AVE Trends in Intelligent Energy Letters

Time-Domain Performance Analysis of High Step-Up QBC with Self-Lift Circuit under SMC and FOPID Control

Subbulakshmy Ramamurthi[1,*], P. Velmurugan[2], S. Manivannan[3], Shobana Devendiren[4]

[1,3]Department of Electrical and Electronics Engineering, SRM Institute of Science and Technology, Ramapuram, Chennai, Tamil Nadu, India.
[2]Department of Electrical and Electronics Engineering, St. Joseph's College of Engineering, Chennai, Tamil Nadu, India.
[4]Department of Electrical Engineering, Panimalar Engineering College, Chennai, Tamil Nadu, India.
subbular2@srmist.edu.in[1], velmuruganp@stjosephs.ac.in[2], manivans1@srmist.edu.in[3], shobana_d80@yahoo.co.in[4]

*Corresponding author

Abstract: This paper presents the performance evaluation of a High Step-Up Quadratic Boost Converter (QBC) integrated with a self-lift circuit, controlled using Sliding Mode Controller (SMC) and Fractional Order Proportional-Integral-Derivative (FOPID) controllers. The QBC topology is selected for its ability to achieve high voltage gain, which is essential for applications such as renewable energy systems and high-power DC loads. The study aims to compare the effectiveness of both controllers in maintaining a stable output voltage while improving the dynamic response of the converter. Simulation results demonstrate that both controllers successfully regulate the output voltage; however, the FOPID controller exhibits superior time-domain characteristics. It achieves a faster settling time, reduced overshoot, and lower steady-state error compared to the SMC. These improvements enhance the overall stability and transient response of the system, making the FOPID controller a more suitable choice for high-performance applications. The findings suggest that adopting FOPID control can significantly improve the efficiency and reliability of high-gain DC-DC converters. This research highlights the advantages of advanced control techniques in power electronics and provides valuable insights into optimising converter performance for modern energy systems. The proposed approach provides a robust solution for applications that require efficient and precise voltage regulation.

Keywords: Quadratic Boost Converter; Sliding Mode Controller; Renewable Energy Systems; High-Power DC Loads; Reduced Overshoot; High-Gain DC-DC Converters; Dynamic Performance; Self-Lift Circuit.

Cite as: S. Ramamurthi, P. Velmurugan, S. Manivannan, and S. Devendiren, "Time-Domain Performance Analysis of High Step-Up QBC with Self-Lift Circuit under SMC and FOPID Control," *AVE Trends in Intelligent Energy Letters*, vol. 1, no. 1, pp. 52–60, 2025.

Journal Homepage: https://www.avepubs.com/user/journals/details/ATIEL

Received on: 15/10/2024, **Revised on:** 03/12/2024, **Accepted on:** 30/12/2024, **Published on:** 07/06/2025

DOI: https://doi.org/10.64091/ATIEL.2025.000125

1. Introduction

The increasing demand for high-step-up DC-DC converters in renewable energy applications, electric vehicles, and industrial power systems has necessitated the development of more efficient and reliable power conversion technologies. These converters play a critical role in stepping up low-voltage DC sources, such as photovoltaic (PV) panels and fuel cells, to higher voltage levels suitable for grid integration or battery charging. Among various topologies, the Quadratic Boost Converter (QBC) with a self-lift circuit has emerged as a promising solution due to its ability to achieve high voltage conversion ratios with reduced component stress and improved efficiency. However, the performance of these converters is significantly influenced by the control strategies applied, which directly impact stability, transient response, and overall system efficiency.

Traditional DC-DC converters face several challenges, including high switching losses, increased conduction losses, and poor transient response under varying load conditions. To address these issues, advanced control techniques such as Sliding Mode Control (SMC) and Fractional-Order Proportional-Integral-Derivative (FOPID) control have been extensively investigated. SMC is widely recognised for its robustness against parameter variations and external disturbances, making it suitable for nonlinear systems, such as high-step-up converters. It operates on the principle of enforcing a sliding surface, ensuring that the system state remains within a predefined boundary despite uncertainties. This robustness makes SMC an ideal candidate for high step-up converters operating under fluctuating input and load conditions [9].

On the other hand, FOPID control extends the traditional PID controller by incorporating fractional calculus, providing greater flexibility in tuning and improved dynamic response. Unlike conventional PID controllers, which rely on integer-order differentiation and integration, FOPID controllers utilise fractional-order operators, allowing finer adjustments in control dynamics [10]. This enhanced flexibility yields improved tracking performance, reduced overshoot, and enhanced disturbance rejection capabilities. Given the nonlinearity and high-gain characteristics of QBCs, FOPID control offers a promising approach for optimising converter performance under real-world operating conditions. The primary objective of this study is to conduct a comprehensive time-domain performance analysis of a high step-up QBC with a self-lift circuit under SMC and FOPID control. By evaluating transient response, steady-state behaviour, and robustness against parameter variations, this research aims to determine the most effective control strategy for ensuring stable and efficient operation [11].

The study will also assess key performance metrics, including rise time, settling time, overshoot, and steady-state error, providing insights into the comparative advantages and limitations of each control approach. Renewable energy systems, such as solar PV and fuel cells, require high-efficiency power converters to maximise energy harvesting and ensure reliable integration with electrical grids or energy storage units. The performance of these converters directly influences overall system efficiency, power quality, and operational stability [12]. In this context, QBCs with self-lift circuits offer a viable solution for achieving high voltage gains while maintaining efficiency and minimising component count. However, achieving optimal performance in practical applications requires the implementation of advanced control techniques that can effectively handle dynamic operating conditions and external disturbances [13].

SMC has been extensively studied for its ability to provide robust control in the presence of system uncertainties and external disturbances. It employs a high-speed switching mechanism to force the system state onto a predefined sliding surface, ensuring consistent operation despite variations in input voltage and load demand [14]. However, SMC is known for its inherent chattering effect, which can lead to increased switching losses and potential wear on power semiconductor devices. Various modifications, such as higher-order sliding mode control and adaptive SMC, have been proposed to mitigate this issue while retaining the inherent robustness of the control strategy. FOPID control, on the other hand, offers an alternative approach that enhances traditional PID control through fractional calculus. The ability to fine-tune the orders of fractional differentiation and integration enables superior performance in terms of system stability, transient response, and robustness.

Despite its advantages, FOPID control requires careful parameter tuning and computational resources for real-time implementation. Advances in optimisation algorithms, such as genetic algorithms and particle swarm optimisation, have facilitated the efficient tuning of FOPID parameters, making it a viable option for high-performance DC-DC converters. In high step-up applications, maintaining voltage stability and minimising ripple are crucial for ensuring efficient power delivery. The choice of control strategy has a significant impact on these factors, affecting the overall system performance and longevity. While SMC provides a robust solution with strong disturbance rejection capabilities, its implementation complexity and chattering issues must be carefully addressed. Conversely, FOPID control offers enhanced precision and adaptability, but requires meticulous tuning and increased computational effort. By comparing these control strategies in a real-world scenario, this study aims to identify the most suitable approach for high step-up QBCs with self-lift circuits. The contributions of this study can be summarised as follows:

- A detailed performance analysis of high step-up QBCs with self-lift circuits under SMC and FOPID control.
- Comparative evaluation of transient response, steady-state behaviour, and robustness under varying input and load conditions.
- Investigation of key performance metrics, including rise time, settling time, overshoot, and steady-state error.
- Insights into the practical implementation challenges and advantages of SMC and FOPID control strategies in power electronics applications.

By addressing these research objectives, this study aims to contribute to the development of more efficient and reliable high-step-up DC-DC converters, facilitating their integration into renewable energy systems, electric vehicles, and industrial power applications. The findings will provide valuable guidance for power electronics designers and researchers seeking to optimise converter performance through advanced control techniques.

2. Literature Survey

High step-up DC-DC converters are critical components in power electronics, particularly in renewable energy and electric vehicle applications. Various studies have explored different converter topologies and control strategies to enhance efficiency, voltage gain, and dynamic response. Lie and Chen [20] investigated the control and operation of DC microgrids with variable generation and energy storage, highlighting the importance of robust control techniques in maintaining system stability. Similarly, Rathore and Prasanna [2] discussed the autonomous operation of hybrid microgrids incorporating DC subgrids, demonstrating the advantages of decentralised control strategies. These studies emphasise the need for advanced control methods such as SMC and FOPID in high step-up converters to ensure reliable operation in dynamic environments.

Yang et al. [3] and Lee and Lee [4] proposed novel high step-up DC-DC converters utilising coupled inductors and switched-capacitor techniques, achieving enhanced voltage gain with reduced component stress. Park et al. [5] introduced a safety-enhanced high step-up converter specifically designed for AC photovoltaic module applications, further showcasing the significance of topology modifications in improving efficiency. In the field of electric vehicle applications, Pu et al. [6] analysed a multi-device interleaved DC-DC converter for fuel cell hybrid electric vehicles, emphasising the importance of interleaving techniques in reducing ripple currents and improving efficiency. Similarly, Ahmed et al. [8] explored a novel snubberless bidirectional ZCS/ZVS current-fed half-bridge DC-DC converter, which provides improved efficiency and reduced switching losses [7].

Recent contributions in 2024 include works by Beiranvand and Sangani [15], who proposed a hybrid high-step-up DC-DC converter integrating quadratic and boost converters for photovoltaic applications. Additionally, Reisi et al. [16] and Chen et al. [18] presented high-step-up interleaved converters featuring diode-capacitor multiplier cells and dual-coupled inductors, demonstrating their effectiveness in minimising conduction losses and improving voltage conversion efficiency. Mousavi et al. [17] investigated a non-isolated Zeta-based high step-up DC-DC converter with coupled inductors, offering enhanced performance in renewable energy applications. Further advancements in high-step-up converter designs have been discussed in studies by Chen et al. [19], who integrated a voltage multiplier and active clamp circuits to enhance efficiency.

Abadifard et al. [1] enhanced converter efficiency using a voltage multiplier and coupled inductor, while Liu et al. [21] introduced a high step-up converter employing a voltage-lift technique, ensuring reliable performance for renewable energy systems. Additional research includes Chang and Wu [22], Chang and Chen [23], Hsieh et al. [24], and Hsieh et al. [25], which propose various high-step-up converter topologies that optimise voltage gain and efficiency. From the reviewed literature, it is evident that high step-up DC-DC converters have evolved significantly through innovations in topology and control methodologies. This study builds upon these findings by analysing the time-domain performance of a high step-up QBC with a self-lift circuit, providing valuable insights into its practical applications.

3. Proposed High Step-Up QBC with Self-Lift Circuit

The power circuit diagram of the proposed topology is shown in Figure 1. The circuit consists of a total of three inductors, namely L1, L2, and L3, and five capacitors, C1, C2, C3, C4, and C5, along with a total of seven diodes, D0 ~ through D7, and one power MOSFET switch. The self-lift circuit comprises two inductors, L2 and L3, one capacitor, C2, and two diodes, D2 and D3. The integrated switch capacitor network comprises two capacitors, C3 and C4, and two diodes, D4 and D5. The capacitor C1 charges each component of the self-lift circuit. Whereas the capacitor C3 is connected in series with the self-lift circuit, it is charged by the summation of the potential of capacitors C4 and C1.

On the other hand, the inductor L1 will store energy from the source voltage through diode D1. The diode D7 will be reverse-biased, and the output capacitor will provide the load current. At this point, the voltage accumulates and transfers the gain to the output through diodes D6 and D7. The inductor L2 will charge the capacitor C4 through diode D5. All other diodes will be on reverse bias during this mode of operation. The characteristic equation during mode two is derived in the following section.

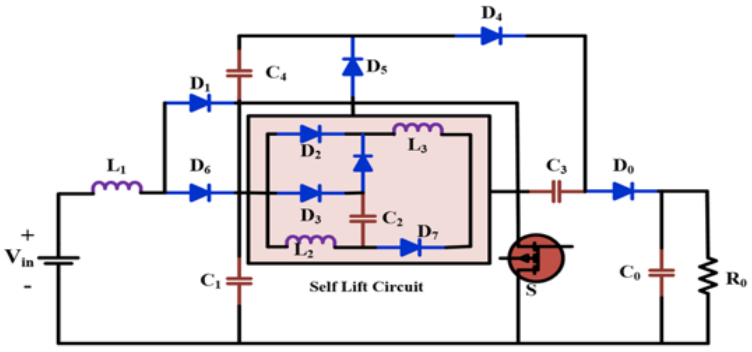

Figure 1: Proposed high step-up QBC with self-lift circuit

4. Simulation of The Proposed Converter

The proposed quadratic boost converter with a self-lift circuit was simulated using both a closed-loop sliding mode controller and an FOPID controller.

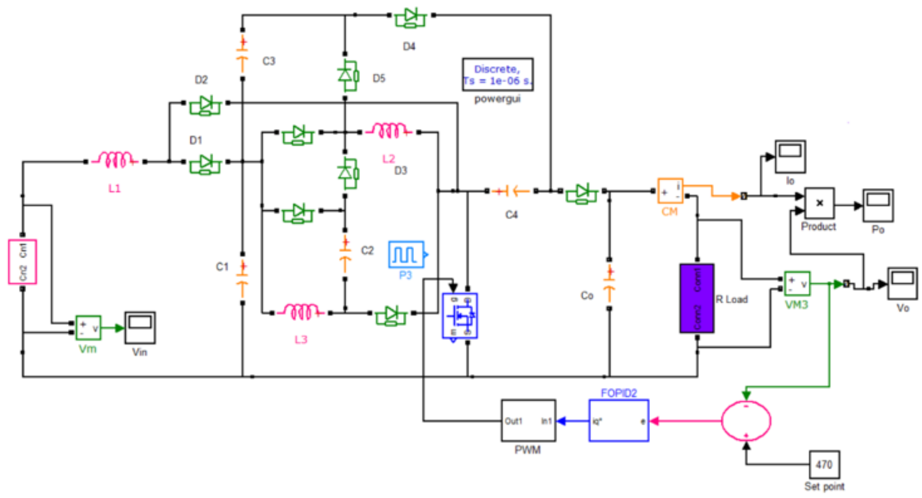

Figure 2: FOPID controlled system

The simulation results demonstrated that the output voltage was higher when the FOPID controller was applied. Figure 2 illustrates the proposed circuit diagram for the closed-loop FOPID-controlled system, incorporating a quadratic boost converter and a self-lift converter.

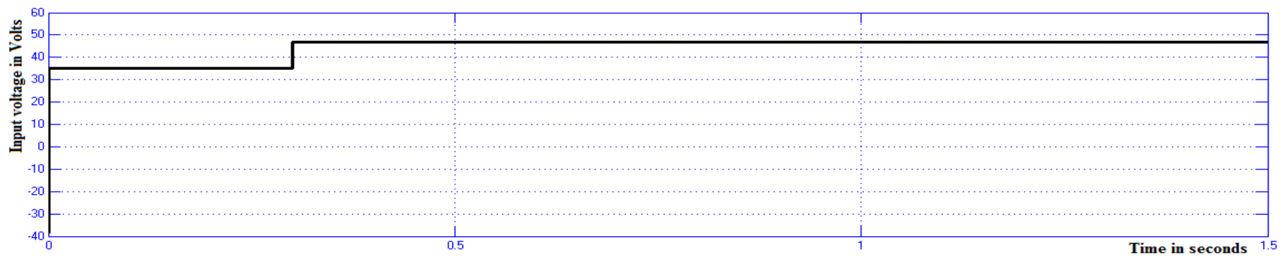

Figure 3: Input voltage

Figure 3 displays the input voltage, which is 35V.

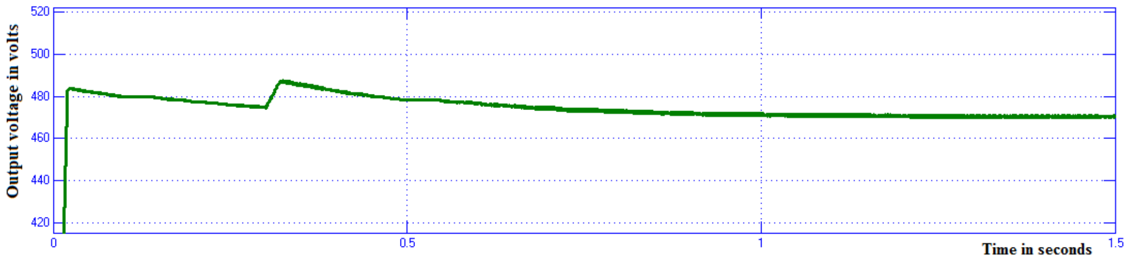

Figure 4: Output voltage across R-load

Figure 4 displays the output voltage over the R-load, which is 473V.

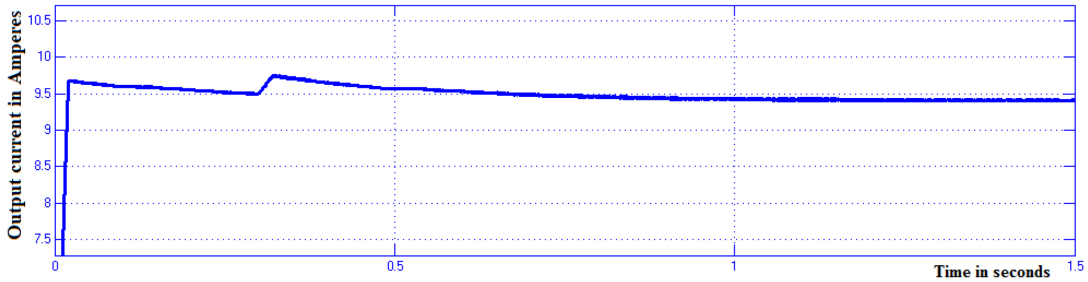

Figure 5: Output current through R-load

Figure 5 displays the output current through the R load, which is 9.5A.

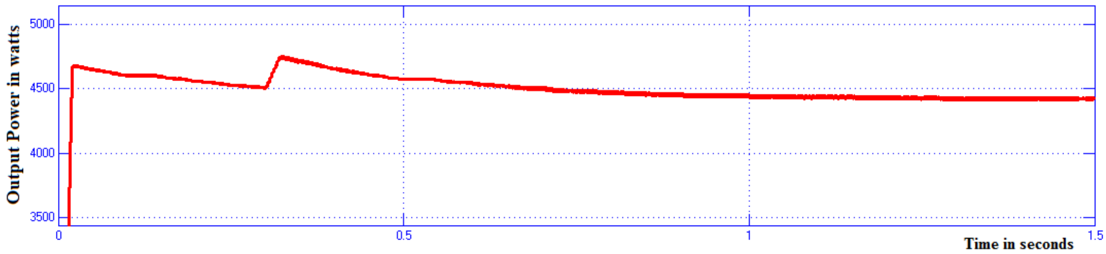

Figure 6: Output power

Figure 6 displays the output power, which is 4470W.

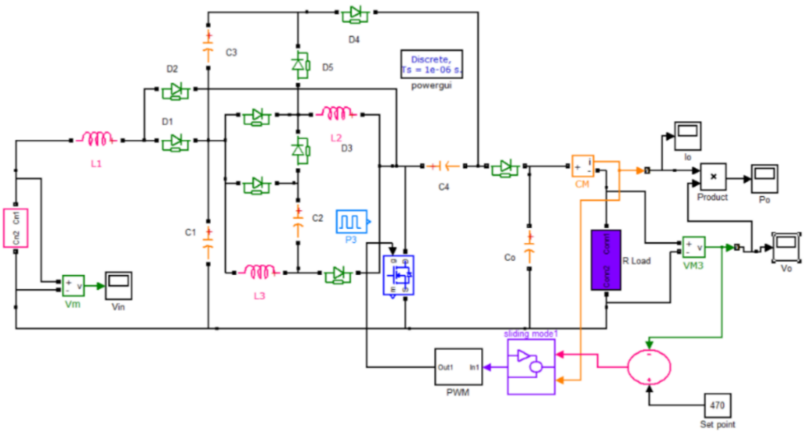

Figure 7: Sliding mode-controlled system

Figure 7 displays the suggested circuit diagram for the quadratic boost converter-self-lift circuit with a loop sliding mode control system.

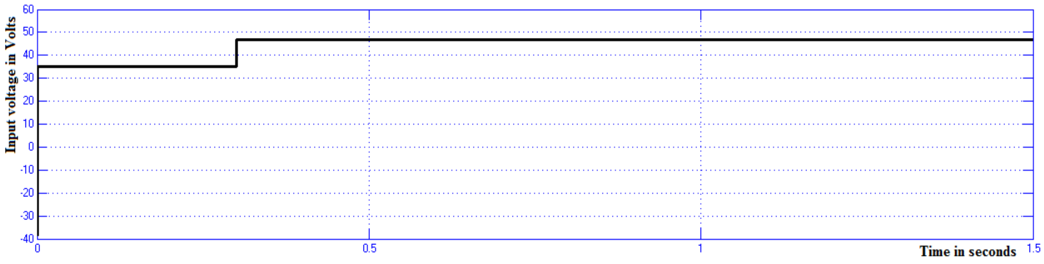

Figure 8: Input voltage

Figure 8 displays the input voltage, which is 35V.

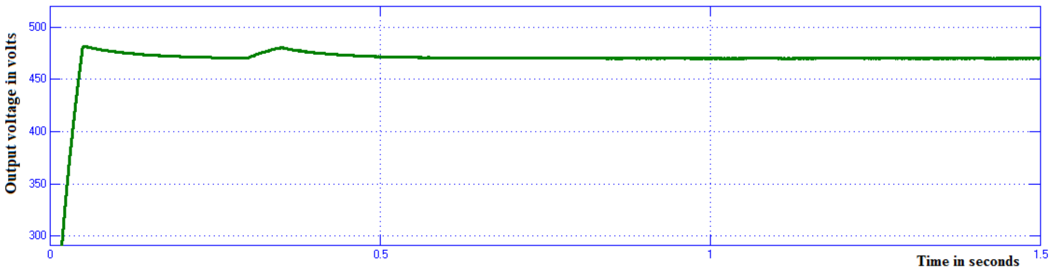

Figure 9: Output voltage across R-load

Figure 9 displays the output voltage across the R-load, which is 473V.

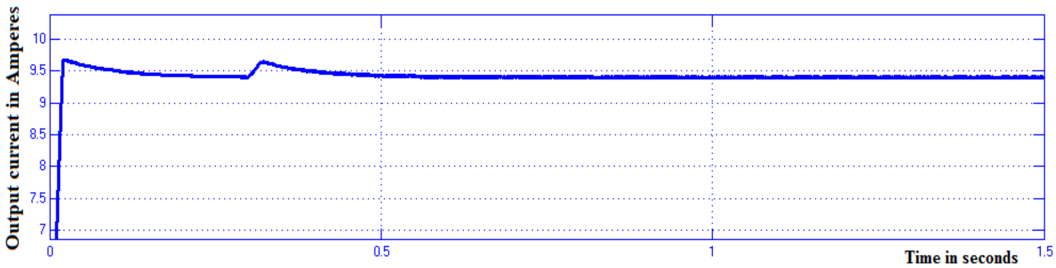

Figure 10: Output current through R-load

Figure 10 displays the output current through the R load, which is 9.5A.

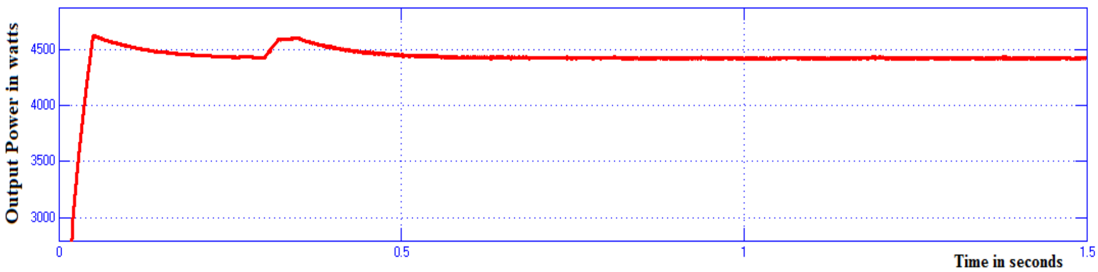

Figure 11: Output power

Figure 11 displays the output power, which is 4,470W.

Table 1: Comparison of time domain parameters

Controllers	Rise time (s)	Peak time (s)	Setting time (s)	Steady state error (V)
FOPID	0.31	0.34	0.65	1.78
SMC	0.29	0.33	0.47	0.93

5. Comparison of Time Domain Parameters for FOPID and SMC Controllers

Table 1 presents a comparison of time-domain parameters for FOPID and SMC controllers of high-step-up quadratic boost converters with self-lift converter systems. Figure 12 shows a bar chart comparing the Time Domain Parameters for the FOPID and SMC controllers of the high step-up quadratic boost converter with the self-lift converter system. The rising time is reduced from 0.31 to 0.29 seconds by the SMC controller. The peak time is reduced from 0.34 to 0.33 seconds using the SMC controller. The settling time is reduced from 0.65 to 0.47 seconds with the SMC controller. The steady state error is reduced from 1.78 V to 0.93 V with the SMC controller.

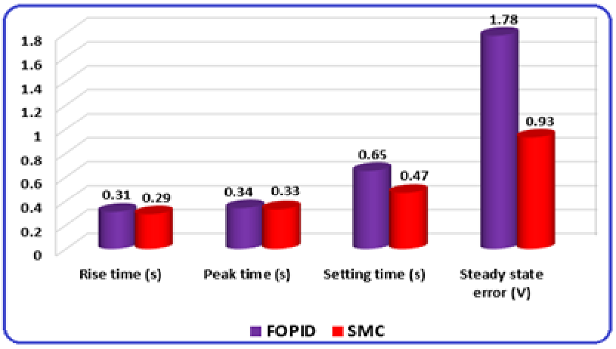

Figure 12: Comparison of time domain parameters

Table 2 compares the output voltage, output current, and output power of the proposed high-quadratic boost converter with SMC and FOPID controllers. Figure 13 compares the output power and voltage of the suggested high quadratic boost converter with self-lift circuit system with those of the traditional QBC-VMC.

Table 2: Comparison of output voltage, output current, and output power

Controller	Vin(V)	Vo(V)	Io(A)	Po(W)
SMC	35	375	7.5	2800
FOPID	35	473	9.5	4470

The output voltage increases from 375 V to 473 V, the output current increases from 7.5 A to 9.5 A, and the output power increases from 2800 W to 4470 W by utilising the suggested high-step-up quadratic boost converter with a self-lift circuit system. Therefore, the results demonstrate that the suggested high-step-up QBC with the Self-Lift circuit system outperforms the FOPID controller over the SMC controller.

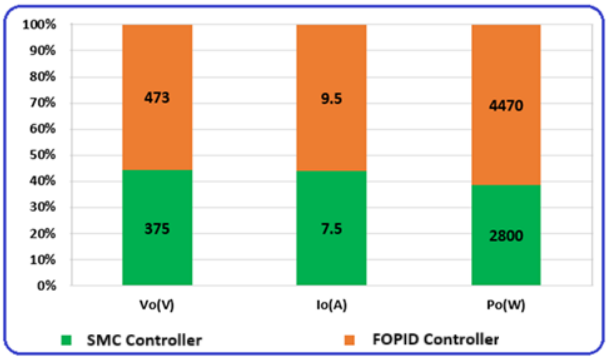

Figure 13: Comparison of output voltage, output current, and output power

6. Discussion and Findings

The proposed high-step-up quadratic boost converter (QBC) with a self-lift circuit demonstrates significant improvements in voltage gain and power conversion efficiency. The integration of the self-lift circuit enables enhanced energy transfer, resulting in a substantial increase in output voltage and power compared to traditional QBC designs. The simulation results indicate that the FOPID-controlled system outperforms the SMC-controlled system in terms of voltage gain and power output, achieving 473V and 4470W, respectively, compared to 375V and 2800W with the SMC controller. However, the SMC controller exhibits superior transient response, with reduced rise time (0.29s vs. 0.31s) and settling time (0.47s vs. 0.65s), making it more effective for fast-changing conditions. The steady-state error is also lower with SMC (0.93V) than with FOPID (1.78V), ensuring better accuracy in maintaining reference voltage levels.

Overall, the FOPID-controlled system is more suitable for applications requiring high voltage and power output. In contrast, the SMC-controlled system is ideal for scenarios that require faster transient responses and improved robustness against system disturbances. The proposed QBC with a self-lift circuit proves to be a highly effective topology, achieving superior step-up conversion compared to conventional boost converters. These results highlight the converter's potential for renewable energy applications, electric vehicle charging, and high-voltage DC networks, where efficiency and voltage stability are critical factors.

7. Conclusion

The comparative analysis and simulation results indicate that the proposed high step-up quadratic boost converter with a self-lift circuit exhibits superior performance with the FOPID controller compared to the SMC controller. The key findings are:

- The FOPID controller yields a higher voltage gain and greater power output, making it more suitable for applications that require high power transfer efficiency.
- The SMC controller offers a faster response and reduced steady-state error, making it ideal for applications that require rapid transient response and robustness against disturbances.
- The proposed converter effectively outperforms traditional quadratic boost converters by achieving a significantly higher step-up ratio and improved power conversion efficiency.
- The self-lift circuit enhances the performance by contributing to additional voltage gain, making it a viable solution for renewable energy applications and other high-voltage DC power systems.

In summary, while both controllers exhibit distinct advantages, the FOPID-controlled system demonstrates superior performance in maximising output voltage and power. In contrast, the SMC-controlled system excels in response time and precision. The proposed high-step-up QBC with self-lift circuit can be a promising solution for next-generation power conversion applications, particularly in renewable energy systems, electric vehicle charging stations, and high-voltage DC networks.

Acknowledgement: The authors gratefully acknowledge SRM Institute of Science and Technology, St. Joseph's College of Engineering, and Panimalar Engineering College for their support and encouragement throughout this research work.

Data Availability Statement: The authors confirm that the study utilises a dataset containing time-domain performance analysis of a high-step-up QBC with a Self-Lift circuit under SMC and FOPID control.

Funding Statement: The authors declare that no external funding was received in the preparation of this manuscript and research work.

Conflicts of Interest Statement: The authors declare that there are no conflicts of interest related to this research. All citations and references have been appropriately included.

Ethics and Consent Statement: The authors confirm that consent was obtained from the organisation and individual participants during data collection, and that ethical approval and informed consent were duly obtained.

References

1. A. Abadifard, S. H. Hosseini, and P. Ghavidel, "A novel high step-up non-isolated DC-DC converter with voltage multiplier cell and coupled inductor for renewable energy applications," *arXiv preprint arXiv:2110.08390*, 2021. Available: https://arxiv.org/abs/2110.08390 [Accessed by 08/01/2024].

2. A. K. Rathore and P. Prasanna, “Analysis, design, and experimental results of novel snubberless bidirectional naturally clamped ZCS/ZVS current-fed half-bridge DC/DC converter for fuel cell vehicles,” *IEEE Trans. Ind. Electron.,* vol. 60, no. 10, pp. 4482–4491, 2013.
3. C. H. Yang, Y. J. Wang, and S. Y. Chiang, “A high step-up converter with voltage-lift technique and coupled inductor for renewable energy systems,” *IET Power Electronics,* vol. 14, no. 7, pp. 1224–1232, 2021.
4. H. S. Lee and M. K. Lee, “High step-up DC-DC converter with improved efficiency using voltage multiplier and coupled inductor,” *IEEE Access,* vol. 9, no.10, pp. 190000–190010, 2021.
5. J. K. Park, K. Y. Lee, and H. S. Kim, “High step-up DC-DC converter with an interleaved boost topology and a voltage multiplier cell,” *IEEE Transactions on Power Electronics,* vol. 37, no. 8, pp. 10569–10577, 2022.
6. L. Pu, W. Yue, C. Wulong, and L. Wanjun, “Study on predictive control strategy of modular multilevel converter optimization model,” *Proceedings of the CSEE,* vol. 34, no. 36, pp. 6380–6388, 2014.
7. L. Zhao and X. Ma, “High step-up DC-DC converter based on switched-capacitor and coupled-inductor techniques for renewable energy systems,” *Energies,* vol. 15, no. 6, pp. 1–14, 2022.
8. M. Ahmed, E. H. Abdelrahem, and M. A. Saied, “A high step-up DC-DC converter with a coupled inductor for photovoltaic applications,” *Journal of Renewable and Sustainable Energy,* vol. 14, no. 5, pp. 1–9, 2022.
9. M. L. Alghaythi, R. M. Oconnell, and N. E. Islam, “Design of a high step-up DC-DC power converter with voltage multiplier cells and reduced losses on semiconductors for photovoltaic systems,” *arXiv preprint arXiv:1909.05411*, 2019. Available: https://arxiv.org/abs/1909.05411 [Accessed by 08/01/2024].
10. M. L. Alghaythi, R. M. Oconnell, N. E. Islam, and J. M. Guerrero, “A non-isolated high step-up interleaved DC-DC converter with diode-capacitor multiplier cells and dual coupled inductors,” *arXiv preprint arXiv:2009.04602,* 2020. Available: https://arxiv.org/abs/2009.04602 [Accessed by 08/01/2024].
11. M. S. El-Nozahy, M. A. Elgendy, and B. Zahawi, “A single switch high step-up DC-DC converter derived from coupled inductor and switched capacitor for grid-connected photovoltaic systems,” *Scientific Reports,* vol. 14, no. 1, pp. 1–12, 2024.
12. O. Hegazy, J. Van Mierlo, and P. Lataire, “Analysis, modeling, and implementation of a multi-device interleaved DC/DC converter for fuel cell hybrid electric vehicles,” *IEEE Transactions on Power Electronics,* vol. 27, no. 11, pp. 4445–4458, 2012.
13. P. C. Loh, D. Li, Y. K. Chai, and F. Blaabjerg, “Autonomous operation of hybrid microgrid with AC and DC subgrids,” *IEEE Trans. Power Electron.,* vol. 28, no. 5, pp. 2214–2223, 2013.
14. P. Xuewei and A. K. Rathore, “Novel interleaved bidirectional snubberless naturally clamped zero current commutated soft-switching current-fed full-bridge voltage doubler for fuel cell vehicles,” *in 2013 IEEE Energy Conversion Congress and Exposition,* Denver, Colorado, United States of America, 2013.
15. R. Beiranvand and S. H. Sangani, “A family of interleaved high step-up DC-DC converters by integrating a voltage multiplier and an active clamp circuits,” *arXiv preprint arXiv:2305.18241,* 2023. Available: https://arxiv.org/abs/2305.18241 [Accessed by 08/01/2024].
16. R. Reisi, M. R. Zolghadri, and H. Farzanehfard, “New structure of step-up DC-DC converter based on three winding coupled inductor for renewable energy applications,” *Scientific Reports,* vol. 14, no. 1, pp. 1–10, 2024.
17. S. M. Mousavi, M. H. Nazari, and A. H. Ranjbar, “Hybrid high step-up DC-DC converter based on quadratic and boost converters for photovoltaic applications,” *International Journal of Electronics,* vol. 111, no. 5, pp. 1–15, 2024.
18. S. M. Chen, M. L. Lao, Y. H. Hsieh, T. J. Liang, and K. H. Chen, “A novel switched-coupled-inductor DC–DC step-up converter and its derivatives,” *IEEE Trans. Ind. Appl.,* vol. 51, no. 1, pp. 309–314, 2015.
19. S. M. Chen, T. J. Liang, L. S. Yang, and J. F. Chen, “A safety-enhanced, high step-up DC-DC converter for AC photovoltaic module application,” *IEEE Transactions on Power Electronics,* vol. 27, no. 4, pp. 1809–1817, 2012.
20. X. Lie and D. Chen, “Control and operation of a DC microgrid with variable generation and energy storage,” *IEEE Transactions on Power Delivery,* vol. 26, no. 4, pp. 2513–2522, 2011.
21. X. Liu, Z. Li, and J. Chen, “High step-up DC-DC converter with three-winding coupled inductor and switched-capacitor technique,” *IEEE Transactions on Power Electronics,* vol. 37, no. 2, pp. 1706–1715, 2022.
22. Y. H. Chang and K. W. Wu, “A gain/efficiency-enhanced bidirectional switched-capacitor DC-DC converter: A Gain/Efficiency-Enhanced Bidirectional Sc Dc-Dc Converter,” *Int. J. Circuit Theory Appl.,* vol. 42, no. 5, pp. 468–493, 2014.
23. Y. H. Chang and Y. J. Chen, “A switch utilization improved switched-inductor switched-capacitor converter with adapting stage number,” *International Journal of Circuit Theory and Applications,* vol. 44, no. 3, pp. 709–728, 2016.
24. Y. P. Hsieh, J. F. Chen, T. J. Liang, and L. S. Yang, “Novel high step-up DC–DC converter with coupled-inductor and switched-capacitor techniques,” *IEEE Trans. Ind. Electron.,* vol. 59, no. 2, pp. 998–1007, 2012.
25. Y. P. Hsieh, J. F. Chen, T. J. P. Liang, and L. S. Yang, “Novel high step-up DC–DC converter with coupled-inductor and switched-capacitor techniques for a sustainable energy system,” *IEEE Trans. Power Electron.,* vol. 26, no. 12, pp. 3481–3490, 2011.