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AI-Enabled Investigation of the Effect of PCB Thickness on Conversion Losses and Efficiency of a DC–DC Buck Converter Under Heatsink-Assisted Operation

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ABSTRACT

This paper presents an Artificial Intelligence–assisted simulation based on python algorithm to investigate the effects of FR-4 PCB thickness on conversion losses and conversion efficiency of a DC–DC buck converter operating with a heatsink. An XL4015-based buck converter delivering 5 V at 5 A from a 6–36 V input was used as case study and modeled over five PCB thicknesses (1.60 mm, 2.00 mm, 2.50 mm, 3.00 mm, 4.00 mm) while maintaining identical electrical components, copper weight, layout geometry, and switching frequency. The results obtained show that conversion loss decreased from 0.6016 to 0.3344 W at 6.00 V as the PCB thickness increased from 1.60 mm to 4.00 mm, and similarly, 0.5900 to 0.3299 W at 10.00 V, 0.5944 to 0.3316 W at 16.00 V, 0.6410 to 0.3498 W at 24.00 V, 0.7069 to 0.3756 at 30.00 V, 0.7998 to 0.4117 at 36.00 V, indicating reduced energy losses due to increase in thermal pathway for heat dissipation as the PCB thickness increases, and the corresponding conversion efficiency increased from 97.65 to 98.68 % at 6.00 V, 97.694 to 98.698 % at 10.00 V, 97.678 to 98.691 % at 16.00 V, 97.5 to 98.62 % at 24.00 V, 97.25 to 98.52 % at 30.00 V, 96.9 to 98.38 % at 36.00 V, demonstrating improved conversion efficiency as the PCB thickness increases. The findings established PCB thickness as a decisive board-level efficiency parameter and provide quantitative guidance for power electronics thermal management in converter design.

Keywords:
Buck converter,
PCB thickness,
Conversion Loss,
Conversion Efficiency,
AI-based Analysis,
Power Electronics,
Thermal Management.

INTRODUCTION

High-efficiency DC–DC buck converters are essential building blocks in modern industrial, automotive, and embedded power systems. These converters are required to operate over wide input voltage ranges while delivering stable, low-voltage outputs with minimal thermal energy loss and high reliability (Rashid, 2018; Mohan *et al*., 2019; Erickson & Maksimovic, 2020; Park and Kim,2021). Achieving such performance is traditionally addressed through optimized switching techniques, advanced control algorithms, and improved semiconductor technologies such as wide-bandgap devices (Alade, 2013; Lidow *et al.,*2020; Dehong *et al*., 2021; Stala *et al*., 2022; Talebian *et al*., 2024).

However, in high-current converters, a significant portion of total power loss originates from non-idealities external to active devices, including printed circuit board (PCB) parasitic resistance and thermally induced conduction losses (Holman, 2016; Rémy *et al*., 2019; Markus *et al*., 2016). The PCB not only provides mechanical support and electrical interconnection but also functions as a thermal pathway for heat dissipation (Holman, 2016; Kumar, 2018; Infineon Technologies,2019). Despite this dual role, PCB structural parameters, particularly dielectric thickness, are often treated as secondary considerations during converter design.

Previous studies have investigated copper thickness, trace width, thermal vias, and multilayer stack-up effects on power delivery and thermal performance (Rashid, 2018; Kumar, 2018; Staliulionis, 2020; Texas Instruments,2021; Sundeep *et al*., 2023). To the best of my knowledge, the isolated impact of PCB dielectric thickness on conversion loss and conversion efficiency has received limited attention, especially under conditions where a heatsink is present and component temperatures are partially controlled (Holman, 2016; Lasance & Poppe, 2017; Staliulionis, 2020; Sundeep *et al*., 2023). Furthermore, existing works rarely employ data-driven or AI-assisted approaches to extract

quantitative relationships between PCB geometry and converter performance (Wang, 2018; IEC 62368-1, 2018; Xinze *et al*., 2021; Edgar *et al*., 2024).
This paper addresses this gap by presenting an AI-assisted analysis of the effect of PCB thickness on conversion losses and efficiency of a DC–DC buck converter operating with a heatsink. By isolating PCB thickness as the sole design variable, the study provides new insights into board-level efficiency optimization beyond conventional circuit-level techniques.

MATERIALS AND METHODS

This research adopts a simulation-based analytical research approach to investigate the influence of printed circuit board (PCB) thickness on the conversion loss and conversion efficiency of a DC–DC step-down (buck) converter, consistent with established electro-thermal modeling practices in power electronics research (Rémy *et al*., 2019; ANSYS Inc., 2020). The analysis focuses on an XL4015-based buck converter implemented on FR4 substrates, selected due to its widespread use in low-to-medium power industrial applications (Rashid, 2018; Mohan *et al*., 2019).
An AI-assisted data analysis framework was employed to evaluate the electrical and thermal performance of the converter across five PCB thicknesses, following recent advances in AI-enabled modeling and prediction techniques for power (Xinze *et al*., 2021; Edgar *et al*., 2024). AI-assisted simulations were conducted under heatsink-assisted configurations to examine the influence of PCB thickness on thermal dissipation and overall converter behavior (Infineon Technologies, 2019).
To ensure a fair and controlled comparison, all electrical components, PCB layout geometry, copper thickness, switching frequency, and load conditions were maintained constant throughout the research, in line with best practices for isolating board-level design variables (Kumar,2018; Rémy *et al*., 2019). The XL4015 DC-DC .

Figure 1: XL4015 DC-DC Step-down Converter

AI-Assisted Computational Modeling

Artificial intelligence tool was employed to support the computational modeling of the DC–DC buck converter performance. The AI system was used to assist in generating simulation algorithms, regression models, and computational procedures for evaluating conversion loss and efficiency under different PCB thickness conditions. The AI tool was provided with structured prompts describing the converter specifications, input voltage range, output requirements, and PCB thickness parameters. Based on these inputs, the AI generated computational algorithms which were implemented in the Python programming environment using scientific libraries such as NumPy, Pandas, and Matplotlib.
The AI assistance was limited to algorithm development and modeling support, while all parameters, equations, and validation procedures were defined and verified by the researcher.

Prompt Design

To guide the AI-assisted modeling process, structured prompts were developed containing the following specifications about XL4015 DC-DC Step-down Converter:

i. Converter topology: DC–DC buck converter
ii. Control IC: XL4015 module
iii. Input voltage range: 6–36 V
iv. Input Current: 10 A
v. Switching Frequency: 180kHz (Fixed Frequency PWM)
vi. Input Capacitor: CS 100µF 50V
vii. Input Fuse: 5A

viii. Inductor: 33µH/5A shielded
ix. Schottky Diode: SS54/MBR1045
x. Feedback Resistors: R1=10kΩ, R2=10kΩ
xi. Potentiometer: 10kΩ
xii. Output voltage: 5 V
xiii. Output Power: 25Wmax
xiv. Maximum load current: 5 A
xv. PCB material: FR4
xvi. PCB thickness values: 1.60 mm, 2.00 mm, 2.50 mm, 3.00 mm, 4.00 mm

The prompts requested the AI system to:

i. Develop computational algorithms for estimating conversion loss.
ii. Model efficiency variation under different PCB thickness conditions.
iii. Generate numerical datasets for analysis.
iv. Produce regression-based predictive models for converter performance.

Algorithm for Conversion Loss and Efficiency Modeling

The AI-assisted algorithm computes converter performance by evaluating the major power loss mechanisms in the buck converter.

Algorithm Steps

1. ***Define Converter Parameters***:
   i. Input voltage (Vin)
   ii. Output voltage (Vout)
   iii. Load current (Iout)
   iv. PCB thickness (tPCB)
2. ***Calculate Output Power***:
   $P_{out} = V_{out} \times I_{out}$
3. ***Estimate MOSFET Conduction Loss***:
   $P_{MOSFET} = I_{out}^2 \times R_{DS(on)}$
4. ***Compute Inductor Copper Loss***:
   $P_{inductor} = I_{out}^2 \times R_L$
5. ***Estimate Switching Loss***:
   $P_{switch} = \frac{1}{2} V_{in} I_{out} (t_r + t_f) f_s$
6. ***Determine Total Power Loss***:
   $P_{loss} = P_{MOSFET} + P_{inductor} + P_{switch} + P_{control}$
7. ***Calculate Converter Efficiency***:
   $l\eta = \frac{P_{out}}{P_{out} + P_{loss}} \times 100$
8. The calculations were repeated for different PCB thickness values.
9. Apply regression modeling to generate predictive relationships between PCB thickness, conversion loss, and efficiency.

The AI-assisted modeling system was provided with the following converter specifications as summarized in Table 1.

Table 1: Model Input Parameters (Converter Module XL4015)

Input Voltage Range	6-36 Vdc, step 1 Vdc
Input Current	10 A
Output Voltage	5 Vdc
Output Current	5 A
Conversion Efficiency Target	≥ 97%
Output Power	25Wmax
Switching Frequency	180kHz (Fixed Frequency PWM)
Input Capacitor	CS 100µF 50V
MOSFET	XL4015IC
Inductor	33µH/5A shielded
Schottky Diode	SS54/MBR1045
Feedback Resistors	R1=10kΩ, R2=10kΩ
Potentiometer	10kΩ
Input Fuse	5 A
PCB material	FR-4
PCB thickness range	1.60 mm – 4.00 mm

The flowchart for modeling and analysis of the effect of PCB thickness on Conversion Losses and Efficiency of a DC–DC Buck Converter is shown in Figure 2.

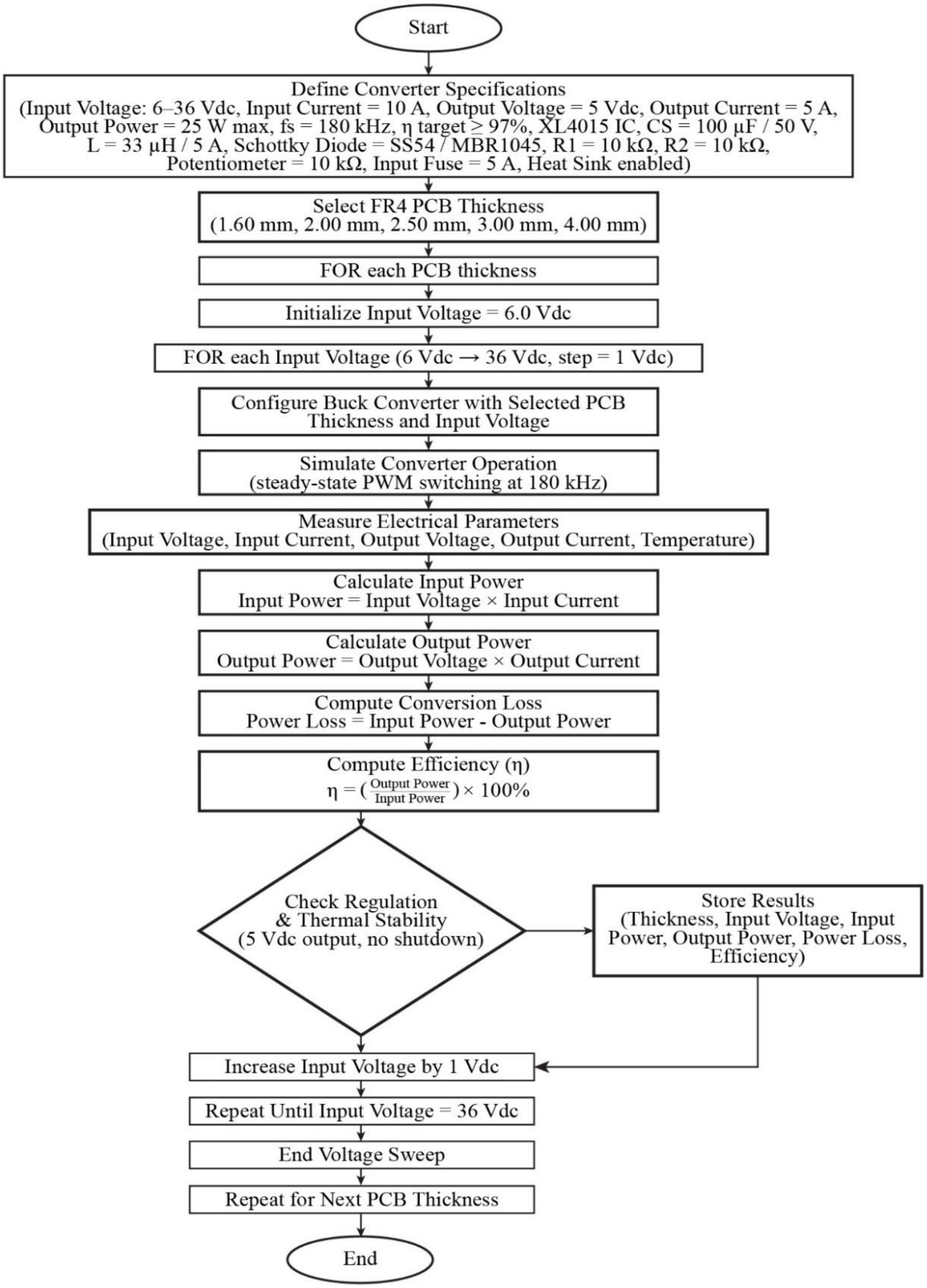

Figure 2: Flowchart formodeling and analysis of the effect of PCB Thickness on Conversion Losses and Efficiency of a DC–DC Buck Converter

RESULTS AND DISCUSSION

Table 2 and Figure 3 show that the effect of PCB thickness on the conversion loss of the step-down DC–DC converter with a heatsink is clearly reflected in both the magnitude of loss and their rate of increase with input voltage, as quantified by the gradient values. For the 1.60 mm PCB, conversion loss gradient of 0.0066 W/V indicates a strong dependence of conversion loss on input voltage. Conversion loss increases sharply from approximately 0.60 W at 6 V to nearly 0.80 W at 36 V, demonstrating that thinner PCBs accumulate conversion loss more rapidly as operating voltage rises. This behavior is associated with limited heat distribution capability, which increases operating temperatures and negatively affects the converter's overall conversion loss performance, making this thickness less suitable for sustained high-voltage operation.

Increasing the thickness to 2.00 mm results in a reduced gradient of 0.0052 W/V, showing an improvement in conversion loss behavior. In this case, conversion loss increases from about 0.55 W at 6 V to 0.70 W at 36 V, indicating lower loss sensitivity compared to the 1.60 mm PCB. The additional thickness improves heat spreading across the board, which stabilizes the operating condition of the converter and suppresses excessive growth in conversion losses as voltage increases. Although the losses still rise with voltage, the reduced gradient reflects improved loss control.

For the 2.50 mm PCB, the gradient further decreases to 0.0042 W/V, corresponding to a more gradual increase in conversion losses from approximately 0.49 W at 6 Vdc to about 0.62 W at 36 V. At this thickness, thermal distribution becomes more uniform, which limits temperature-driven loss escalation and enhances stability across the operating voltage range. This thickness represents a balanced improvement, where conversion losses are significantly lower than thinner boards while maintaining practical design flexibility.

The 3.00 mm PCB exhibits an even lower gradient of 0.0035 W/V, indicating reduced sensitivity of conversion losses to changes in input voltage. Conversion losses remain relatively low, increasing only from around 0.41 W at 6 Vdc to approximately 0.52 W at 36 Vdc. The increased substrate mass allows heat to spread more effectively before reaching the heatsink, resulting in consistently lower loss levels and improved operational robustness. The smaller gradient highlights the strong relationship between increased PCB thickness and reduced voltage-dependent loss variation.

The 4.00 mm PCB demonstrates the most favorable performance, with the lowest gradient of 0.0026 W/V. Conversion losses range from approximately 0.33 W at 6 Vdc to about 0.41 W at 36 Vdc, which are the minimum values observed across all tested thicknesses. The substantial thermal mass and enhanced heat-spreading capability significantly limit the rise in conversion losses as input voltage increases. The very low gradient indicates excellent resistance to voltage-induced loss escalation, confirming that greater PCB thickness effectively suppresses conversion losses.

Table 2: Conversion Loss of XL4015 Converter with Heatsink

Vin (V)	Conversion Loss at 1.60mm (W)	Conversion Loss at 2.00mm (W)	Conversion Loss at 2.50mm (W)	Conversion Loss at 3.00mm (W)	Conversion Loss at 4.00mm (W)
6	0.6016	0.5467	0.4925	0.4134	0.3344
7	0.5976	0.5435	0.49	0.4113	0.3328
8	0.5944	0.5409	0.4879	0.4096	0.3316
9	0.5918	0.5389	0.4863	0.4082	0.3306
10	0.59	0.5374	0.4851	0.4073	0.3299
11	0.5889	0.5366	0.4844	0.4067	0.3294
12	0.5885	0.5363	0.4842	0.4065	0.3293
13	0.5889	0.5366	0.4844	0.4067	0.3294
14	0.59	0.5374	0.4851	0.4073	0.3299
15	0.5918	0.5389	0.4863	0.4082	0.3306
16	0.5944	0.5409	0.4879	0.4096	0.3316
17	0.5976	0.5435	0.49	0.4113	0.3328
18	0.6016	0.5467	0.4925	0.4134	0.3344
19	0.6064	0.5505	0.4955	0.4159	0.3363
20	0.6118	0.5548	0.499	0.4188	0.3384
21	0.618	0.5598	0.5029	0.422	0.3408
22	0.625	0.5653	0.5073	0.4256	0.3435
23	0.6326	0.5714	0.5122	0.4297	0.3465
24	0.641	0.5781	0.5175	0.4341	0.3498
25	0.6502	0.5853	0.5233	0.4389	0.3534
26	0.66	0.5932	0.5295	0.444	0.3573
27	0.6706	0.6016	0.5363	0.4496	0.3614
28	0.682	0.6107	0.5435	0.4556	0.3658
29	0.6941	0.6203	0.5511	0.4619	0.3706
30	0.7069	0.6305	0.5592	0.4686	0.3756
31	0.7205	0.6413	0.5678	0.4757	0.3809

Vin (V)	Conversion Loss at 1.60mm (W)	Conversion Loss at 2.00mm (W)	Conversion Loss at 2.50mm (W)	Conversion Loss at 3.00mm (W)	Conversion Loss at 4.00mm (W)
32	0.7349	0.6527	0.5769	0.4832	0.3864
33	0.75	0.6647	0.5864	0.4911	0.3923
34	0.7658	0.6773	0.5965	0.4994	0.3985
35	0.7824	0.6905	0.6069	0.5081	0.4049
36	0.7998	0.7043	0.6179	0.5171	0.4117

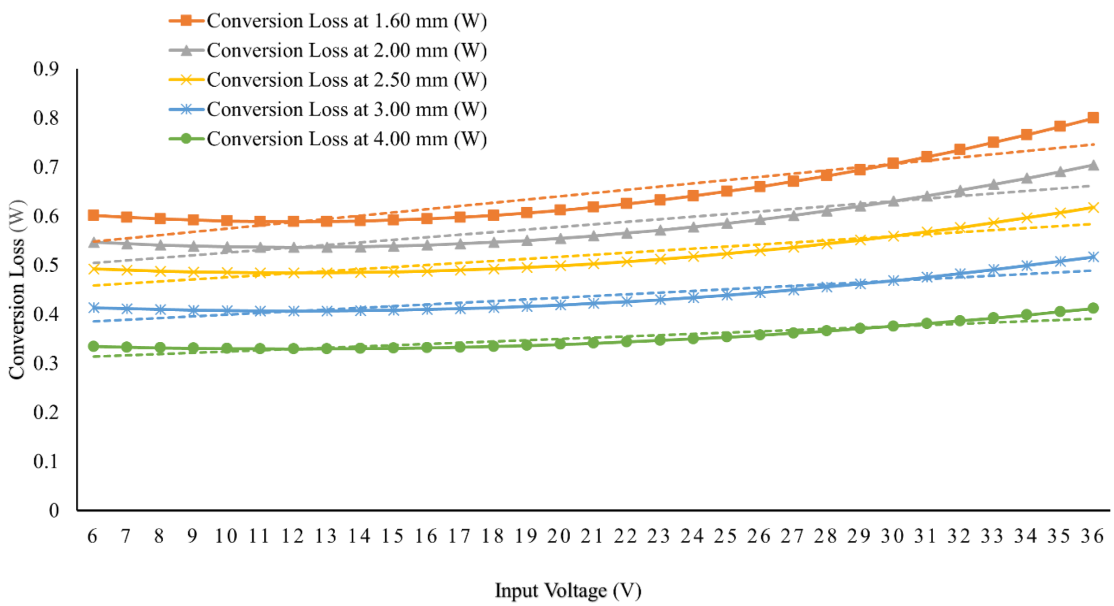

Figure 3: Variation of Conversion Loss against Input Voltage for Various PCB Thicknesses with Heatsink

Conversion efficiency trends mirror the conversion loss behavior. Table 4 and Figure 4 show the conversion efficiency of the XL4015 step-down converter increased with input voltage up to a certain point because the device operated closer to its optimal switching and regulation region. In the mid-range input voltages, particularly around 10–14 V, the converter achieved stable duty-cycle operation, reduced internal stress, and more favorable energy transfer conditions, which resulted in higher conversion efficiency. Beyond this range, as the input voltage increased further, a gradual drop in conversion efficiency was observed. This reduction occurred because higher input voltages increased the internal energy processing demand of the converter, leading to greater efficiency degradation despite the presence of a heatsink. Additionally, at lower input voltages, efficiency was reduced due to less optimal regulation conditions. Therefore, the conversion efficiency peak represented the balance point where the converter operated most effectively, after which efficiency declined as operating conditions moved away from this optimal region, even though overall efficiency remained high.

The 1.60 mm PCB consistently recorded the lowest conversion efficiency across the entire input voltage range of 6–36 V. The efficiency peaked at 97.7% at 12 V and declined steadily to 96.9% at 36 V, indicating reduced conversion efficiency retention at higher voltages. The maximum negative gradient value of −0.025 %/V indicated a high sensitivity of conversion efficiency to variations in input voltage. This behavior confirmed that the thinner PCB limited the ability of the converter to maintain high conversion efficiency as voltage increased.

For the 2.00 mm PCB, conversion efficiency improved across all input voltages when compared to the 1.60 mm PCB thickness. The efficiency reached 97.9% at 12 V and gradually reduced to 97.26% at 36 V, indicating better efficiency preservation at elevated voltages. The reduced gradient of −0.02 %/V reflected a moderate decline in conversion efficiency with increasing input voltage. This result showed that increasing PCB thickness enhanced the converter's ability to maintain higher efficiency. The heatsink continued to provide thermal stability, particularly within the optimal 10–14 V operating range. The combined influence of increased PCB thickness and the heatsink resulted in improved conversion efficiency across the operating range.

The 2.50 mm PCB exhibited further improvement in conversion efficiency, achieving a peak value of 98.1% at 12 V and decreasing to 97.588% at 36 V. The gradient value of −0.016 %/V indicated enhanced conversion efficiency retention and reduced sensitivity to input voltage changes. This thickness demonstrated a balanced performance, where higher conversion efficiency was maintained without significant degradation at higher voltages. Improved heat spreading through the thicker PCB contributed to this stability, while the heatsink ensured consistent thermal conditions throughout operation.

For the 3.00 mm PCB, conversion efficiency remained consistently high across the full input voltage range. The conversion efficiency reached a maximum of 98.4% at 12 V and decreased to 97.973% at 36 V, showing strong conversion efficiency retention at high voltages. The gradient value of −0.0133 %/V confirmed a slower rate of conversion efficiency decline compared to thinner PCBs. This behavior indicated improved thermal distribution within the PCB, which helped maintain stable conversion efficiency as input voltage increased. The presence of the heatsink ensured controlled operating temperatures, particularly within 10–14 V input voltage range. PCB thickness improved conversion efficiency stability, while the heatsink reinforced thermal regulation.

The 4.00 mm PCB produced the highest conversion efficiency among all tested PCB thicknesses. The conversion efficiency peaked at 98.7% at 12 V and maintained a high value of 98.38% at 36 V, confirming the best conversion efficiency preservation across the voltage range. The minimal negative gradient of −0.01 %/V demonstrated the best conversion efficiency stability and minimal sensitivity to input voltage variations compared to the other four PCB thicknesses. This thickness provided the most effective improvement of conversion efficiency due to improved heat spreading and thermal mass within the PCB. The heatsink further strengthened this performance by maintaining consistent thermal conditions throughout operation.

Table 3: Conversion Efficiency of XL4015 Converter with Heatsink

Vin (V)	Conversion Efficiency at 1.60mm (%)	Conversion Efficiency at 2.00mm (%)	Conversion Efficiency at 2.50mm (%)	Conversion Efficiency at 3.00mm (%)	Conversion Efficiency at 4.00mm (%)
6	97.65	97.86	98.068	98.373	98.68
7	97.665	97.872	98.078	98.381	98.686
8	97.678	97.882	98.086	98.388	98.691
9	97.688	97.89	98.092	98.393	98.695
10	97.694	97.896	98.096	98.397	98.698
11	97.699	97.899	98.099	98.399	98.699
12	97.7	97.9	98.1	98.4	98.7
13	97.699	97.899	98.099	98.399	98.699
14	97.694	97.896	98.096	98.397	98.698
15	97.688	97.89	98.092	98.393	98.695
16	97.678	97.882	98.086	98.388	98.691
17	97.665	97.872	98.078	98.381	98.686
18	97.65	97.86	98.068	98.373	98.68
19	97.632	97.846	98.056	98.364	98.673
20	97.611	97.829	98.043	98.353	98.664
21	97.587	97.81	98.028	98.34	98.655
22	97.561	97.789	98.011	98.326	98.644
23	97.532	97.766	97.992	98.31	98.633
24	97.5	97.74	97.972	98.293	98.62
25	97.465	97.712	97.95	98.275	98.606
26	97.428	97.682	97.926	98.255	98.591
27	97.387	97.65	97.9	98.233	98.575
28	97.344	97.616	97.872	98.21	98.558
29	97.299	97.579	97.843	98.186	98.539
30	97.25	97.54	97.812	98.16	98.52
31	97.199	97.499	97.779	98.133	98.499
32	97.144	97.456	97.744	98.104	98.478
33	97.087	97.41	97.708	98.073	98.455
34	97.028	97.362	97.67	98.041	98.431
35	96.965	97.312	97.63	98.008	98.406
36	96.9	97.26	97.588	97.973	98.38

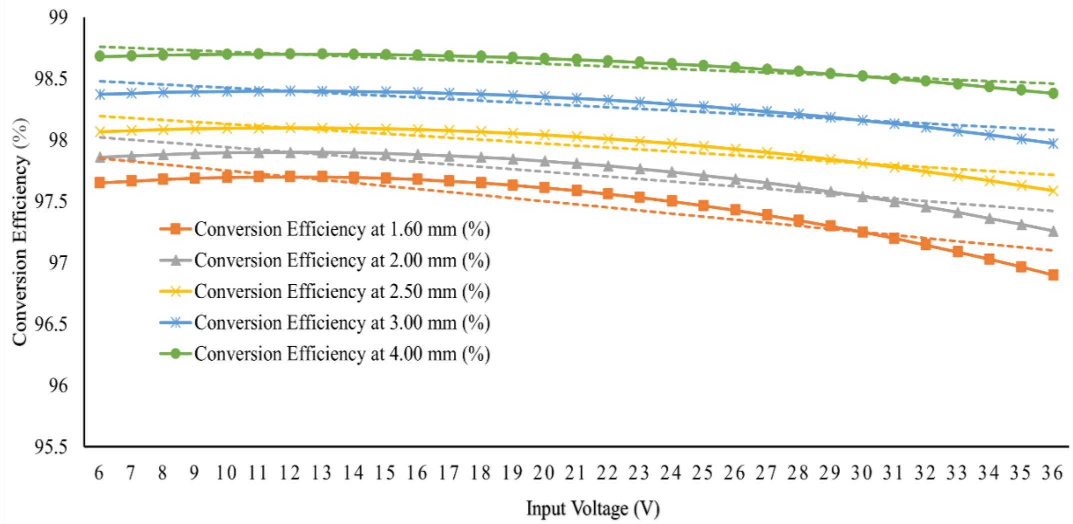

Figure 4: Conversion Efficiency against Input Voltage for Various PCB Thicknesses with Heatsink

CONCLUSION

This paper has presented an AI-assisted modeling of the effect of PCB thickness on conversion loss and conversion efficiency of a DC–DC buck converter operating with a heatsink. Results demonstrate that increasing PCB thickness significantly reduces conversion losses and improves efficiency by enhancing thermal spreading and stabilizing temperature-dependent electrical behavior. The study establishes PCB thickness as a first-order board-level design parameter and provides quantitative evidence that even in heatsink-assisted systems, PCB structural optimization is essential for achieving high efficiency and robust performance in industrial power converters.

RECOMMENDATIONS

Future work will involve experimental validation of the simulation results. Laboratory measurements of conversion losses, conversion efficiency, and thermal behavior to confirm the accuracy of the AI-assisted simulation findings.

Future studies may employ advanced machine learning or optimization algorithms to determine optimal PCB structural parameters for improved thermal management and converter efficiency.

AI DISCLOSURE STATEMENT

Use of Artificial Intelligence Tool

An artificial intelligence tool (ChatGPT) was used to assist in generating computational algorithms and modeling workflows. The authors defined all system parameters, verified the generated algorithms, and conducted the final analysis and interpretation of the results.

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