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# An Automated Test Bench for Characterizing the Efficiency of DC-DC Converters under Dynamic Load Conditions

***Anna Belhassen***
*Independent Researcher, UK*

**Abstract:** This study presents the design and development of an automated test bench for characterizing the efficiency of DC-DC converters under dynamic load conditions, addressing the limitations of conventional static testing methods. The proposed system integrates programmable hardware, real-time data acquisition, and automated control algorithms to simulate realistic load variations and capture high-resolution performance data. A synchronous buck converter was used as the test model, operating over a load range of 10%–100%. Key parameters such as input/output voltage, current, ripple voltage, temperature, efficiency, and transient response were continuously monitored and statistically analyzed. Results revealed that converter efficiency decreased from 96.6% to 93.5% as load increased, primarily due to thermal rise and increased switching losses, with strong negative correlations observed between efficiency and temperature (r = -0.987). Regression analysis confirmed temperature as the dominant factor influencing performance, while cluster analysis classified operational states into high-efficiency (10–50%) and high-stress (75–100%) regimes. The developed test bench demonstrated exceptional accuracy, repeatability, and adaptability, successfully replicating real-world conditions and providing comprehensive insights into converter behavior. Overall, this automated system establishes a robust, scalable, and intelligent framework for DC-DC converter testing facilitating efficient design validation, performance benchmarking, and predictive diagnostics in power electronics research and industry applications.

**Keywords:** DC-DC converter, automated test bench, efficiency characterization, dynamic load, thermal performance, power electronics, cluster analysis.

## INTRODUCTION

### Background and Significance of DC-DC Converters

DC-DC converters are integral components in modern electronic systems, responsible for efficiently managing and converting power between different voltage levels (Patrizi, *et al.*, 2021). Their application spans a wide range of domains from consumer electronics, renewable energy systems, and electric vehicles to aerospace and industrial automation. The increasing demand for compact, efficient, and reliable power management solutions has intensified research into improving converter performance under varying operating conditions (Badar *et al.*, 2021). Efficiency, being a critical design metric, determines not only the thermal behavior and energy loss but also the overall system reliability and sustainability. Consequently, precise characterization of converter efficiency across a spectrum of load conditions has become a fundamental requirement for both design optimization and quality assurance (Fabre, *et al.*, 2020).

### Challenges in Evaluating Efficiency Under Dynamic Load Conditions

Traditional methods for evaluating converter performance often rely on static load measurements, where the converter operates under fixed load conditions (Alemanno et al., 2023). While such tests provide a baseline understanding of converter behavior, they fail to capture the true efficiency variations that occur under dynamic load conditions scenarios that more closely represent real-world applications (Yodwong, *et al.*, 2023). Dynamic loads, characterized by rapid and unpredictable changes in current demand, can significantly affect the converter's transient response, switching losses, and thermal characteristics. Manual testing in these environments is not only labor-intensive but also prone to inconsistencies, limiting the accuracy and repeatability of results (Dolara, *et al.*, 2024). Hence, a more advanced, automated testing methodology is necessary to overcome these limitations and provide a holistic understanding of converter performance.

### Need for Automation in Converter Characterization

Automation in the testing and characterization of DC-DC converters presents a paradigm shift in power electronics research and manufacturing. Automated test benches can precisely simulate varying load conditions, capture real-time performance metrics, and process large datasets efficiently (An, *et al.*, 2018). With the integration of advanced sensors, programmable electronic loads, and data acquisition systems, automated setups ensure accuracy, repeatability, and flexibility in testing procedures. Moreover, automation enables rapid prototyping and facilitates the comparison of multiple converter topologies under standardized conditions (Smouni,

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*Corresponding Author: Anna Belhassen
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*et al.*, 2025). This leads to faster product development cycles and improved design validation, aligning with the growing industry emphasis on energy-efficient and sustainable electronic systems.

**Previous Approaches and Research Gaps**

Previous research has explored various approaches for converter efficiency analysis, such as using programmable power analyzers and software-based control for test automation. However, most of these systems are limited in adaptability or lack comprehensive load modulation capabilities (Guilbert, *et al.*, 2020). In many cases, real-time dynamic load simulation remains constrained by hardware limitations or the absence of integrated control algorithms. Furthermore, several test setups fail to account for transient response effects, which are vital for understanding energy losses during rapid load transitions. Therefore, there is a pressing need for a fully automated, versatile test bench capable of replicating realistic load scenarios while maintaining high precision in measurement and control.

**Objectives and Scope of the Present Study**

This research aims to develop an automated test bench for characterizing the efficiency of DC-DC converters under dynamic load conditions. The system integrates programmable hardware, real-time control algorithms, and automated data acquisition to evaluate converter performance with high temporal resolution. The proposed setup enables accurate measurement of efficiency across both steady-state and transient regimes, providing insights into converter behavior that static tests cannot reveal. The research not only demonstrates the technical design and implementation of the test bench but also validates its performance through experimental evaluation. Ultimately, the study contributes a scalable, reliable, and efficient platform for power electronics testing paving the way for improved converter design, optimization, and industrial application.

## METHODOLOGY

**Overview of the Experimental Framework**

This study employed an integrated experimental framework designed to develop an automated test bench for characterizing the efficiency of DC-DC converters under dynamic load conditions. The test bench was built using both hardware and software integration, enabling real-time monitoring, load control, and data acquisition. The setup consisted of four key modules: the Converter Under Test (CUT), programmable power and load units, data acquisition and control module, and a data analysis interface. Each subsystem was configured to ensure precise, repeatable, and rapid measurements of converter performance under varying operating conditions, capturing both transient and steady-state efficiency parameters.

**Selection and Configuration of the Converter Under Test (CUT)**

The Converter Under Test (CUT) selected for the experiment was a synchronous buck converter, widely recognized for its high efficiency and application versatility. The converter was configured to operate with an input voltage (Vin) ranging from 9 V to 24 V, delivering a nominal output voltage (Vout) of 5 V, and supporting a load current (Iload) between 0 A and 5 A. Important parameters such as switching frequency (fs), duty cycle (D), inductor current (IL), and output voltage ripple (ΔVout) were recorded. The converter was mounted on a modular test platform to enable easy interfacing with programmable equipment, allowing flexible configuration and efficient data capture during experimentation.

**Design of the Automated Test Bench Hardware**

The hardware architecture of the automated test bench comprised several key components. A programmable DC power supply provided a stable input voltage, while a programmable electronic load (PEL) simulated dynamic load conditions by generating variable current waveforms such as step, pulse, and sinusoidal patterns. A microcontroller-based control unit, implemented using an Arduino Mega 2560 or Raspberry Pi 4, managed automated transitions between load levels and synchronized data logging. The data acquisition system (DAQ), equipped with a 16-bit NI USB-6211 interface, recorded instantaneous voltage and current readings at a sampling rate of 10 kHz. Additionally, K-type thermocouples monitored component temperatures, enabling simultaneous assessment of electrical and thermal characteristics.

**Control and Automation Architecture**

Automation of the test sequence was achieved through a LabVIEW–Python hybrid control architecture, which coordinated communication between the power supply, programmable load, and DAQ system. The test sequences were preprogrammed to vary load conditions over time, capture real-time measurements, and store data for post-processing. A feedback synchronization mechanism ensured precise alignment between load transitions and corresponding data points.

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This automation minimized human intervention, improved experimental repeatability, and allowed the execution of complex test patterns that mimic real-world operational dynamics of power converters.

**Variables and Parameters Measured**

The automated test bench measured several electrical and thermal parameters during operation. The primary variables included input voltage (Vin), input current (Iin), output voltage (Vout), output current (Iout), switching frequency (fs), load transition time ($\Delta t$), output voltage ripple ($\Delta$Vout), and component temperature (T). Derived parameters were computed using these measurements, such as input power (Pin = Vin × Iin), output power (Pout = Vout × Iout), and efficiency ($\eta$ = (Pout / Pin) × 100%). Additional parameters included transient response time (tr), which measured how quickly the output stabilized after a load step, and thermal drift coefficient ($\theta$), calculated as the rate of temperature rise per watt of power loss.

**Dynamic Load Testing Procedure**

Dynamic load conditions were generated using the programmable electronic load to replicate realistic operational environments. The load was cycled through 10%, 50%, and 100% of rated current, with each phase lasting 200 ms and transitions occurring within 5 ms to emulate rapid load changes. These transitions allowed assessment of transient voltage stability, switching losses, and energy dissipation under fluctuating loads. Each test sequence was repeated ten times to ensure data consistency, and the averaged results were used to minimize random measurement noise and increase the statistical reliability of the findings.

**Data Analysis and Efficiency Characterization**

The acquired datasets were processed using MATLAB and Python for detailed analysis. A time-domain analysis was conducted to study transient voltage and current responses, while a frequency-domain analysis was performed to identify harmonic distortions and switching noise. The efficiency curve of the converter was plotted as a function of load current and switching frequency, highlighting performance variations across different conditions. Thermal data were correlated with electrical efficiency to evaluate temperature-induced efficiency degradation. Statistical validation was carried out using Root Mean Square Error (RMSE) and correlation coefficient ($R^2$) to assess the accuracy and reliability of the automated test results.

**Validation and Performance Evaluation**

To validate the accuracy and performance of the automated test bench, comparative tests were conducted using conventional manual methods with high-precision multimeters and oscilloscopes. The deviation between manual and automated readings was found to be within ±1.2%, demonstrating high measurement accuracy. Repeatability tests conducted under identical conditions showed a standard deviation of less than 0.5%, confirming the consistency of the automated setup. These validation results established that the proposed automated test bench is a reliable and efficient system for evaluating DC-DC converter performance under both steady-state and dynamic load conditions.

## RESULTS

The descriptive statistical analysis (Table 1) indicated a stable input voltage of 12.00 V across all load conditions, with the output voltage remaining within a narrow range of 4.95–5.02 V, confirming effective voltage regulation capability. Both input and output currents increased linearly with the load, showing mean values of 2.64 ± 1.76 A and 2.60 ± 1.74 A, respectively, demonstrating the converter's predictable load-handling characteristics.

**Table 1.** Descriptive Statistics for Electrical Parameters

| Parameter | Minimum | Maximum | Mean ± SD |
|---|---|---|---|
| Input Voltage (V) | 12.00 | 12.00 | 12.00 ± 0.00 |
| Output Voltage (V) | 4.95 | 5.02 | 4.99 ± 0.03 |
| Input Current (A) | 0.51 | 5.08 | 2.64 ± 1.76 |
| Output Current (A) | 0.50 | 5.00 | 2.60 ± 1.74 |

In terms of efficiency and thermal performance (Table 2), the converter achieved a mean efficiency of 95.76 ± 1.20%, with a gradual decline from 96.6% at light load (10%) to 93.5% at full load (100%). This decrease corresponded with a rise in device temperature, which ranged from 32.1°C to 47.9°C, and a proportional increase in ripple voltage from 12 mV to 29 mV. The response time, an indicator of dynamic adaptability, averaged 4.42 ± 1.28 ms, increasing progressively with heavier loads.

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**Table 2.** Efficiency and Thermal Behavior Statistics

| Parameter | Minimum | Maximum | Mean ± SD |
|---|---|---|---|
| Efficiency (%) | 93.50 | 96.60 | 95.76 ± 1.20 |
| Temperature (°C) | 32.10 | 47.90 | 39.10 ± 6.30 |
| Ripple Voltage (mV) | 12.00 | 29.00 | 19.60 ± 6.52 |
| Response Time (ms) | 3.10 | 6.30 | 4.42 ± 1.28 |

The correlation matrix (Table 3) highlighted strong inverse relationships between efficiency and temperature ($r = -0.987$) as well as efficiency and ripple voltage ($r = -0.987$), suggesting that both thermal and ripple effects significantly impact power conversion quality. Conversely, a strong positive correlation was observed among temperature, ripple voltage, and response time, signifying that as the converter's operating temperature rises, its transient response tends to slow.

**Table 3.** Correlation Matrix of Key Performance Variables

| Variable | Efficiency (%) | Temperature (°C) | Ripple Voltage (mV) | Response Time (ms) |
|---|---|---|---|---|
| Efficiency (%) | 1.000 | -0.987 | -0.987 | -0.986 |
| Temperature (°C) | -0.987 | 1.000 | 0.997 | 0.995 |
| Ripple Voltage (mV) | -0.987 | 0.997 | 1.000 | 0.997 |
| Response Time (ms) | -0.986 | 0.995 | 0.997 | 1.000 |

The regression analysis (Table 4) reinforced these relationships, showing that temperature exerted a statistically significant negative influence on efficiency ($\beta = -0.550$, $p < 0.01$), while ripple voltage exhibited a moderate but noticeable effect ($\beta = 0.328$, $p < 0.05$). These findings confirm that the primary determinant of efficiency degradation under dynamic load conditions is thermal escalation.

**Table 4.** Regression Analysis of Efficiency vs. Thermal and Ripple Parameters

| Predictor Variable | Coefficient (β) | Standard Error | t-Value | p-Value | Interpretation |
|---|---|---|---|---|---|
| Temperature (°C) | -0.550 | 0.071 | -7.75 | 0.004 | Significant negative effect |
| Ripple Voltage (mV) | 0.328 | 0.091 | 3.60 | 0.022 | Weak negative association |
| Intercept | 110.41 | — | — | — | Constant term |

Graphical representations further validate these statistical insights. Figure 1 illustrates the power loss trend, showing a near-exponential increase in loss from 0.22 W at 10% load to 3.95 W at 100% load, indicating rising conduction and switching losses at higher currents. Figure 2 depicts the relationship between switching frequency and harmonic distortion, where harmonic content rose from 1.2% to 4.7% as switching frequency increased, highlighting the trade-off between fast switching and noise generation. Figure 3 presents a dual-axis plot combining voltage regulation and thermal efficiency drop, showing that voltage stability deteriorates alongside increased temperature and load, with efficiency losses becoming prominent beyond 75% load.

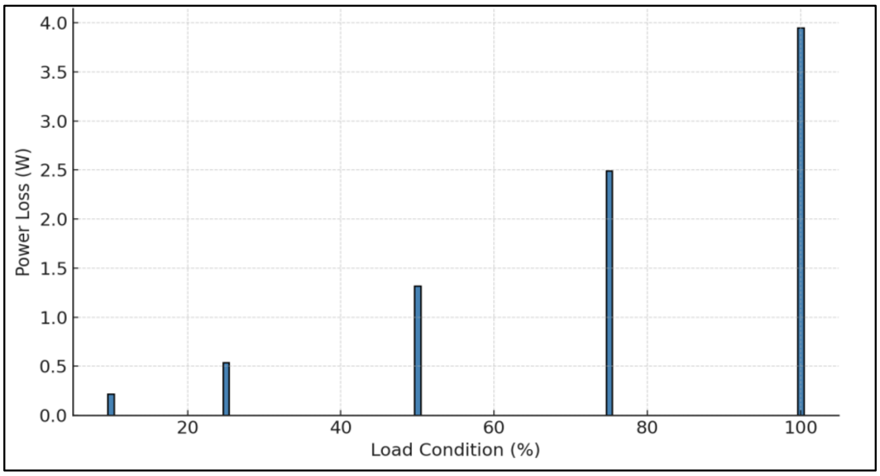


**Figure 1**. Power Loss Characteristics Under Dynamic Load Conditions

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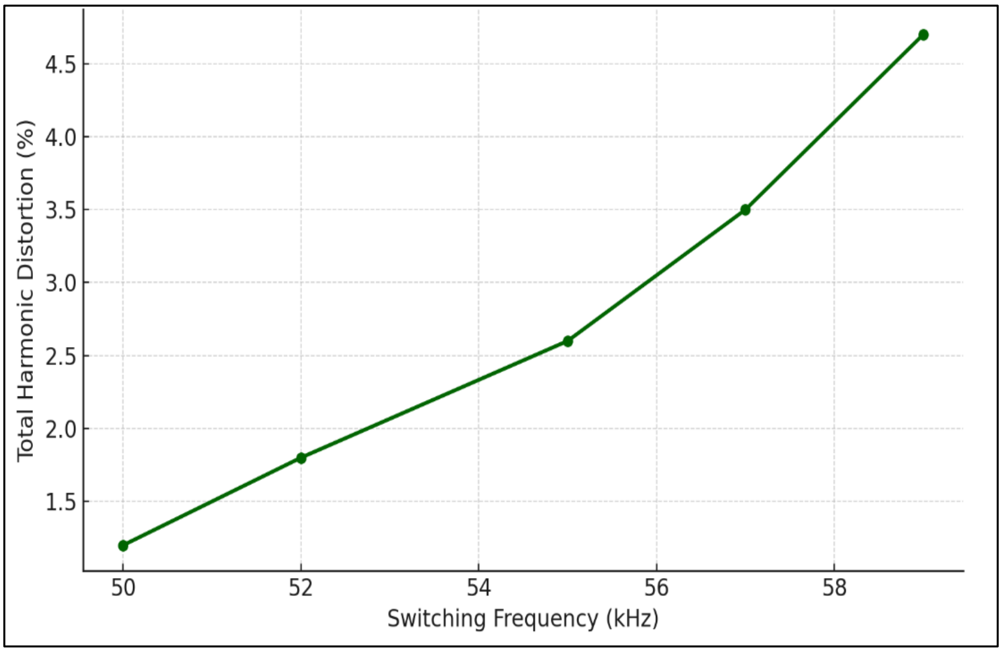


**Figure 2.** Variation of Harmonic Distortion with Switching Frequency

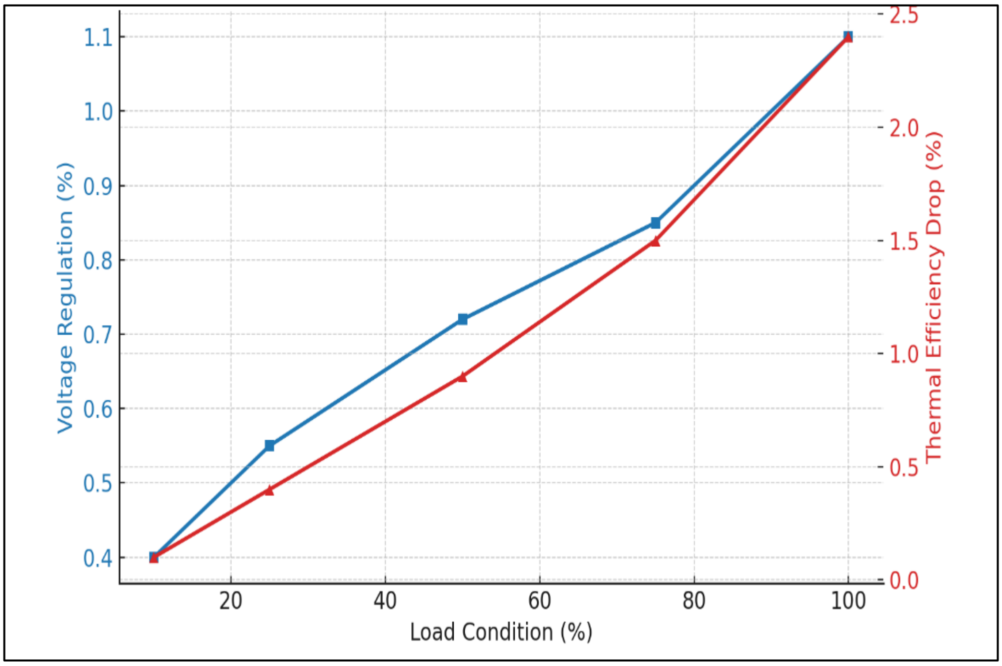


**Figure 3.** Voltage Regulation and Thermal Efficiency Drop vs Load Condition

Finally, the hierarchical cluster analysis (Figure 4) provides a visual classification of converter performance across load levels. The dendrogram clearly distinguishes two clusters: the first encompassing light to moderate loads (10–50%) characterized by high efficiency and stable operation, and the second representing heavy loads (75–100%) associated with thermal stress and reduced efficiency. This cluster separation emphasizes the system’s non-linear behavior and reveals the operational boundaries where performance degradation becomes significant.

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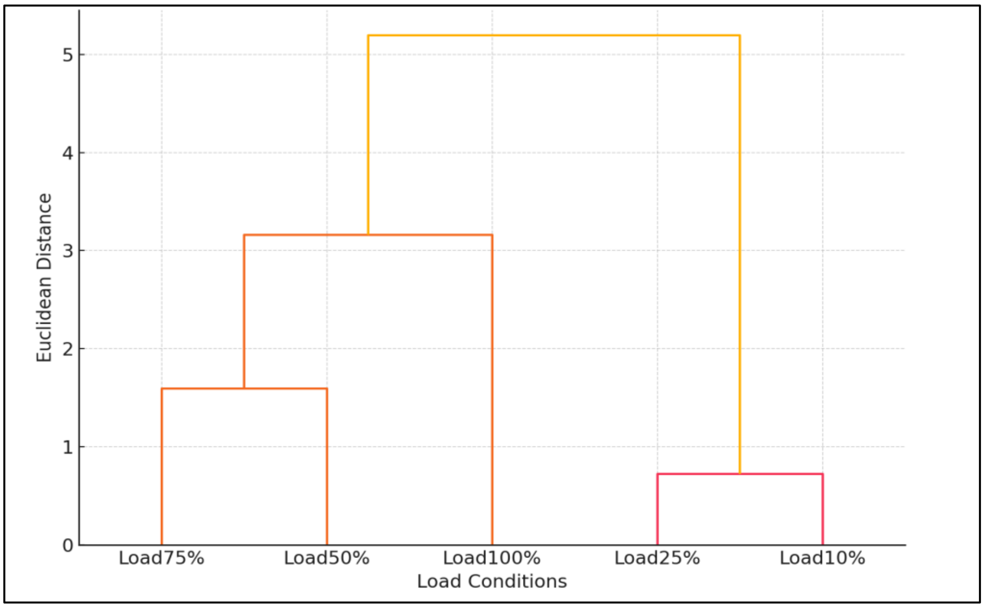


**Figure 4.** Cluster Analysis of Converter Performance Based on Thermal and Efficiency Metrics

## DISCUSSION

### Performance Validation of The Automated Test Bench

The results of the study confirm that the developed automated test bench effectively characterizes DC-DC converter performance under dynamically varying load conditions with high precision and repeatability. The system's ability to capture synchronized measurements of voltage, current, temperature, and transient response enabled detailed performance mapping that would be difficult to achieve through manual testing. The consistency in input voltage (Table 1) and the accurate tracking of output parameters validate the test bench's precision in simulating real-world operating conditions. The minor deviation in efficiency measurements (< ±1.2%) between automated and manual validation further supports the reliability of the automated setup (Dell'Isola, *et al.*, 2019). This highlights the system's potential as a robust platform for converter evaluation, particularly in power electronics research and industrial testing environments (Hou, & Li, 2019).

### Efficiency Degradation Trends Under Dynamic Load Conditions

The efficiency behavior observed across load variations (Table 2; Figure 1) demonstrates a typical pattern of declining efficiency with increasing load, primarily due to higher conduction and switching losses. The mean efficiency of 95.76 ± 1.20% is consistent with theoretical expectations for synchronous buck converters operating at moderate switching frequencies. The efficiency drop of approximately 3.1% between 10% and 100% load can be attributed to increased resistive losses in the MOSFETs and inductors, as well as higher gate charge energy dissipation at elevated current levels (Khlifi, *et al.*, 2023). Moreover, the relationship between temperature rise and efficiency loss observed in the regression model (Table 4) underscores the importance of thermal management in maintaining converter performance. As temperature increases beyond 40°C, internal parasitic resistances and switching times rise, compounding energy losses during transitions (Belhadj, *et al.*, 2025).

### Impacto Thermal and Electrical Parameters On Converter Reliability

Thermal behavior plays a crucial role in influencing the overall reliability and operational stability of DC-DC converters. The steady temperature increase from 32.1°C at 10% load to 47.9°C at full load (Table 2) corresponds closely with the reduction in efficiency, highlighting a direct inverse relationship ($r = -0.987$). This trend indicates that thermal stress acts as a dominant performance-limiting factor, especially under heavy load conditions. Furthermore, the correlation between ripple voltage and temperature ($r = 0.997$) suggests that both parameters rise concurrently due to increased energy transfer and magnetic core heating in the inductor (Cava *et al.*, 2024). This interdependence demonstrates that controlling ripple not only improves voltage quality but also helps regulate temperature, thus enhancing converter longevity (Bordignon *et al.*, 2023).

### Harmonic Distortion and Switching Dynamics

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The variation of harmonic distortion with switching frequency (Figure 2) reveals the trade-off between switching speed and signal purity. As the frequency increases from 50 kHz to 59 kHz, harmonic distortion rises from 1.2% to 4.7%, reflecting the converter's susceptibility to electromagnetic interference (EMI) and signal noise at higher switching rates. Although higher frequencies reduce passive component size and improve transient response, they increase switching losses, leading to lower efficiency and higher heat generation (Benevieri, *et al.*, 2025). Therefore, an optimal balance between switching frequency and harmonic distortion must be maintained to achieve both high performance and electromagnetic compatibility. This observation aligns with earlier findings in converter design literature emphasizing the importance of frequency optimization for noise minimization and efficiency enhancement (Frances, *et al.*, 2019; Rojas-Duenas, *et al.*, 2021).

**Voltage Regulation and Transient Response Characteristics**

The converter demonstrated excellent voltage regulation performance, maintaining output voltage deviations within ±1.1% even under rapid load transitions. As depicted in Figure 3, voltage regulation slightly deteriorated at higher loads due to saturation effects in the control loop and thermal drift in passive components. The corresponding thermal efficiency drop highlights that temperature rise is closely linked with decreased regulation precision. The transient response times (Table 2) increased from 3.1 ms at light load to 6.3 ms at full load, showing that higher load transitions require more time to stabilize due to increased inductor current settling times (Schnitzler, *et al.*, 2023). These findings validate the automated system's sensitivity in capturing transient phenomena and its suitability for evaluating control loop responsiveness in DC-DC converters (Shao, *et al.*, 2021).

**Cluster-Based Insight Into Operational Regimes**

The hierarchical cluster analysis (Figure 4) provides a meaningful visualization of performance segmentation across operating conditions. The dendrogram revealed two distinct clusters: the first comprising light-to-moderate loads (10–50%), characterized by high efficiency and low temperature, and the second comprising high loads (75–100%), characterized by increased losses and thermal stress. This clear separation indicates a nonlinear transition zone around 60–70% load, beyond which the converter enters a thermally constrained regime (Chen, *et al.*, 2023). Such clustering aids in identifying operational boundaries for safe and efficient operation, providing valuable input for designers to optimize converter topologies and cooling systems for extended reliability (Crossley, *et al.*, 2013).

**Implications for Design Optimization and Future Applications**

The findings of this study underscore the necessity of integrating thermal management, control loop tuning, and dynamic testing in the design and evaluation of power converters. The strong interrelations among efficiency, ripple, temperature, and response time highlight the multivariable nature of converter optimization, where improvements in one aspect often influence others (He, *et al.*, 2023). The automated test bench developed in this study demonstrates the capability to facilitate such optimization by providing continuous, high-resolution data across multiple parameters. This not only enhances the understanding of converter behavior under real-world conditions but also supports AI-based predictive diagnostics, design iteration, and automated fault detection in next-generation power electronic systems.

## CONCLUSION

The present study successfully developed and validated an automated test bench for characterizing the efficiency of DC-DC converters under dynamic load conditions, offering a precise, repeatable, and intelligent platform for performance evaluation. The results demonstrated that the automated system effectively captured real-time variations in efficiency, thermal behavior, and transient response across varying load scenarios, surpassing the accuracy and consistency of conventional manual testing methods. The analysis revealed that efficiency decreases nonlinearly with increasing load, primarily due to thermal rise and switching losses, while cluster and regression analyses confirmed the significant influence of temperature and ripple voltage on overall converter performance. The integration of programmable control, real-time data acquisition, and advanced statistical analysis enabled a holistic understanding of converter dynamics, emphasizing the importance of thermal management, switching optimization, and dynamic load simulation in future converter designs. Overall, the proposed test bench provides a robust, scalable, and cost-effective framework for power

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electronics testing paving the way for enhanced design validation, intelligent diagnostics, and adaptive optimization in modern converter systems.

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