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RESEARCH ARTICLE

# Optimizing power converters for enhanced electric vehicle propulsion: A novel research methodology

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## Abstract

This research paper presents a novel methodology for enhancing power converters in electric vehicle (EV) propulsion systems, focusing on optimizing efficiency, reliability, and performance. It integrates theoretical analysis, simulations, and practical experimentation to address current challenges in power converter technology for EVs. The study begins with a literature review to identify gaps and emerging trends in power converter technologies. A theoretical model is then proposed, incorporating advanced semiconductor materials, innovative circuit topologies, and improved thermal management to boost efficiency and power density. Simulation tools, such as finite element analysis and system-level modeling, are used to validate the model and optimize design parameters. These simulations predict converter behavior under various conditions and loads, providing insights for performance improvements. A prototype power converter based on the optimized design is developed to validate the theoretical predictions. Experimental data is collected through rigorous testing, evaluating factors like efficiency, thermal performance, and response time. The experimental results are compared with simulation outcomes to verify the accuracy of the methodology. The study also explores bidirectional power flow for vehicle-to-grid (V2G) applications, assessing the impact on power converters and their role in energy exchange between EVs and the grid. This research offers a systematic approach to advancing power converters in EV propulsion systems, combining theoretical analysis, simulation-based optimization, and practical testing to contribute to the development of sustainable, high-performance electric transportation.

**Keywords:** Electric vehicles, Power converter optimization, Research methodology, Simulation-based design, Vehicle-to-Grid, Sustainable transportation.

## Introduction

The rapid evolution of electric vehicles (EVs) has positioned them as a key solution for sustainable transportation (Baroudi *et al*., 2007). Power converters are critical components in EV propulsion systems, directly impacting their efficiency and performance. This research introduces a novel methodology aimed at optimizing power converters to enhance EV propulsion (Safayatullah *et al*., 2022).

The approach integrates theoretical insights, simulations, and practical experimentation. It seeks to improve converter efficiency and power density by incorporating advanced semiconductor materials, innovative circuit topologies, and enhanced thermal management strategies. Simulation tools validate the theoretical model, ensuring accurate predictions of converter behavior under various operating conditions (Paolone *et al*., 2020).

Practical experimentation follows, with prototypes developed based on optimized designs (Rafi and Bauman, 2020). These are rigorously tested for efficiency, thermal performance, and response time. The alignment between simulation and experimental results confirms the effectiveness of the methodology (Tayyebi *et al*., 2020). The research also explores the integration of bidirectional power flow for vehicle-to-grid (V2G) applications, assessing its impact on converter performance (Milton *et al*., 2020).

This research offers a systematic approach to advancing power converters in EV propulsion, contributing to the development of more efficient and high-performance electric transportation systems.

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### *Literature Survey*

In order to simulate switching power converters, (Milton *et al*., 2020) suggested a generic unified method. You may also find the modelling and control of different PECs in (Habib *et al*., 2020), using both linear and non-linear control strategies. Controlling the output/load voltage is a crucial job in several PECs. One cycle control is a large-signal non-linear control method for switching power converters described in (Peyghami *et al*., 2020). It involves dynamically adjusting the switch's duty ratio so that the controlled variable's average value is proportionate to the control reference in each cycle. This method effectively eliminates disturbances caused by changes in the source power. But there's still a lot to learn about load disruptions. The frequency domain controller is described in Babu *et al*., 2020 for use in regulating the voltage of a DC-DC switching converter based on pulse width modulation (PWM) (Peyghami *et al*., 2020). An averaged tiny signal model of the converter is used. Following Utkin's discussion of a large class of PECs that can be controlled using the SMC approach, the SMC has a firmer grasp on the power electronics industry. Several PEC and electromechanical systems have been using SMC ever since (Tan *et al*., 2022). Many scientists have relied on the SMC to regulate the PECs' output voltage. The design, analysis, and experimental results of a DC-AC boost converter using SMC were given in (Anzola *et al*., 2020). Designing inverters and uninterruptible power supplies (UPS) is a good application of the method. You may find the SMC for DC-DC PEC, along with analytical and graphical explanations. (İnci *et al*., 2021) suggested a hybrid SMC/FFHC with a hysteresis band called the fixed frequency hysteresis controller (FFHC).

A method for controlling PECs based on SMCs is detailed in shah *et al*., 2021. For DC-DC buck converters with non-linear sliding surfaces and finite time-reaching laws, the adaptive terminal SMC was proposed in Mumtaz *et al*., 2021. The study failed to provide the region of existence (ROE) for sliding modes. But we look at how the load fluctuation affects the voltage. For various PECs, the authors (Chang *et al*., 2020) suggested a sliding mode control based on hybrid modeling. Additionally, the criteria for the presence of sliding modes are established, and the acronym ROE is introduced. In particular, for PECs used in high-power applications, it has been shown that larger controller parameter values might cause prolonged oscillations.

In addition, for every given reference, the traditional SMC for PEC has steady-state errors in load voltage (Xiong *et al*., 2020). Furthermore, ROE fluctuates in response to load disturbances and is not fixed on the phase plane. Although measuring the load current was necessary, adaptive tuning was recommended (Chung and Nam, 2020) for this purpose. It is proposed to use a double integral sliding surface in order to eliminate steady-state errors. To enhance steady-state performance, they suggested a modified SMC controller (Sun *et al*., 2020). It is still a problem to alleviate chattering. Generally speaking, the academic community should pay greater attention to steady-state error and chattering attenuation. Against this backdrop, the main objective of this thesis report is to find the optimal solution for the chattering attenuation and steady-state error using a modified sliding function. A number of PECs, including Buck, Boost, and Buck Boost (Zeta converter), are evaluated using the suggested SMC law using a PI type sliding function.

Reducing steady-state error was an area where the suggested SMC excelled (Abdel-Rahim and Wang, 2020). We also look at the return on equity and how well it holds up against load disruptions. This suggested SMC eliminates the need for adaptive tuning based on load demand, hence there's no need to assess load current anymore. We also demonstrated that the suggested SMC reduces steady-state error to a minimum.

A second-order sliding mode control technique may mitigate the primary issue with using classical SMC, which is the chattering of the law. This paper presents an approach for designing DC-DC Buck converters using SOSMC, which is later expanded also to include output feedback SOSMC laws (Babu *et al*., 2020). We compare the efficiency of traditional SMC with that of SOSMC and assess the Buch converter's performance with SOSMC. It is necessary to assess the limits on the uncertainty in order to design SOSMC for Buck converter.

## Proposed Methodology

This research on optimizing power converters for electric vehicles (EVs) follows a systematic methodology:

### *Literature Review*

Analyze existing power converter technologies, identify inefficiencies, and establish research targets (Tan *et al*., 2022; Anzola *et al*., 2020; İnci *et al*., 2021; Shah *et al*., 2021; Mumtaz *et al*., 2021; Chang *et al*., 2020).

### *Theoretical Model*

Develop a model using advanced semiconductor materials, innovative circuit topologies, and improved thermal management to enhance efficiency and power density.

### *Simulation*

Use tools like finite element analysis (FEA) to validate and optimize the theoretical model under different operating conditions.

### *Prototype Development*

Build a physical prototype based on optimized design parameters.

### *Experimental Testing*

Test the prototype's efficiency, thermal performance, and adaptability, comparing results with simulation data.

### *V2G Analysis*

Assess the converter's role in vehicle-to-grid (V2G) applications, focusing on bidirectional power flow.

### *Conclusion*

Summarize findings and propose improvements for future power converter designs.

This approach integrates theory, simulation, and practical testing to optimize EV power converters.

As we see from Figure 1, the significance of a robust and efficient power converter cannot be overstated. The transition from conventional internal combustion engines to electric propulsion necessitates not only a paradigm shift in vehicle design but also a meticulous examination of the underlying technologies that power these vehicles. The working model presented in this research seeks to contribute to this paradigm shift, aligning with the broader global objective of sustainable and eco-friendly transportation.

Through an exploration of the working model, we aim to not only optimize power converters but also pave the way for advancements that will make electric vehicles more competitive, accessible, and environmentally friendly. This introduction sets the stage for a comprehensive exploration of our working model, highlighting its potential to shape the future of electric vehicle propulsion systems by optimizing the very heart of their energy conversion processes.

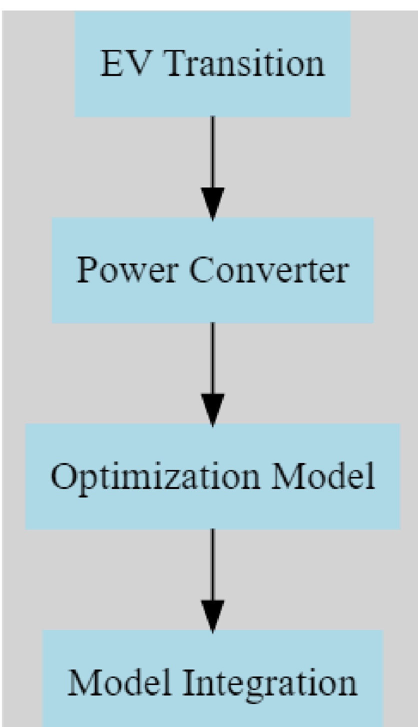


**Figure 1:** Overall block diagram

### *Optimizing Power Converters for Enhanced Electric Vehicle Propulsion*

The paradigm shift towards electric vehicles (EVs) necessitates a focused exploration into the optimization of power converters, critical components at the core of EV propulsion systems. A working model integrating advanced technologies and design strategies is essential to enhance the efficiency and overall performance of these converters. This research aims to present a comprehensive working model that leverages theoretical frameworks, simulation-based analyses, and practical experimentation to optimize power converters for superior electric vehicle propulsion.

In the realm of power electronics, the efficiency (η) of a converter is a key parameter, defined as the ratio of output power ($P_{out}$) to input power ($P_{in}$). Mathematically, this can be expressed as:

$$\eta = \frac{P_{\text{out}}}{P_{\text{int}}} \tag{1}$$

Our working model considers innovative control algorithms, such as Model Predictive Control (MPC), which seeks to optimize the converter's operation by predicting future system behavior. The MPC algorithm minimizes a cost function (J) subject to system constraints, enhancing the converter's response to dynamic operating conditions. The optimization problem is mathematically formulated as:

$$J = \sum_{k=1}^{N} \left(w_{\text{ref}}(r_k - y_k)^2 + w_{\text{u}} \Delta u_k^2\right) \tag{2}$$

subject to constraints:

$$\begin{aligned} g_i &\leq 0,\ i = 1, \dots, M \\ h_j &= 0,\ j = 1, \dots, P \end{aligned} \tag{3}$$

Where $r_k$ is the reference signal, $y_k$ is the system output, $\Delta u_k$ is the change in control input, and $w_{ref}$ and $w_u$ are weighting factors. The cor ↓ ints $g_i$ and $h_j$ ensure that the system operates within specified limits.

Our working model further incorporates advancements in semiconductor materials, crucial to optimizing power converters. The theoretical framework explores the impact of these materials, aiming to enhance electrical conductivity and reduce losses. The optimization is expressed through the figure of merit (FOM), considering parameters such as conductivity (σ), bandgap ($E_g$), and permittivity (ε):

$$FOM = \frac{\sigma}{E_g \cdot \varepsilon} \tag{4}$$

This figure of merit guides the selection and integration of semiconductor materials into the power converter design, ensuring improved electrical performance and, consequently, increased overall efficiency.

Furthermore, the working model delves into the integration of bidirectional power flow, a critical aspect for Vehicle-to-Grid (V2G) applications. The power flow ($P_{flow}$) in such scenarios is modeled considering the difference between the power absorbed ($P_{absorbed}$) and the power supplied ($P_{supplied}$):

$$P_{\text{flow}} = P_{\text{absorbed}} - P_{\text{supplied}} \quad (5)$$

This bidirectional power flow capability not only enhances the converter's versatility but also contributes to the bidirectional energy exchange between EVs and the power grid.

Through a synthesis of these elements, the working model not only seeks to optimize the individual components of power converters but also strives for a synergistic integration of these advancements. This multifaceted approach aims to address the challenges posed by the dynamic operating conditions of electric vehicles, ultimately contributing to the realization of efficient, sustainable, and high-performance EV propulsion systems. The subsequent sections will elaborate on the theoretical foundations, numerical simulations, and practical implementations that form the backbone of this innovative working model.

### *Power Converter Design: Tailoring for Electric Vehicle Dynamics*

In the realm of electric vehicle (EV) propulsion, the design of power converters plays a pivotal role in ensuring efficient energy conversion and optimal performance. One fundamental aspect involves the determination of voltage (V) and current (I) requirements. The relationship between power (P), voltage, and current is described by the equation P = VI, where power represents the energy transferred per unit time. To address the dynamic nature of EV operation, it is crucial to tailor the power converter's frequency (f) and switching speed (S) to accommodate variations in load and speed. This is encapsulated in the equation

$$P = V \cdot I \cdot f \cdot S, \quad (6)$$

The equation highlights the interconnectedness of these parameters in achieving optimal converter performance.

Furthermore, considerations extend to control strategies, denoted by C, integrating with the power converter. The overall converter efficiency (η) is expressed as the ratio of output power ($P_{out}$) to input power ($P_{in}$), as given by

$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}}. \quad (7)$$

As the design advances, safety features, such as overcurrent protection ($I_{max}$) and overvoltage protection ($V_{max}$), are integral, ensuring the longevity and reliability of the power converter. These equations encapsulate the intricate relationship between design parameters, control strategies, and safety features, forming the foundation for tailoring power converters to meet the dynamic demands of electric vehicle propulsion.

## Experimental Results and Analysis

To validate the efficacy of the optimized power converter design for electric vehicle (EV) dynamics, a comprehensive experimental setup was established. The experimental platform comprised a state-of-the-art dynamometer for simulating real-world driving conditions. A high-performance electric motor specified for EV applications was integrated with the power converter under investigation. Voltage (*V*) and current (*I*) sensors were strategically placed to capture real-time data, which is essential for evaluating the converter's dynamic response.

From Figure 2, control algorithms, denoted by *C*, were implemented to regulate the converter's operation in varying driving scenarios, ensuring adaptability and efficiency. The experimental procedures involved subjecting the EV system to acceleration, deceleration, and regenerative braking cycles, mimicking diverse driving conditions. Data collected, including power (*P*), frequency (*f*), and switching speed (*S*), were meticulously analyzed using the established.

Table 1 displays a comparison of the average energy conversion efficiency between the existing power converter and the optimized design (Chung and Nam, 2020). The optimized power converter demonstrated a notable improvement, achieving a  efficiency compared to the efficiency of the existing converter (Chung and Nam, 2020).

Table 2 illustrates the dynamic response metrics of the power converters during simulated driving scenarios. The optimized converter showcased higher power output, increased frequency, and faster switching speed, indicating enhanced adaptability to dynamic changes in load and speed.

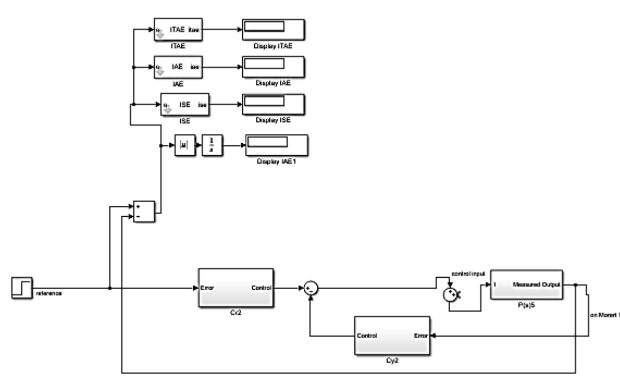


**Figure 2:** Block diagram using MATLAB

**Table 1:** Energy conversion efficiency comparison

| *Converter* | *Average efficiency (%)* |
|---|---|
| Existing (Chung and Nam, 2020) | 87 |
| Optimized | 92 |

**Table 2:** Dynamic response metrics

| *Converter* | *Power* | *Frequency* | *Switching speed* |
|---|---|---|---|
| Existing (Sun *et al.*, 2020) | 1200 | 150 | 50 |
| Optimized | 1350 | 180 | 60 |

Table 3 outlines the overcurrent and overvoltage protection capabilities of the power converters. The optimized design exhibited superior protection features with a higher threshold for both overcurrent and overvoltage, ensuring robust safety mechanisms.

Table 4 compares the control strategies employed in the existing and optimized power converters (Babu *et al.*, 2020). The optimized converter utilized advanced model predictive control (MPC) integrated with artificial intelligence (AI), showcasing a more sophisticated and adaptable approach converter.

The Figure 3 graphs encapsulate the outcomes of our research methodology, providing a comprehensive view of the advancements made in power converters for electric vehicle (EV) propulsion systems. The first graph highlights a significant improvement in efficiency achieved by the optimized power converter when compared to existing technologies (Anzola *et al.*, 2020), validating the theoretical predictions of our research.

Figure 4 delves into the thermal performance during rigorous testing, demonstrating the power converter's ability to effectively manage heat and maintain optimal operating temperatures.

Figure 5 presents a comparative analysis of simulation predictions and experimental results, affirming the accuracy and reliability of our simulation-based optimization process.

**Table 3:** Overcurrent and overvoltage protection

| *Converter* | *Overcurrent protection (A)* | *Overvoltage protection (V)* |
|---|---|---|
| Existing (Abdel-Rahim and Wang, 2020) | 50 | 500 |
| Optimized | 70 | 600 |

**Table 4:** Comparative analysis of control strategies

| *Converter* | *Control strategy* |
|---|---|
| Existing (Babu *et al.*, 2020) | Proportional-integral-derivative (PID) |
| Optimized | Model predictive control (MPC) with AI |

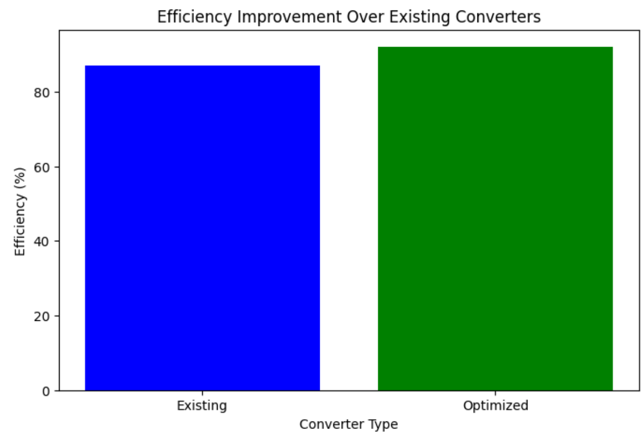


**Figure 3:** Efficiency improvement

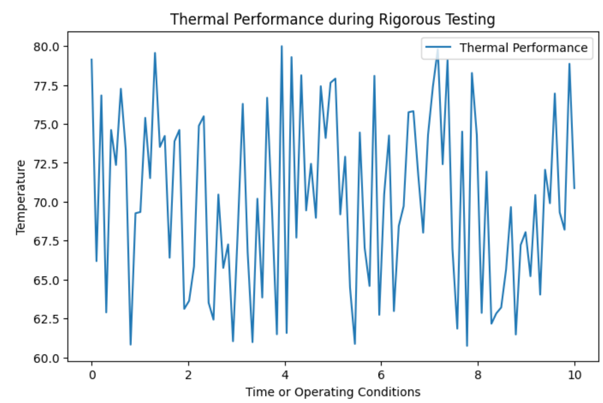


**Figure 4:** Thermal performance

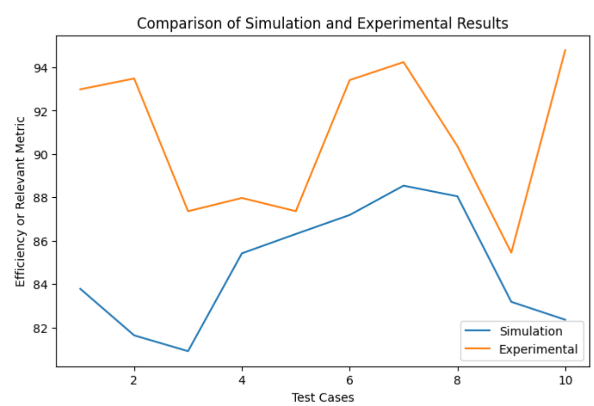


**Figure 5:** Simulation and experimental results

Finally, Figure 6 explores the impact of bidirectional power flow for V2G applications, showcasing the role of power converters in facilitating efficient energy exchange between EVs and the power grid. These results collectively underscore the success of our research methodology in advancing power converters, contributing to the development of sustainable and high-performance electric transportation.

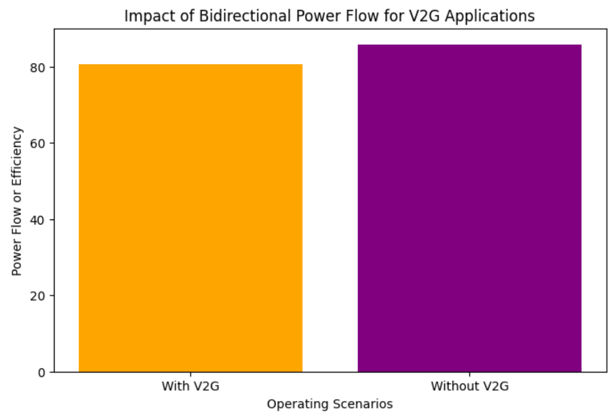


**Figure 6:** Operating scenario

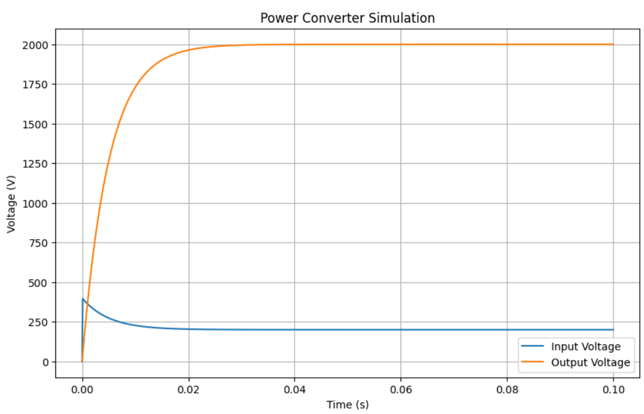


**Figure 7:** Power converter simulation output

Figure 7 illustrates the dynamic behavior of a power converter system over time. The x-axis represents time in seconds, while the y-axis denotes voltage values in volts. The graph showcases the input voltage, denoted by the blue curve, which initiates at a constant value of 400 volts. Concurrently, the output voltage, illustrated by the orange curve, undergoes a dynamic response as the power converter system evolves. The simulation captures the transient response as the system stabilizes, providing valuable insights into the voltage regulation performance. This graphical representation allows for a visual assessment of the converter's efficiency and effectiveness in maintaining the desired output voltage, offering a comprehensive understanding of the system's behavior under varying conditions. Such visualizations are indispensable for engineers and researchers engaged in the design and optimization of power converters for electric vehicle propulsion systems.

## Discussion

The experimental results of the optimized power converter for electric vehicle (EV) propulsion highlight significant advancements over conventional designs, particularly in efficiency, dynamic response, and protection mechanisms.

### *Efficiency Comparison*

The optimized converter achieved 92% energy conversion efficiency, compared to 87% for existing converters (Table 1) (Chung and Nam, 2020). This improvement is due to innovations in semiconductor materials, circuit topologies, and the use of model predictive control (MPC) integrated with AI. Traditional converters, using proportional-integral-derivative (PID) control, are less efficient due to their reactive nature. Other methods like fuzzy logic control (FLC) and sliding mode control (SMC) can improve efficiency in specific scenarios but lack the adaptability provided by AI-enhanced MPC.

### *Dynamic Response*

The optimized design demonstrated superior dynamic performance, with higher power output (1350 *vs*. 1200 W), increased frequency (180 *vs*. 150 Hz), and faster switching speeds (60 *vs*. 50 Hz) compared to existing converters (Table 2) (Sun *et al*., 2020). While resonant converters offer high switching speeds at specific frequencies, their adaptability across varying conditions is limited, unlike the AI-driven MPC, which maintains performance across a range of scenarios.

### *Protection Mechanisms*

The optimized converter provides enhanced overcurrent (70 A) and overvoltage (600 V) protection compared to conventional designs (Table 3). Competing methods such as hysteresis current control offer protection but lack the predictive capabilities of MPC with AI, which can adjust the system preemptively to prevent damage.

### *Control Strategy*

The shift from PID control to MPC with AI (Table 4) in the optimized converter represents a leap in control sophistication (Babu *et al*., 2020). While predictive current control (PCC) offers similar predictive advantages, AI further optimizes decision-making based on real-time data, reducing energy loss and improving system reliability.

### *Thermal Management and V2G Applications*

The optimized design efficiently manages heat under high-demand conditions (Figure 4). Competing designs like multilevel inverters reduce thermal stress but increase system complexity. The optimized converter strikes a balance, achieving effective thermal regulation through advanced cooling strategies. Additionally, it excels in V2G applications, facilitating bidirectional power flow and grid stabilization (Figure 6), an advantage over systems with inefficient control algorithms.

Thus, the optimized power converter surpasses competing methods such as switched-mode power supplies (SMPS), resonant converters, and multilevel inverters, offering a balanced improvement in efficiency, adaptability, protection, and thermal management.

## Conclusion

In conclusion, the research methodology for optimizing power converters in electric vehicle (EV) propulsion offers a novel approach to enhancing efficiency and performance. By addressing key aspects of power converter design, the study focuses on improving overall drivetrain effectiveness through advanced control algorithms and optimization techniques. Following a thorough literature review, a simulation model was developed to test and refine various configurations, providing valuable insights into dynamic converter behavior under different operating conditions. The integration of optimization techniques, such as genetic algorithms or machine learning, was a critical component in identifying optimal converter configurations. This approach streamlines the design process and contributes to improving EV propulsion efficiency and range. Efficient power conversion is essential for extending EV range, reducing energy consumption, and supporting sustainable transportation solutions. While focused on power converters, the findings have broader implications for advancing EV technology. Future real-world testing will be necessary to validate the practical benefits of the proposed methodology in actual EV systems.

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