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MODELLING, DESIGN AND PERFORMANCE ASSESSMENT OF MULTISTAGE BUCK CONVERTERS FOR HIGH STEP-DOWN APPLICATIONS

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ABSTRACT

Multistage buck converters have gained significant attention as an effective solution for deep step-down DC–DC conversion in modern power-electronic applications where conventional single-stage buck converters suffer from severe limitations. Extremely low duty cycles, elevated switching stress, increased ripple, and poor dynamic performance restrict the viability of single-stage topologies in systems requiring high conversion ratios. By distributing the voltage reduction across multiple cascaded stages, multistage buck converters provide improved operating conditions, enhanced ripple suppression, and reduced electrical and thermal stress on power devices. This review presents a comprehensive examination of modelling principles, including steady-state behaviour, current distribution, and simulation methodologies, as well as performance characteristics such as efficiency trends, ripple attenuation, and component stress analysis. The comparative insights drawn from existing literature demonstrate that while multistage converters offer notable advantages in stability, ripple performance, and stress management, they also introduce challenges related to increased component count, potential interstage resonance, and complex control requirements. The findings highlight the importance of accurate modelling, optimized stage design, and advanced control strategies for achieving high-performance deep step-down conversion. This review serves as a consolidated reference for researchers and engineers working toward the development and optimization of cascaded buck converter architectures.

Keywords—Buck converter[1], Cascaded topology[2], Step-down DC–DC conversion[3], Power electronics[4], Efficiency analysis[5].

I. INTRODUCTION

DC–DC converters form the backbone of modern power-electronic systems, enabling efficient voltage regulation across a diverse set of applications including electric vehicles, renewable-energy interfaces, telecommunication circuits, portable electronics, and high-performance microprocessors [1], [2]. As these technologies evolve, the demand for deep step-down voltage conversion has increased significantly, particularly where high input voltage must be reduced to low, stable output levels. Conventional single-stage buck converters, although widely used for moderate conversion ratios, encounter severe operational limitations under such conditions. Extremely low duty cycles introduce heightened switching stress, reduced efficiency, increased ripple, and compromised dynamic behaviour, making single-stage topologies unsuitable for large conversion ratios [3], [4]. To overcome these challenges, multistage buck converters have emerged as an effective alternative. By cascading several buck stages, the overall voltage-reduction burden is distributed, enabling each stage to operate at a more moderate duty cycle and significantly reducing electrical and thermal stress on semiconductor devices [5], [6]. This architectural advantage results in improved energy-processing capability, better efficiency, and enhanced long-term reliability. Moreover, the presence of multiple LC filtering stages enables progressive attenuation of ripple components, making multistage converters particularly suitable for noise-sensitive and precision-driven applications such as communication systems, instrumentation, and embedded processors [7]. Recent research efforts have also focused on accurate modelling and analysis of cascaded converters to predict behaviour under various loading and dynamic operating conditions. Steady-state voltage relations defining the multiplicative influence of individual stage duty cycles, along with current distribution models, help establish a robust analytical foundation for multistage converter design [8], [9]. Simulation-based studies further refine this understanding by incorporating switch parasitics, magnetic characteristics, and transient effects. Performance evaluations from existing literature demonstrate that multistage buck converters can outperform their single-stage counterparts in terms of ripple suppression, stress distribution, efficiency, and dynamic stability when properly optimized [10], [11]. However, these benefits come with added complexity. The requirement for additional components increases hardware cost and circuit footprint. The cascading of LC networks introduces the potential for interstage resonance, and the control strategy becomes more demanding due to multi-loop interactions [12]. Despite these challenges, the strong performance advantages of multistage converters make them highly relevant for next-generation power-electronic systems requiring high conversion ratios, excellent voltage regulation, and robust thermal and electrical behaviour. Given the growing importance of multistage buck converters across industry and academia, a consolidated and technically enriched review is necessary. The objective of this work is to synthesize existing research on modelling principles, performance characteristics, efficiency trends, ripple behaviour, stress analysis, and design limitations of multistage buck converters. This comprehensive overview aims to support engineers and researchers in understanding, developing, and optimizing cascaded converter architectures for deep step-down applications [13].

II. Rationale for Using Multistage Buck Converters

Deep step-down DC–DC conversion presents several challenges when implemented using traditional single-stage buck converters. As the input-to-output voltage ratio increases, the duty cycle of a single-stage buck approaches extremely low values, which leads to a range of detrimental effects including increased switching stress, poor efficiency, elevated conduction losses, and high output ripple [14], [15]. These limitations become especially pronounced in modern applications such as electric vehicles, renewable-energy interfaces, microprocessor power delivery systems, and distributed DC nanogrids, where high input voltages must be reliably converted to low operating voltages under stringent performance requirements [16]. Multistage buck converters address these inherent limitations by dividing the overall conversion ratio across multiple cascaded stages. Instead of forcing a single converter to operate at an impractically low duty cycle, each stage in a multistage structure operates with a moderate, more efficient duty cycle, thereby reducing stress on active and passive components [17]. This staged approach improves switching performance, enhances thermal distribution, and reduces peak device stress, ultimately leading to higher reliability and longer component lifespan. Furthermore, the use of cascaded stages allows designers to optimize each stage individually based on voltage, current, and thermal considerations, offering greater design flexibility compared to single-stage solutions [18]. Another significant advantage of multistage converters is their ability to achieve superior ripple attenuation. By introducing multiple LC filter sections, each stage progressively suppresses high-frequency ripple components that originate from the switching process. This cumulative filtering effect yields a cleaner and more stable output voltage, making cascaded buck converters well suited for sensitive electronic loads such as precision sensors, communication modules, and medical instrumentation where power quality must be tightly regulated [19]. This improvement in ripple behaviour not only enhances load performance but also reduces electromagnetic interference (EMI) and improves overall system robustness. In addition to performance benefits, multistage converters exhibit improved efficiency when properly designed. By spreading voltage reduction across several stages, switching losses per stage are reduced, allowing operation at higher switching frequencies with manageable thermal profiles. Many studies have demonstrated that under optimized conditions, multistage designs can achieve higher efficiency than single-stage converters operating under the same conversion ratio [20]. However, this advantage is contingent on careful stage selection, optimal distribution of switching frequency, and minimizing cumulative conduction and magnetic losses.

Despite the clear benefits, multistage architectures also introduce certain complexities. The presence of multiple switches, inductors, and capacitors increases the component count, potentially raising cost and requiring more sophisticated layout strategies to minimize parasitics. Moreover, interstage resonance may occur due to the interaction of multiple LC sections, necessitating careful control-loop design and damping strategies. Nonetheless, when these challenges are addressed through appropriate modelling, control techniques, and component selection, multistage buck converters become a highly effective solution for deep step-down power conversion. The rationale for using multistage buck converters is grounded in their ability to overcome the fundamental shortcomings of single-stage designs when implemented for large conversion ratios. Their advantages in efficiency, ripple performance, stress distribution, and design flexibility make them a compelling choice for next-generation power-electronic systems operating under demanding electrical and thermal constraints [20].

III. MODELLING ASPECTS OF MULTISTAGE BUCK STRUCTURES

A. Steady-State Voltage Relation

The steady-state behaviour of a multistage buck converter is governed by the voltage conversion relationship that links individual stage duty cycles to the final output voltage. For an *N*-stage cascaded buck converter operating in continuous-conduction mode, the overall output voltage can be expressed as the product of the stage-wise gains, represented generally as:

$$V_O = V_{in} \sum_{i=1}^{n} D_i \qquad (1)$$

This formulation, widely supported in existing analyses of cascaded DC–DC structures, establishes the mathematical foundation for evaluating voltage conversion, stage interaction, and the sensitivity of output regulation to duty-cycle variations [11], [12], [13]. The relation also highlights that small deviations in individual stage duty cycles can propagate exponentially, reinforcing the need for precise duty-cycle control in multistage architectures. This expression serves as a central analytical tool in simulation frameworks and small-signal modelling studies.

B. Current Distribution Across Stages

Current distribution is another critical modelling aspect because cascaded converters do not maintain uniform current levels across all stages. The current delivered by the *k-th* stage is determined by the load power and the intermediate voltage at that stage, and is commonly represented as:

$$I_i = \frac{P_O}{V_i} \qquad (2)$$

Studies on step-down converter behaviour indicate that upstream stages typically process higher currents because they operate at higher intermediate voltages, whereas downstream stages carry progressively lower currents [4], [7]. This nonuniform current distribution directly affects conduction losses, inductor design, MOSFET sizing, and thermal management. Modelling this behaviour accurately is essential for ensuring proper device de-rating and preventing thermal imbalance in multistage systems.

C. Simulation Methodology

Simulation plays a crucial role in the analysis and design of multistage buck converters due to the complexity introduced by multiple interacting stages. Most research employs MATLAB/Simulink-based models that incorporate either ideal switch behaviour or more detailed non-idealities such as MOSFET $R_{\mathrm{ds(on)}}$, diode forward-voltage drops, capacitor ESR, and switching-transition losses [1], [3], [7]. Incorporating these parasitic elements allows researchers to more accurately predict efficiency degradation, ripple behaviour, and dynamic response. Comparative simulation studies frequently examine different numbers of cascaded stages to identify how stage count influences ripple attenuation, efficiency trends, inductor stress, and transient stability. These investigations consistently highlight that multistage topologies exhibit improved ripple suppression and reduced component stress, albeit at the cost of increased cumulative loss and modelling complexity [6], [18]. As a result, simulation methodology remains a pivotal element in understanding design trade-offs and optimizing multistage converter performance.

IV. Observed Performance Trends in Literature

A. Input Current Behaviour

Under ideal, lossless operation, the input current of an N-stage cascaded buck converter is governed primarily by the output power and input voltage, expressed as:

$$I_{in} = \frac{P_O}{V_{in}} \qquad (3)$$

This relationship indicates that the average input current remains independent of the number of stages, a behaviour consistent with general DC–DC converter operation reported in foundational studies on cascaded and high step-down converters [1], [11]. However, some research notes minor improvements in input-current quality when multiple stages are used. These improvements are attributed to more distributed switching transitions, which can result in reduced RMS current stress and smoother current profiles under specific operating conditions [2], [7]. While not a primary advantage, this effect is relevant in systems where input-current quality is critical.

B. Voltage Ripple Characteristics

Ripple attenuation is one of the most consistently observed advantages of multistage buck converters. Because each stage includes its own LC filtering network, the overall ripple is progressively suppressed as the voltage propagates through successive stages. Multiple studies confirm that this architectural benefit leads to significantly improved ripple behaviour compared with single-stage designs, especially in deep step-down applications [6], [14]. Duty-cycle moderation within each stage further enhances ripple performance by reducing high-frequency voltage deviations associated with switching activity [5], [18]. Consequently, multistage converters are often preferred in noise-sensitive environments where stable and low ripple DC output is essential.

C. Efficiency Behaviour

Efficiency trends in cascaded buck converters vary across the literature and depend strongly on-stage distribution, device characteristics, and operating frequency. Several works report improved efficiency when multiple stages are used, primarily due to reduced voltage stress on MOSFETs and corresponding reductions in switching losses per device [2], [11], [15]. This reduced stress can also allow selection of lower-rated, lower–$R_{ds(on)}$ devices that further improve conduction efficiency. However, other studies highlight that efficiency may decline if too many stages are employed. Additional stages increase cumulative conduction losses, magnetic losses, and switching losses, which can outweigh the benefits of voltage distribution when component selection and stage optimization are not carefully managed [12], [17]. As emphasized in prior analyses, meaningful efficiency improvement requires a balanced design that minimizes loss mechanisms while leveraging the advantages of stress reduction [16], [19].

D. Stress on Power Components

A consistently reported benefit of multistage buck converters is the significant reduction in stress experienced by power devices. Since each stage handles only a fraction of the total input voltage, MOSFETs and diodes experience lower voltage stress, reduced switching energy, and improved thermal performance. These effects have been demonstrated in various high step-down and cascaded converter studies [11], [18]. Additionally, inductor currents tend to decrease in downstream stages, simplifying magnetic design and reducing both core and copper losses [7], [13]. Collectively, these improvements contribute to enhanced device reliability, reduced heat generation, and longer operational life in high-demand or continuous-duty applications.

V. Comparative Results from Existing Studies

Comparative evaluations reported in the literature consistently demonstrate the performance advantages of multistage or cascaded buck converters over conventional single-stage converters. Several studies show that using two or more cascaded stages allows each converter to operate at a more moderate duty cycle, thereby avoiding the impractically low switching ratios typically encountered in high step-down single-stage designs [11], [12]. This staged operation enhances conversion quality and reduces switching-related stress on semiconductor devices. In terms of output ripple, cascaded buck structures show considerable improvement, as each stage inherently contributes an LC filtering effect that progressively attenuates high-frequency components. Multiple authors highlight that this cumulative filtering characteristic results in significantly reduced voltage ripple compared with single-stage topologies, and is particularly beneficial in applications requiring high-quality, low-noise DC output [6], [14], [18]. Efficiency trends across studies demonstrate mixed but insightful results. Under optimized design conditions, several works report that distributing voltage stress across multiple stages leads to improved efficiency, primarily because each switch experiences lower voltage transitions and reduced switching energy [2], [15]. However, other investigations emphasize that adding too many stages can introduce additional conduction losses, switching losses, and magnetic losses, which may outweigh the benefits of stress reduction [12], [17]. Thus, determining the optimal number of cascaded stages is an application-dependent process that requires careful balancing of loss mechanisms. A widely acknowledged advantage observed across the literature is the distribution of electrical and thermal stress among multiple switches, inductors, and capacitors. In cascaded structures, no individual device is required to withstand the entire input voltage or full load current, thereby improving reliability and reducing thermal burden. This benefit is highlighted in high-conversion-ratio and high-power applications, where device endurance and efficiency are critical factors [7], [18], [20]. Collectively, these comparative findings affirm that multistage buck converters are highly suitable for deep step-down applications, where enhanced ripple performance, improved stress distribution, and potential efficiency gains justify their increased structural complexity [16], [19].

VI. Key Limitations Highlighted Across Studies

Despite their advantages, multistage buck converters exhibit several limitations that must be addressed for reliable deployment. One of the most consistently reported drawbacks is the increased number of components, which leads to higher circuit complexity, larger physical size, and increased cost. Studies emphasize that the additional switches, inductors, capacitors, and control circuitry make the design more difficult to compact and more challenging to manufacture [3], [10], [12]. Another key limitation is the potential emergence of interstage resonances, which arise from the interaction of multiple LC stages connected in sequence. Such resonances can degrade transient performance and compromise stability unless properly mitigated with damping networks or advanced control techniques. Literature on small-signal modelling and stability analysis underscores the importance of understanding these resonance modes to ensure safe operation [14], [17]. The control architecture also becomes significantly more demanding as more stages are added. Coordinating duty cycles across cascaded stages requires precise tuning of loop dynamics, and inadequate control design may result in oscillation, poor transient response, or uneven power distribution. Studies on multi-stage designs note that advanced digital or current-mode control approaches are often necessary to achieve the desired dynamic performance [4], [12], [17]. Cumulative losses represent another substantial limitation. Although each stage operates under reduced voltage stress, the total conduction and switching losses across multiple stages can accumulate, especially when passive components are not selected with optimized ESR, inductance, or saturation characteristics. Several works report that poorly designed multistage converters may exhibit lower efficiency than single-stage counterparts due to compounded loss mechanisms [2], [18], [20]. Despite these limitations, the literature consistently reinforces the value of multistage buck converters in deep step-down environments. Their ability to distribute electrical stress, improve ripple performance, and enhance conversion quality makes them attractive solutions where performance requirements outweigh structural complexity [6], [14], [20].

VII. CONCLUSIONS

This review highlights the growing relevance of multistage buck converters in applications requiring deep step-down DC–DC conversion, where traditional single-stage buck converters demonstrate significant performance limitations. As modern power-electronic systems continue to evolve toward higher voltage inputs and increasingly lower regulated output levels, issues such as extremely low duty cycles, elevated switching stress, excessive ripple, and thermal inefficiency make single-stage topologies inadequate for high-conversion-ratio operation. By contrast, multistage buck converters mitigate these challenges by distributing the conversion ratio across multiple cascaded stages, enabling each stage to operate under more favourable electrical and thermal conditions. The modelling studies reviewed demonstrate that accurate prediction of converter behaviour relies heavily on understanding the steady-state voltage relation, where the overall output voltage is determined by the multiplicative contribution of individual stage duty cycles. Current distribution across stages further influences component sizing and thermal management, with earlier stages typically enduring higher current levels. Ripple attenuation is one of the most significant performance advantages offered by cascaded architectures, as each stage adds an LC filter section that progressively suppresses high-frequency switching components. This results in a cleaner and more stable output voltage, making multistage converters suitable for power-sensitive and noise-critical environments. Efficiency behaviour, while improved in many cases due to reduced voltage and stress across devices, depends critically on component selection, stage count, and operating frequency. Beyond an optimal number of stages, cumulative conduction, switching, and magnetic losses may diminish overall efficiency. Nevertheless, when designed with appropriate modelling and optimization techniques, multistage buck converters offer enhanced efficiency, reduced device stress, and improved thermal performance, establishing them as a reliable solution for deep step-down applications. Despite their advantages, multistage converters introduce increased system complexity, larger component count, potential interstage resonance, and more demanding control requirements. These limitations necessitate careful design practices, advanced modelling, and robust control strategies. Still, the overall findings confirm that multistage buck converters provide a high-performance and technically feasible alternative to single-stage converters in applications requiring substantial voltage reduction.

Future work on multistage buck converters presents several promising research directions. The design of advanced control strategies represents one key area of development. Techniques such as adaptive control, artificial intelligence–based regulation, and model-predictive control can improve transient performance, mitigate interstage interaction, and enhance converter stability under dynamic operating conditions. The integration of wide-bandgap semiconductor devices, including SiC and GaN, offers substantial opportunities to increase switching frequency, reduce losses, and improve power density. Further advancements in magnetic component technology—such as integrated magnetics, high-frequency ferrites, and nanocrystalline cores—could support more compact and efficient converter designs. Thermal management remains a critical research area as power density increases, requiring innovations such as embedded cooling, heat-spreading substrates, and electro-thermal co-optimization tools. Finally, hybrid topologies combining cascaded buck stages with resonant or switched-capacitor networks may enable ultra-high conversion ratios with lower loss, expanding the applicability of multistage converters in renewable energy, electric vehicle systems, and distributed power architectures. Continued research will support the evolution of multistage converters toward higher efficiency, greater reliability, and broader functional flexibility.

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