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# Power electronic converter design for industrial energy systems

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## Abstract

DC–DC converters contribute significantly to the efficient functioning of energy conversion devices employed in industries due to their functions such as voltage regulation and power control. Their performance affects conversion efficiency, thermal stress, output voltage quality, and the operating condition of connected components. In industrial applications, these factors must be considered together because a design that performs well in one area may still show limitations in another. This paper presents a simulation-based study of DC–DC converter design with emphasis on the combined effect of component selection, switching losses, thermal conditions, and voltage regulation. Several converter configurations are evaluated under nominal, variable-load, and thermal-stress operating conditions to compare their electrical response and temperature behavior under common design requirements. The analysis examines how semiconductor and passive component choices influence total power loss, device temperature rise, ripple characteristics, and output stability. The results show that converter performance should not be assessed from efficiency alone, since different component combinations produce noticeable differences in loss distribution, thermal response, and regulation quality. Among the tested cases, the preferred configuration achieved lower total loss, moderate temperature rise, and more stable output performance than the alternative designs. The study shows that combined electrical and thermal assessment provides a practical basis for DC–DC converter selection in industrial energy systems.

**Keywords:** DC–DC converters; Industrial energy systems; Switching losses; Thermal analysis; Voltage regulation; Converter component selection; Power electronics

## 1. Introduction

Power electronic converters are a core part of industrial energy systems because they regulate voltage, current, and power transfer between sources, storage units, and electrical loads. Modern industrial facilities no longer rely on a single power source. Many now operate with utility supply, battery storage, solar generation, electric drive systems, and converter-fed equipment in the same network. This shift has increased the importance of converter design for stable operation, acceptable efficiency, and reliable power delivery throughout the system. A DC–DC converter does more than change one voltage level to another. Its design influences switching losses, thermal stress, output quality, and the service life of connected components. Industrial applications also present operating conditions that are more demanding than simplified laboratory cases. Load demand can change over time, input sources can fluctuate, and equipment often operates for long periods without interruption. Under such conditions, weak component selection or limited design margins may lead to excess power loss, unstable voltage regulation, overheating, and reduced system performance. These effects can lower efficiency and increase stress on semiconductor and passive components. For this reason, studies of industrial converters should move beyond basic voltage conversion and examine electrical and thermal

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performance within the same evaluation framework. This paper addresses that need through a focused study of DC–DC converter component selection and performance analysis for industrial energy systems. The work examines how design choices affect switching losses, temperature rise, and voltage regulation, with the aim of identifying configurations that support stable and efficient converter operation under representative industrial conditions.

### 1.1. Background and Motivation

Industrial energy systems rely on controlled power conversion to support automation equipment, communication units, storage devices, motor drives, and process loads. DC–DC converters are widely used in these systems because they provide regulated voltage levels across different stages of power transfer. Their relevance has increased with the expansion of renewable generation, battery-supported operation, electric vehicle charging, and digital control platforms in industrial facilities. As a result, converter quality has a direct effect on system efficiency, thermal stress, equipment life, and operating stability. The motivation for this study comes from practical design issues that appear in real operating environments. A converter selected only on the basis of voltage conversion ratio may not perform satisfactorily once switching frequency, device stress, and heat dissipation are taken into account. Long operating hours, fluctuating load current, and changing source conditions can expose weaknesses in component selection and converter configuration. These concerns are common in industrial systems where operating continuity and energy use matter. For that reason, converter studies should examine the combined effect of electrical and thermal variables. This paper responds to that need through a focused evaluation of DC–DC converter component selection and performance characteristics in industrial energy applications.

### 1.2. Problem Statement

Despite the widespread use of DC–DC converters in industrial systems, converter design is often treated as a simple voltage regulation task. In practice, converter operation depends on a set of interacting variables. Switching devices generate transition losses, passive components shape ripple and transient response, and heat accumulation affects both immediate performance and long-term component condition. A design may produce acceptable output voltage while still operating with unnecessary power loss or elevated temperature. Such limitations become more serious when the converter is exposed to changing load conditions over extended periods. This creates a technical problem for industrial energy systems. Engineers need converter designs that satisfy electrical requirements without imposing excessive thermal stress or poor efficiency. At the same time, the converter must maintain stable output under variable operating conditions. Many design methods focus on one performance factor at a time, such as output regulation or conversion efficiency, and this narrow treatment leaves important interactions unexplored. The main problem addressed in this paper is the absence of an integrated evaluation of component selection, switching losses, thermal conditions, and voltage regulation for DC–DC converters used in industrial energy systems. A more complete assessment is needed to support sound design choices for industrial use.

### 1.3. Proposed Solution

This paper presents a simulation-based evaluation of DC–DC converter systems with emphasis on the relation between component selection and operating performance in industrial conditions. The proposed approach examines switching devices, passive components, and converter operating parameters in one analytical framework. Instead of treating electrical performance and thermal response as separate concerns, the study considers their interaction during converter operation. This makes it possible to compare design choices on the basis of loss behavior, temperature conditions, and output stability at the same time. A set of converter models is developed to represent industrial operating cases. These models are used to examine how changes in component configuration affect switching losses, voltage regulation, and thermal conditions. The analysis then identifies configurations that offer lower losses and stable output with acceptable thermal performance. The purpose of this approach is practical. Industrial systems require converter designs that can operate for long periods without excessive stress on semiconductor devices and passive elements. This study therefore provides a design-oriented evaluation rather than a purely descriptive analysis. The result is a clearer basis for selecting DC–DC converter components for industrial energy systems.

### 1.4. Contributions

This paper makes several contributions to the study of DC–DC converters for industrial energy systems. First, it presents a focused analysis of component selection in relation to three connected performance factors: switching losses, thermal conditions, and voltage regulation. This gives a broader view of converter design than studies that examine only one performance measure. Second, the paper develops simulation models for representative industrial operating conditions and uses them to compare the effect of different component choices on converter behavior. Third, the study identifies component configurations that support lower losses and more stable power delivery in industrial applications. This result has practical value because industrial converters are expected to operate over long service periods with limited tolerance for inefficiency or excessive temperature rise. Fourth, the paper offers a structured basis for future work on converter optimization, thermal analysis, and reliability studies in industrial systems. These contributions place the study within a clear engineering context and provide results that are relevant to converter design practice as well as academic investigation.

### 1.5. Paper Organization

The rest of the paper follows a technical sequence. Section II reviews previous work on DC–DC converter topologies, smart grid integration, control methods, intelligent monitoring, and industrial converter applications. That discussion provides the context needed to define the research gap addressed in this study. The next section presents the methodology, including the converter model, component selection process, simulation setup, and evaluation criteria used for analysis. Particular attention is given to the electrical and thermal parameters chosen for performance comparison. The results and discussion section presents converter behavior under different design configurations and operating conditions. It examines switching losses, voltage regulation, and thermal response in order to compare alternative component selections. From that comparison, the paper identifies configurations that provide efficient operation and stable power delivery for industrial use. The final section summarizes the main findings, states the significance of the results, and notes possible directions for future study. This structure moves the paper from background and problem definition to method, analysis, and concluding

The objective of this paper is to evaluate the design and performance characteristics of DC–DC converters used in industrial energy systems through a combined analysis of component selection, switching losses, thermal conditions, and voltage regulation. The study aims to determine how different converter component configurations affect electrical efficiency and operating stability under representative industrial conditions. It also seeks to identify design choices that reduce loss, maintain acceptable thermal performance, and provide consistent output regulation. Through this analysis, the paper presents a practical basis for improving converter design in industrial applications that require stable power delivery and efficient energy conversion.

## 2. Related Work

Power electronic converters form the backbone of modern industrial energy systems, where they regulate power flow between sources, storage units, and loads. Recent research has examined converter topologies, control strategies, smart grid integration, and intelligent monitoring techniques. The following subsections review key developments in these areas and identify the limitations that motivate this study.

### 2.1. DC–DC Converter Topologies, Control, and Interface Foundations

Research on power electronic converters has consistently focused on topology selection, control methods, and design choices for different operating conditions. Hossain et al. [2] provided a review of DC–DC converter topologies and discussed progress in converter structures, control strategies, design methods, and application areas. Their study showed that converter performance depends on the selected topology, switching characteristics, voltage conversion requirements, and the intended application. Pires et al. [13] examined power converter interfaces for electrochemical energy storage systems and explained the role of converter design in bidirectional power transfer, battery integration, and energy management. These works provide a technical basis for industrial DC–DC converter studies, especially in systems that require voltage regulation, storage interfacing, and stable operation under variable load conditions.

### 2.2. Smart Grid and Renewable Energy Integration

Recent studies have connected converter research with smart grid operation and renewable energy systems. Hasan et al. [1] studied IoT-integrated solar energy monitoring together with bidirectional DC–DC converters for smart grids. Their work showed the growing role of converter systems that operate with real-time sensing and communication functions. Razaq [10] addressed renewable energy integration into smart grids and examined the contribution of power electronic systems to controlled energy exchange. Karim et al. [11] presented a framework for renewable energy monitoring and adaptive load optimization using intelligent control algorithms. Their study placed converter operation within a broader smart grid setting. Emon [12] proposed an intelligent energy management system for cost optimization and peak demand reduction with battery-integrated dispatch. That work showed the value of converter-based storage systems in system operation and energy cost management. Together, these studies indicate that converter design for industrial energy systems must be considered in relation to grid interaction, storage operation, and renewable energy variability.

### 2.3. MPPT, Grid Synchronization, and Advanced Control Strategies

Control methods remain a major part of converter research, especially for renewable and grid-connected systems. Rabbi [3] presented an extremum-seeking MPPT control method for Z-source inverters in grid-connected solar PV systems. The study focused on adaptive power tracking under changing environmental conditions. Ashraf [6] compared AI-optimized MPPT algorithms for grid-connected solar PV systems and reported improvements in tracking performance and dynamic response. Rabbi [9] also studied grid synchronization algorithms for intermittent renewable energy sources using AI control loops. That work addressed synchronization issues caused by fluctuating generation. These studies show that current converter research extends beyond hardware configuration alone. Control quality, dynamic performance, and operating response now form part of converter evaluation in renewable and industrial applications.

### 2.4. AI-Based Monitoring, Maintenance, and Forecasting

Another direction in recent literature concerns artificial intelligence for monitoring, fault detection, and maintenance planning in converter-connected systems. Karim [8] examined AI-driven predictive maintenance for solar inverter systems and discussed the use of data-based methods to reduce downtime and support long-term operation. Rayhan [15] presented AI-powered condition monitoring for solar inverters using embedded edge devices. The study focused on local intelligence for real-time fault identification. Rayhan [16] extended this work to off-grid solar networks through a combination of energy forecasting and fault detection. That study linked operational prediction with reliability assessment in distributed energy systems. In addition, Rayhan [14] proposed a hybrid deep learning model for wind and solar power forecasting in smart grids. Forecasting accuracy has direct relevance for converter-connected renewable systems because operating conditions change with source availability. These studies show a shift in recent work from standard converter efficiency analysis toward intelligent supervision of power electronic energy systems.

### 2.5. Emerging Industrial Applications and System Resilience

Industrial applications now place additional demands on converter systems, including compatibility with electric vehicle charging, resilience under environmental stress, and adaptation to modern power distribution structures. Karim et al. [5] investigated AI-enabled smart energy meters with DC–DC converter integration for electric vehicle charging systems. Their work reflected the growing use of converter technologies in charging infrastructure and metering systems. Rabbi [4] studied fire-resilient solar inverter systems for wildfire-prone regions and introduced environmental risk as a design concern in power electronic systems. Battal et al. [7] reviewed power electronic transformers and discussed their use in future distribution systems because of their compact design, controllability, and integration features. These works show that converter research now includes application areas where operational safety, grid flexibility, and infrastructure compatibility receive direct attention.

### 2.6. Research Gap and Motivation

The existing literature covers converter topologies [2], energy storage interfaces [13], smart grid and renewable integration [1], [10]–[12], advanced control methods [3], [6], [9], AI-based monitoring [8], [14]–[16], and newer industrial applications [4], [5], [7]. Even so, a gap remains in the combined evaluation of DC–DC converter component selection and performance for industrial energy systems. Most studies focus on a single area, such as topology reviews, MPPT control, forecasting, predictive maintenance, or renewable integration. Fewer studies examine component-level design choices together with switching losses, thermal conditions, and voltage regulation in one industrial DC–DC converter framework. This study addresses that gap through an analysis of converter component configurations and their effect on stable and efficient power delivery in industrial energy systems.

## 3. Methodology

This study applies a simulation-based methodology to examine DC–DC converter design for industrial energy systems. The method reflects the main novelty of the paper: a combined evaluation of component selection, switching losses, thermal conditions, and voltage regulation within one design framework. Electrical efficiency and thermal performance are treated as connected design factors. The analysis focuses on how semiconductor devices, passive elements, and operating conditions affect converter behavior under representative industrial load cases. The methodology is divided into five subsections. The first defines the converter architecture and design scope. The second describes the simulation model and operating scenarios. The third presents the component selection procedure. The fourth introduces the performance metrics and selected equations. The fifth explains the comparative evaluation process used to determine the preferred configuration.

### 3.1. Converter Architecture and Design Scope

The study considers a DC–DC converter used as a regulated power interface in industrial energy systems. Such a converter may connect a DC source, battery unit, renewable source, or intermediate DC bus to a controlled load stage. The work does not propose a new topology. Instead, it develops a design evaluation method that studies how component choices affect electrical and thermal performance under the same operating targets. The converter structure includes an active switching device, a rectification path, an inductor, an output capacitor, and a controlled load model. The switching stage governs power transfer, while the passive stage smooths current and stabilizes output voltage. Semiconductor properties such as on-state resistance, switching frequency, current rating, voltage rating, and transition behavior are included because they influence both power loss and device temperature. Passive elements are also selected within practical design ranges so that the analysis can capture the effect of inductance and capacitance values on ripple, transient response, and regulation quality. Several component configurations are tested under identical operating conditions. Each case uses a defined set of semiconductor and passive element values. This arrangement makes it possible to compare the effect of component selection on converter operation without changing the design target. The scope of the study remains at converter level. Plant-wide dispatch and grid scheduling are outside the present analysis.

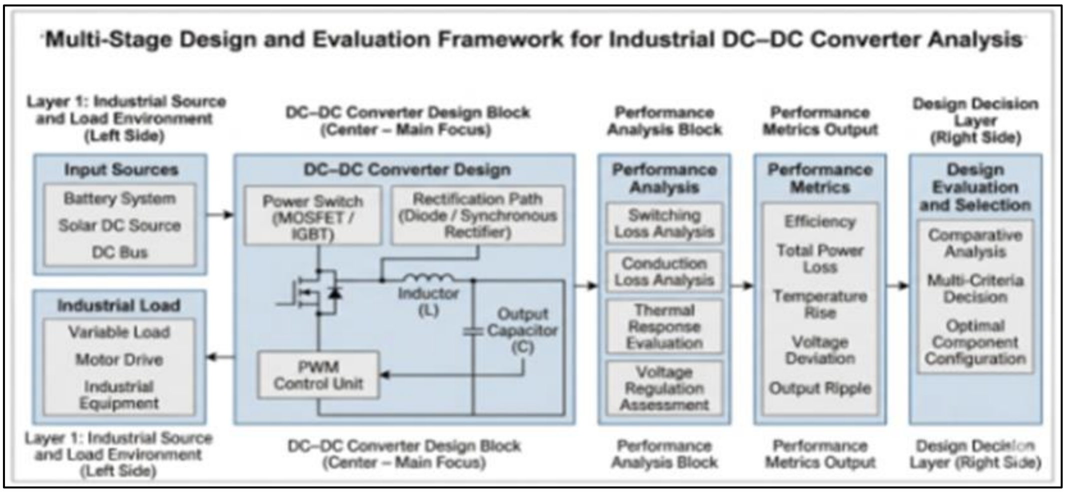


**Figure 1** Multi-stage design and evaluation framework for industrial DC–DC converter analysis

Figure 1 presents a journal-style layered architecture. The first layer is the industrial source and load environment, including battery input, renewable DC input, or regulated DC bus on the source side and industrial load demand on the output side. The second layer is the converter design block, which includes the switch, rectifier path, inductor, capacitor, and control unit. The third layer is the analysis block, where switching loss estimation, thermal response, and voltage regulation are evaluated. The fourth layer contains the performance outputs, namely efficiency, total loss, thermal rise, and voltage deviation. The last layer shows the design decision stage, where the most suitable component configuration is selected. The figure should use grouped blocks, aligned arrows, and consistent technical formatting.

### 3.2. Simulation Model and Industrial Operating Scenarios

A detailed simulation model is developed to capture the electrical and thermal behavior of the converter under industrial operating conditions. The model is implemented in a circuit simulation environment capable of tracking switching waveforms, output voltage, converter loss, and device temperature response. Closed-loop duty control is included so that the output voltage remains near the reference value as load conditions vary. This reflects practical industrial converter operation, where output stability is expected across changing load demand. Three operating cases are used in the analysis. The first is the nominal case, where the converter operates at rated input voltage and rated load. This provides a reference point for steady-state comparison. The second is a variable-load case, where output demand changes over time to represent industrial equipment with non-constant power consumption. The third is a thermal-stress case, where the converter operates over a longer interval so that loss accumulation and device temperature trends can be observed. These cases provide a wider view of converter performance than a single steady-state test. The model also includes non-ideal effects found in practical converter operation. These include switch conduction resistance, inductor series resistance, capacitor equivalent series resistance, and finite switching intervals. Without these features, the simulation would not capture the main sources of electrical loss and thermal rise. The recorded outputs include input current, output voltage, inductor current, semiconductor switching waveforms, total converter loss, and estimated device temperature. All design configurations are tested under the same simulation conditions, which allows direct comparison across cases.

### 3.3. Component Selection Procedure

Component selection is treated as a structured design problem rather than a simple replacement of individual parts. The procedure begins with the converter specification. This includes input voltage range, output voltage target, switching frequency range, load requirement, and acceptable output ripple. Once these limits are defined, candidate components are selected for the active and passive sections of the converter. Semiconductor selection is based on voltage rating, current rating, conduction characteristic, switching speed, and thermal tolerance. Passive component selection considers inductance value, current ripple capacity, resistance, capacitance value, and equivalent series resistance. Multiple configurations are then created from these candidate values. Each configuration meets the same operating target, which allows the analysis to compare performance without changing the system requirement. This arrangement captures the tradeoff among design choices. A faster switching device may improve some aspects of operation while increasing switching loss at higher frequency. A larger inductor may reduce current ripple but alter transient response and component size. A capacitor with lower equivalent series resistance may improve output filtering but affect cost or design margin. The evaluation therefore considers the combined effect of these variables rather than isolating one parameter at a time. Designs that fail to maintain voltage stability or show unacceptable thermal conditions are removed from the comparison. The remaining configurations are examined with the full set of electrical and thermal performance metrics.

**Table 1** Parameters used in converter performance evaluation

| Parameter Group | Parameter | Description | Role in Analysis |
|---|---|---|---|
| Electrical Input | $V_{in}$ | Input voltage | Defines the converter operating condition |
| Electrical Output | $V_{out}$ | Output voltage | Used to assess regulation quality |
| Load Condition | $R_{load}$ | Load demand | Represents industrial operating variation |
| Switching Stage | $f_s$ | Switching frequency | Affects loss, ripple, and dynamic response |
| Semiconductor | $R_{on}$ , current rating, voltage rating | Device stress and conduction properties | Used in electrical and thermal comparison |
| Inductor | $L$, $ESR$ | Current smoothing element | Influences ripple and conduction loss |
| Capacitor | $C$, $ESR$ | Output filtering element | Affects voltage ripple and output stability |
| Thermal Metric | $T_{rise}$ | Temperature increase above ambient | Indicates thermal stress |
| Loss Metric | $P_{loss}$ | Total converter loss | Used in efficiency calculation |
| Regulation Metric | $\Delta V$ | Output voltage deviation | Measures output stability |

### 3.4. Performance Metrics and Governing Equations

The methodology uses a limited set of equations tied directly to the objectives of the paper. The first metric is converter efficiency:

$$\eta = \frac{P_{out}}{P_{in}} \times 100$$

where $\eta$ is efficiency in percent, $P_{out}$ is output power, and $P_{in}$ is input power. This quantity shows the fraction of supplied power delivered to the load.

The second metric is total converter loss:

$$P_{loss} = P_{cond} + P_{sw}$$

where
$P_{loss}$ is total power loss, $P_{cond}$ is conduction loss, and $P_{sw}$ is switching loss. This form separates the two main loss components affected by device selection and switching frequency.

Voltage regulation is measured with the following expression:

$$V_{reg} = \frac{V_{ref} - V_{out}}{V_{ref}} \times 100$$

where $V_{reg}$ is the percentage regulation error, $V_{ref}$ is the reference output voltage, and $V_{out}$ is the average measured output voltage. A lower value indicates better regulation.

Thermal performance is represented through device temperature rise:

$$T_{rise} = T_{device} - T_{amb}$$

where $T_{rise}$ is the increase above ambient temperature, $T_{device}$ is the device operating temperature, and $T_{amb}$ is ambient temperature. This value reflects the thermal burden placed on the selected components. These equations are sufficient for the present study because they connect component selection with efficiency, power loss, regulation quality, and thermal condition without adding unnecessary mathematical detail.

### 3.5. Comparative Evaluation and Decision Process

The comparative evaluation follows a fixed sequence. A baseline converter model is first created with nominal electrical ratings and reference component values. Alternative semiconductor and passive component combinations are then introduced while the operating specifications remain unchanged. Each configuration is simulated under nominal, variable-load, and thermal-stress conditions. The simulation outputs are processed to obtain efficiency, total loss, regulation error, ripple level, and temperature rise. The final comparison uses a multi-criteria decision process. Efficiency, voltage regulation, and thermal condition are treated as the main evaluation criteria because they correspond directly to the research objective. A configuration with low loss but poor output stability is not selected. In the same way, a design with acceptable regulation but high device temperature is also rejected. This prevents the analysis from favoring a design that performs well in one measure but poorly in another. The preferred converter configuration is selected from the group of designs that maintain stable output while operating with lower losses and acceptable temperature rise. This procedure gives the study a practical design outcome. It also reflects the novelty of the paper, since the final decision is based on combined electrical and thermal performance rather than on efficiency alone.

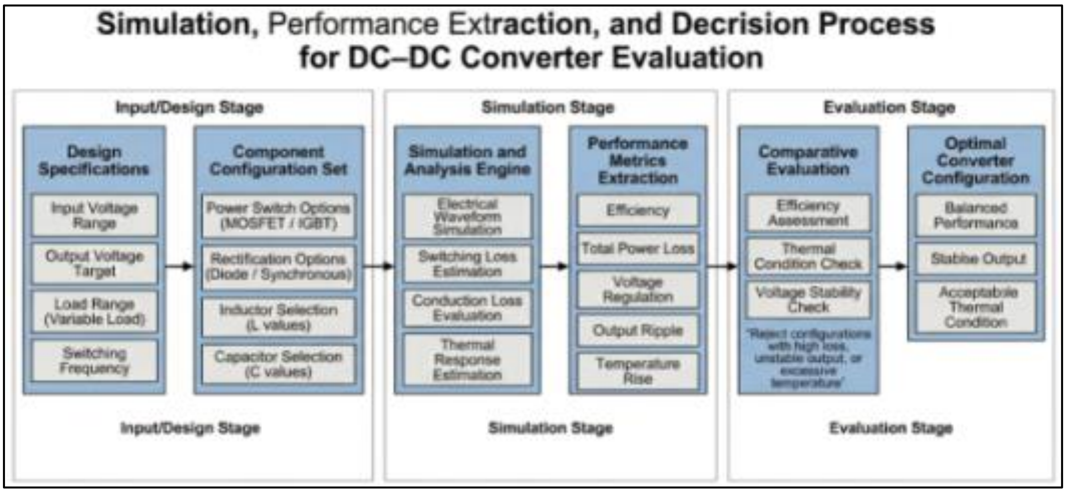


**Figure 2** Simulation, extraction, and ranking process for converter component evaluation

Figure 2 shows a refined technical flow diagram. The sequence should begin with design specifications, including input voltage range, output voltage target, load range, and switching frequency. The next stage should present candidate component generation for the switch, rectification path, inductor, and capacitor. The following stage should show the simulation engine, including waveform analysis, loss estimation, and thermal estimation. After that, the figure should include a performance extraction block containing efficiency, voltage regulation, ripple, and temperature rise. The last stage should present comparative ranking and final configuration selection. The figure should use consistent spacing, aligned arrows, grouped modules, and journal-style labeling rather than a simple classroom flowchart.

## 4. Discussion and Results

This section presents the simulated performance of the candidate DC–DC converter configurations under representative industrial operating conditions. The analysis follows the central contribution of the paper: a combined assessment of component selection, switching losses, thermal conditions, and voltage regulation within one framework. The results are discussed as connected performance outcomes rather than isolated efficiency values. Each configuration is evaluated through its electrical response, temperature rise, and output stability under common test conditions. This makes the comparison more relevant for industrial energy systems, where converter design must satisfy several operating requirements at the same time.

### 4.1. Steady-State Electrical Performance of the Candidate Configurations

The first stage of analysis examined the steady-state response of the candidate converter configurations under nominal industrial operating conditions. All configurations were tested with the same input voltage, output target, switching frequency range, and rated load condition. This comparison was used to determine how component selection affected the electrical response before variable-load and thermal-stress cases were considered. The main outputs observed in this stage were average output voltage, inductor current profile, current ripple, and output voltage ripple. All configurations reached the required output range, but the quality of operation differed across the tested designs. Configurations with lower-resistance switching devices and better-matched passive components produced smoother output behavior and smaller ripple levels. Designs with higher conduction loss or less suitable filter values showed larger ripple magnitude and weaker waveform quality. These differences did not cause failure under nominal load, yet they became more important in later stages because ripple and waveform distortion contributed to higher loss and greater device temperature. The nominal results show that component selection should be treated as a connected design problem rather than a simple substitution of parts.

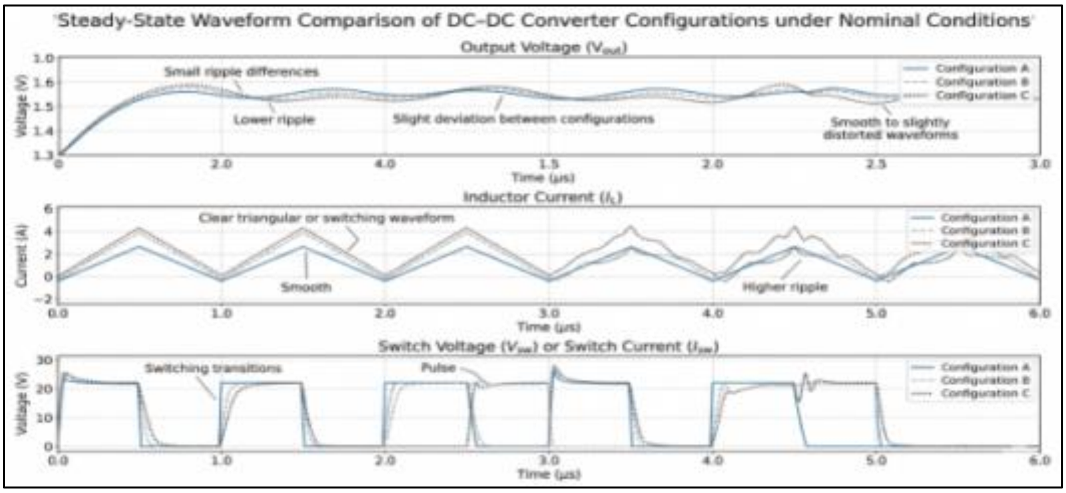


**Figure 3** Steady-state output voltage, inductor current, and switching waveforms for different converter configurations under nominal conditions

Figure 3 presents a multi-panel technical plot with synchronized time axes. The upper panel should show output voltage waveforms for three representative configurations. The middle panel should show inductor current waveforms, including ripple magnitude and current smoothness. The lower panel should show switch voltage or switch current during steady-state operation. Use distinct line styles, consistent axis scaling, and well-labeled legends. The figure should appear as a polished journal-quality simulation result, not as a raw screenshot from simulation software.

### 4.2. Switching Loss Trends and Efficiency Comparison

The second stage of the results examined switching losses and converter efficiency across all candidate configurations. This comparison is central to the paper because the study links component selection with both electrical and thermal performance. Total converter loss was considered through its conduction and switching portions, but the discussion remains focused on observed design trends rather than an extended mathematical treatment. The simulation results showed that semiconductor selection had a direct effect on loss behavior. Configurations using devices with lower conduction resistance produced smaller steady-state power dissipation at moderate load levels. As switching speed and operating frequency increased, transition-related loss became more visible in some design cases. This created a tradeoff between conduction performance and switching activity. In several configurations, a device that appeared favorable under lower-frequency operation became less attractive once switching intensity increased. Efficiency rankings also changed across operating cases. Under nominal load, several configurations performed closely in average efficiency. Under variable-load operation, the differences became clearer because devices with better switching characteristics maintained lower accumulated loss as current demand changed. These results indicate that a single-point efficiency value is not sufficient for converter selection in industrial applications.

**Table 2** Comparative performance summary of the candidate converter configurations

| Configuration | Average Efficiency (%) | Total Loss Trend | Thermal Rise Trend | Voltage Regulation Quality | Overall Assessment |
|---|---|---|---|---|---|
| Config. A | 92.1 | Moderate conduction and switching loss | High | Acceptable | Baseline performance |
| Config. B | 94.6 | Lower total loss under nominal and variable load | Moderate | Very good | Preferred balanced design |
| Config. C | 95.0 | Low conduction loss but higher switching loss at elevated frequency | Low | Good | Suitable with operating limits |
| Config. D | 89.8 | Higher cumulative loss | Moderate to high | Acceptable to weak | Less suitable for long-duration use |

Table 2 summarizes the comparative performance of the candidate converter configurations. Config. C showed the lowest thermal rise among the tested cases, although its switching-related loss increased at elevated frequency. Config. B provided the best overall balance of efficiency, loss behavior, thermal condition, and voltage regulation, which made it the preferred configuration for industrial operation. Config. A served as a baseline case but showed the highest thermal rise. Config. D produced the weakest overall performance because of higher cumulative loss and poorer regulation quality under extended operating conditions

### 4.3. Thermal Response and Component Stress Analysis

Thermal behavior formed the third stage of the results because temperature rise separates a technically acceptable converter from a design suitable for industrial service. The thermal analysis considered the estimated temperature rise of the main switching device and other stressed elements under nominal, variable-load, and longer-duration operating cases. Since thermal conditions are closely linked to electrical loss, this subsection extends the previous discussion and shows how differences in component selection translate into practical temperature outcomes. The results showed that configurations with lower total loss also maintained lower device temperature over the simulation interval. This trend was expected, but the size of the difference among the configurations was notable. Some cases that showed only a small difference in electrical efficiency developed a much larger temperature rise over time. That observation indicates that a design with acceptable efficiency may still present long-term operating concerns if thermal accumulation is ignored during selection. The passive stage also influenced thermal behavior. Higher series resistance in the inductor and output capacitor contributed additional heat generation, especially under variable current conditions. The best thermal result came from a balanced component set rather than from a single high-performance device placed in an otherwise unchanged circuit.

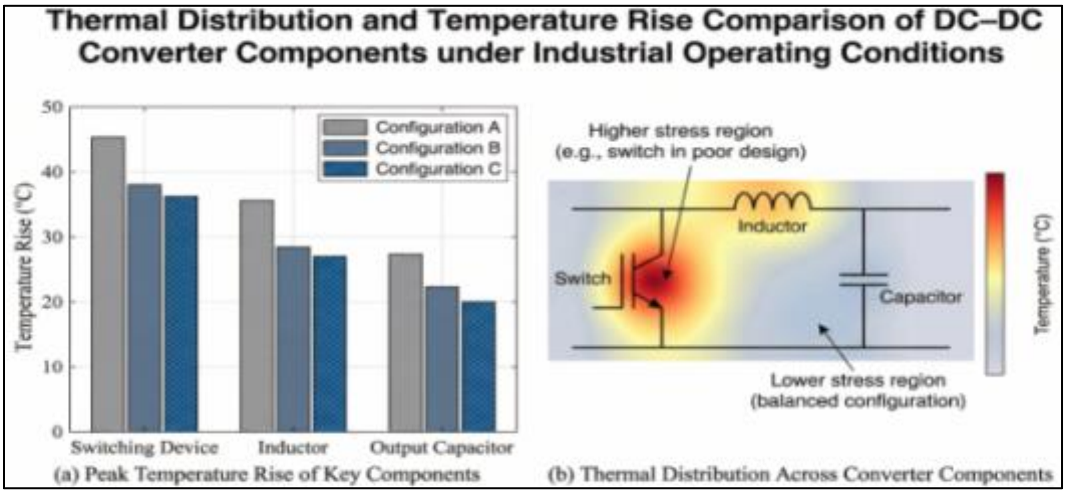


**Figure 4** Thermal distribution and temperature-rise comparison for representative converter configurations

Figure 4 combines two refined visual elements. The first should present a bar comparison of peak temperature rise for the switching device, inductor, and output capacitor across the main configurations. The second should present a heat-map style schematic or thermal trend plot showing relative stress concentration in the preferred and non-preferred designs. Use a restrained academic color palette, consistent labels, and clean spacing. Avoid decorative thermal effects or oversimplified drawings.

### 4.4. Voltage Regulation and Dynamic Response Under Variable Load

Voltage regulation was analyzed under variable-load conditions to determine how well each converter configuration maintained stable output as load demand changed over time. This test is important for industrial applications because many practical loads do not operate at constant power. Drives, control units, and process equipment often draw changing current over short or extended intervals. A converter that performs well under fixed conditions but shows large voltage deviation during load transitions may not be suitable for industrial use. The results indicated that the preferred configurations were not simply those with the lowest total loss. Some design cases with favorable efficiency values showed larger output variation during load transitions because their passive filtering and transient response characteristics were less suitable. This is one of the main findings of the paper. It shows that component selection should not prioritize efficiency alone when the converter is intended for an industrial environment. Stable voltage regulation requires a proper balance among switching behavior, inductor sizing, and output capacitance. The simulations also showed that the better-performing configurations recovered more quickly after step changes in load demand, while less suitable configurations showed larger transient sag or overshoot followed by a slower return to the reference level.

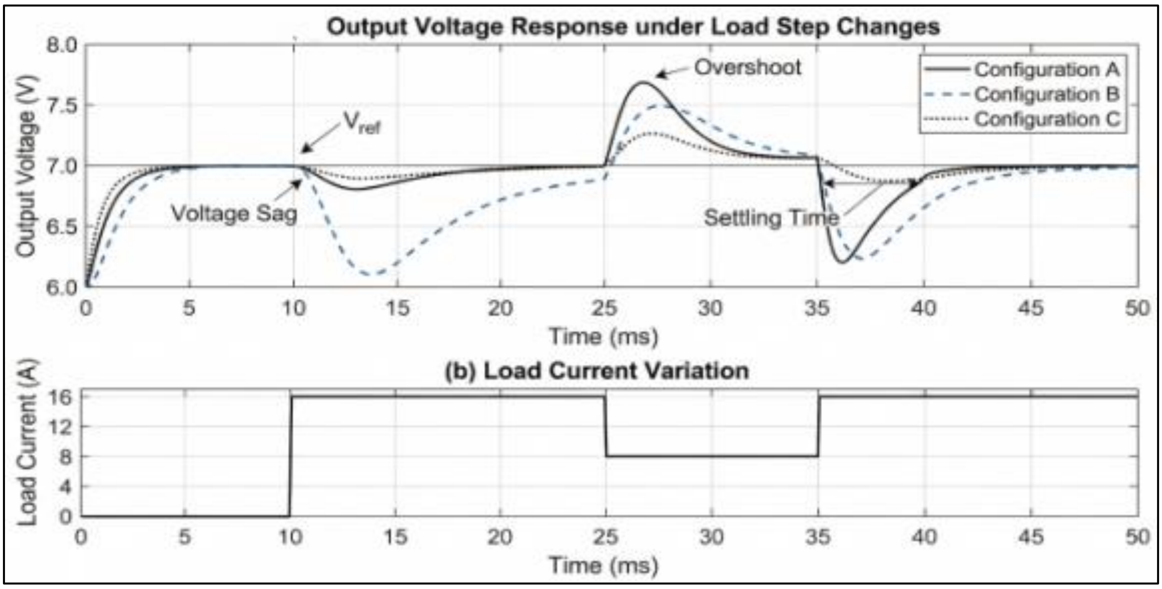


**Figure 5** Dynamic output response under load variation for selected converter configurations

Figure 5 presents a high-quality transient comparison plot. The main graph should show output voltage response over time for multiple configurations during a defined load-step sequence. A secondary plot or inset should show the corresponding load current variation so that the source of each transient event is clear. The figure should mark transient sag, overshoot, and settling behavior with concise annotations. Formatting should follow journal standards, with aligned axes, consistent legend placement, and no simulation-interface elements.

### 4.5. Integrated Performance Interpretation and Final Design Selection

The final stage of discussion combines the electrical, thermal, and regulation results to identify the most suitable converter configuration for industrial energy systems. This subsection reflects the central contribution of the paper, since the decision is based on connected performance measures rather than on one design target. The comparison showed that the preferred configuration was not always the one with the best result in a single category. Instead, the most suitable design was the one that maintained a consistent balance across efficiency, thermal condition, and voltage regulation. One configuration emerged as the strongest overall candidate because it produced low total loss, moderate temperature rise, stable nominal output, and acceptable transient response under load variation. Another configuration showed competitive efficiency under fixed operation but produced higher temperature rise as switching activity increased. A third case maintained reasonable regulation yet operated with greater accumulated loss, which reduced its value for long-duration industrial use. These outcomes show that the final design decision must account for the interaction among semiconductor properties, passive component values, and operating scenarios. The preferred configuration therefore represents a balanced engineering solution rather than a design selected from one metric alone.

## 5. Conclusion

This paper presented a simulation-based study of DC–DC converter design for industrial energy systems with attention to component selection, switching losses, thermal conditions, and voltage regulation. The results showed that converter performance cannot be judged from efficiency alone. Loss behavior, temperature rise, and output stability are closely related and should be examined together during design evaluation. Different component configurations produced clear differences in electrical response and thermal stress, even under the same operating conditions. Among the tested cases, the preferred configuration provided lower loss, moderate temperature rise, and more stable output performance. These findings show that an integrated electrical and thermal assessment provides a sound basis for converter design in industrial applications.

Future work will extend this study to hardware implementation and experimental testing under practical industrial load conditions. Additional analysis can examine wide-bandgap semiconductor devices and compare their performance with conventional switching components in the same converter structure. Reliability assessment, lifetime estimation, and fault-condition analysis also remain open for further investigation. Another direction involves adaptive control strategies that respond to changes in load and source conditions during operation. The study can also be expanded to battery-supported systems, electric vehicle charging units, and hybrid industrial DC networks, where converter design has a direct effect on power quality and system performance.

### *Limitations of the study*

This study has several limitations. First, the analysis relies on simulation and does not include hardware implementation. As a result, the findings do not fully represent practical effects such as device aging, electromagnetic interference, sensor inaccuracy, and manufacturing tolerance. Second, the evaluation covers only selected component configurations and representative operating cases. Other converter topologies, wider operating ranges, and different industrial load profiles may lead to different results. Third, the thermal assessment is based on simulated temperature behavior and does not include long-duration experimental observation under continuous industrial duty cycles. Fourth, the scope remains at converter level. Plant-level effects, including grid disturbances, coordinated energy management, and system-wide fault propagation, are outside the present study. In addition, the work does not include reliability modeling, lifetime prediction, or cost analysis. These limitations mean that the results should be read as a comparative design study focused on converter performance under controlled conditions. Further investigation with hardware testing and broader operating scenarios is needed before drawing conclusions for full-scale industrial deployment.

## Compliance with ethical standards

### *Disclosure of conflict of interest*

No conflict of interest to be disclosed.

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