a step in the load occurs, the output voltage of the closed-loop ZL3-Buck-Boost remains at the desired value, as may be remarked in Figure 15.



Trace	t	y	MinX	MaxX	MinY	MaxY	Mean	RMS	Peak-Peak	Abs Mean	RMS ac	Integral	Ripple
1 - Vo			400.007m	1	52.107	54.650	53.417	53.416	2.542	53.417	0	32.047	999.988m
2 - IL			400.007m	1	293.168m	443.366m	384.822m	390.215m	150.198m	384.822m	64.649m	230.763m	1.014

Figure 15. The output voltage v_o stabilisation when a load step perturbation appears for the system (ZL3-Buck-Boost) with the Op. Amp. connected as integrator: the output voltage v_o (blue) and the total output current through the loads i_o (red) [original]

7.4. Applicability to Similar Converters

The design strategy developed in this thesis is not limited to the specific converters studied; it can be generalised and applied to other similar converter topologies. This versatility enhances the practical utility of research, providing a framework for future controller designs in the field of power electronics.

In summary, the controller design proposed in this thesis effectively addresses the complexities of high-order converter systems, employing classical techniques and demonstrating robust performance through simulation, making it a valuable contribution to the field of power electronics.

8. Small-Signal Modelling of Converters Employing a Capacitive Loop

The small-signal modelling of converters with capacitive loops, as discussed in the thesis, presents unique challenges and methodologies.

8.1. Challenges with Singularity

The presence of capacitive loops in converters, such as the 1L2C boost converter, leads to singularity in one system matrix. This complicates the traditional approach to derive the transfer functions, as the assumption of small ripples and slow variation in capacitive voltages is not valid.

8.2. Innovative Modelling Techniques

To address this challenge, the thesis proposes alternative methods for small-signal modelling, including a discrete time modelling and continuous time modelling with a loss resistor included. These approaches allow for the effective handling of the capacitive nature of the loops by avoiding matrix inversions and focussing on the system dynamic behaviour or transforming the matrix in a non-singular one.

8.3. Transfer Function Derivation

The small-signal model is derived by considering the equivalent capacitance of parallel capacitors and reducing the system to two state variables, despite the 1L2C converter contains one inductor and two capacitors. This results in a second-order transfer function which aligns with the behaviour of classical boost converters, facilitating easier analysis and control design.

8.4. Validation and Application

The small-signal models developed are validated through simulations and experimental results, demonstrating their accuracy in predicting the converters performance. E.g., the Bodé plots of the computed audiosusceptibility for the 1L2C boost converter using the proposed methods are depicted in Figure 16. These models are crucial for designing controllers and optimising the operation of topologies with capacitive loops in various applications.

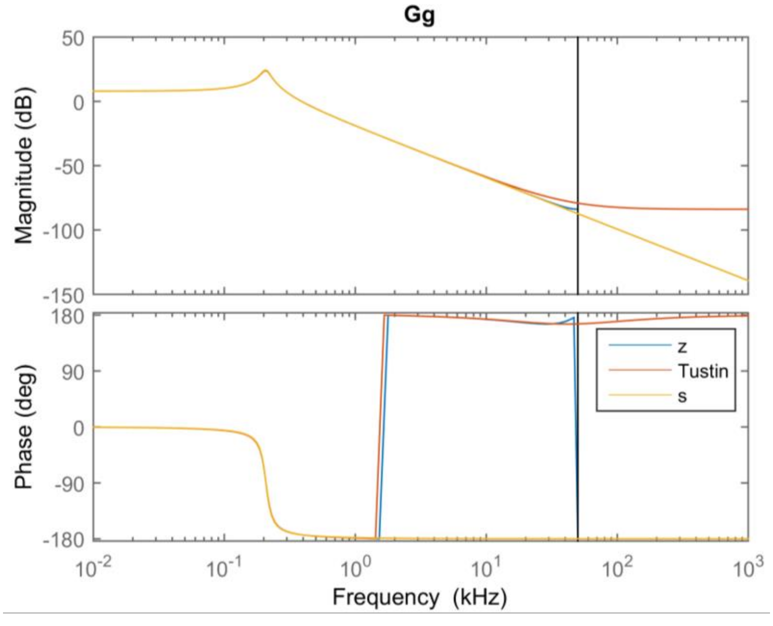


Figure 16. The 1L2C boost converter audiosusceptibility from z domain, converted with Tustin method and in Laplace domain [original]

In summary, the small-signal modelling of converters employing a capacitive loop is effectively addressed in the thesis through innovative techniques that overcome traditional challenges, resulting in accurate models that are essential for control design and performance optimisation.

9. Conclusions

9.1. Findings

The thesis presents several key findings related to the development and analysis of new dc-dc converter topologies:

- *Innovative converter topologies*: Three new ZL-Buck converters and three ZL-Buck-Boost converters were successfully proposed, utilising the rotating cell method. In addition, two families of stacked buck and boost converters were introduced, featuring improved efficiency and performance compared to traditional counterparts.
- *High efficiency and performance*: The proposed converters exhibit efficiencies exceeding 90%, with enhanced static conversion ratios and reduced semiconductor stresses. These improvements make them suitable for applications in renewable energy systems, EVs, and portable electronics.
- *Effective controller design*: A robust controller design was developed for the converters, utilizing classical control techniques to manage high-order systems equivalated with a 2^{nd} order system. The controller demonstrated stable output regulation under varying load conditions, validated through simulations.
- *Small-signal modelling insights*: The thesis addressed the complexities of small-signal modelling for converters with capacitive loops, proposing innovative modelling techniques that avoid singularities in the system matrix. The derived models accurately predict the converter behaviour, facilitating control design and optimisation. It is confirmed through experiment that the proposed calculated model is accurate with the real converter dynamics.
- *Simulation and experimental results*: The simulation results indicated promising performance metrics, such as voltage and current stresses, while the experimental validations confirmed the theoretical predictions. The findings encourage further investigation and practical implementation of the proposed converters.

In conclusion, the thesis significantly contributes to the field of power electronics by introducing novel converter topologies, effective control strategies, and advanced modelling techniques, paving the way for enhanced energy management in various applications.

9.2. Future Research Directions and Implications for the Field

Ongoing research in the field of dc-dc converters focusses on improving efficiency, reducing costs, and enhancing reliability, exploring the boundaries of what is possible in converter technology. The findings of this thesis open several directions for future research and have significant implications for the field of power electronics:

- *Advanced control strategies*: Future research can explore the implementation of advanced control techniques, such as one cycle control and adaptive control, to further enhance the performance of the proposed converters. These strategies could improve dynamic response and stability, particularly in applications with rapidly changing load conditions.

- *Integration with energy storage systems*: Investigating the integration of the new converter topologies with energy storage systems, such as batteries and supercapacitors, can lead to improved energy management solutions. This research could focus on optimising the charging and discharging cycles to maximise the lifespan and efficiency of storage devices.
- *Application in smart grids*: The converters capabilities can be further explored in the context of smart grid technologies, where efficient energy conversion and management are critical. Research could focus on developing control algorithms that enable the seamless integration of renewable energy sources into the grid while maintaining stability and reliability.
- *Thermal management and reliability*: Future studies could address thermal management strategies for the proposed converters to enhance their reliability and performance under high-stress conditions. Investigating materials and designs that improve heat dissipation will be essential for long-term operation in demanding environments.
- *Broader applications and topology variations*: Expanding research to include variations of the proposed topologies for specific applications, such as electric vehicles, industrial automation, and consumer electronics, can lead to customised solutions that meet diverse energy conversion needs. This could involve exploring multi-level converter designs and hybrid systems.

In summary, the implications of this research extend beyond the immediate findings, encouraging further exploration of new topologies, advanced control methods, integration with energy systems, and application in emerging technologies, ultimately contributing to the advancement of efficient and sustainable power electronics solutions. As technology continues to evolve, the focus on optimising these electronic systems will be crucial for meeting the demands of modern electrification.

10. Key References

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