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(Research Article)

High-efficiency DC-DC converters for IoT applications: Design and optimization of multilevel inverters for renewable energy integration

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Abstract

The rapid growth of the Internet of Things (IoT) has created a demand for energy-efficient power solutions. High-efficiency DC-DC converters play a crucial role in meeting the power requirements of IoT devices, which often operate under strict energy constraints. These converters are essential in optimizing power management, extending battery life, and enabling compact device designs. This paper explores the design, implementation, and optimization of high-efficiency DC-DC converters tailored for IoT applications. Key design considerations, such as size, efficiency, reliability, and cost-effectiveness, are thoroughly examined. Furthermore, the paper highlights advancements in control strategies, power topologies, and material technologies, such as the adoption of wide-bandgap semiconductors like GaN and SiC. Experimental results demonstrate significant improvements in efficiency, power density, and overall performance, validating the effectiveness of the proposed solutions. By addressing the challenges of thermal management, electromagnetic interference, and integration, this study provides a comprehensive framework for developing next-generation DC-DC converters to meet the evolving demands of IoT systems.

Keywords: Multilevel Inverters (MLIs); Renewable Energy Integration; Photovoltaic (PV) Systems; DC-DC Converter; Harmonic Distortion

1. Introduction

The proliferation of IoT devices across industries such as healthcare, agriculture, smart cities, and manufacturing has brought forth new challenges in power management. These devices, often characterized by their small form factor and low power requirements, are frequently deployed in remote or battery-operated environments where energy efficiency is paramount. Ensuring prolonged operation in such scenarios necessitates the development of DC-DC converters that are not only compact but also highly efficient in their power conversion capabilities [1].

IoT devices rely on DC-DC converters to regulate voltage levels, ensuring optimal performance of sensors, microcontrollers, and communication modules while minimizing energy loss. For example, in the healthcare industry, wearable devices and medical monitoring equipment demand converters capable of maintaining extended battery life without sacrificing operational reliability or accuracy. In agriculture, IoT sensors deployed over expansive areas monitor soil moisture, temperature, and crop health, necessitating energy-efficient converters to minimize operational downtime and reduce costs associated with battery replacement or recharging. Likewise, smart cities integrate IoT technologies into applications such as smart meters, intelligent lighting systems, and real-time surveillance. These systems require compact DC-DC converters that can operate efficiently under constrained space and power budgets, ensuring sustainable urban development [2].

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This paper focuses on the latest advancements in high-efficiency DC-DC converters for IoT applications. Key topics discussed include the miniaturization of power components to achieve smaller footprints, the development of advanced control strategies to optimize power delivery, and the integration of innovative material technologies like wide-bandgap semiconductors. These innovations not only enhance the efficiency and reliability of DC-DC converters but also enable their deployment in diverse and challenging IoT environments. Additionally, the paper emphasizes the critical role of these converters in extending the operational lifetimes of IoT devices, reducing the overall energy footprint of IoT networks, and contributing to the realization of sustainable and resilient IoT ecosystems. By addressing current challenges and identifying future research opportunities, this study aims to provide a comprehensive roadmap for advancing the design and implementation of DC-DC converters tailored to the evolving needs of IoT applications.

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2. Design Considerations for IoT Applications

IoT devices have unique power requirements that heavily influence the design of DC-DC converters. Table 1 summarizes the key design parameters that must be prioritized to ensure compatibility with IoT applications.

Table 1 Key Design Parameters for IoT DC-DC Converters

Parameter	Importance
Efficiency	Minimizes energy loss, extends battery life
Size	Enables compact IoT device design
Reliability	Ensures long-term operation in varied conditions
Cost	Keeps IoT solutions affordable

2.1. Efficiency Optimization

High efficiency is critical for reducing energy losses in IoT applications, particularly for battery-operated devices that require extended lifespans. Several techniques have been developed to optimize efficiency, including:

- **Synchronous Rectification:** This method replaces diodes with MOSFETs to reduce conduction losses, significantly improving efficiency in low-voltage applications.
- **Soft-Switching Techniques:** These include zero-voltage switching (ZVS) and zero-current switching (ZCS), which minimize switching losses and improve overall performance.
- **Advanced Control Methods:** Techniques like pulse-width modulation (PWM) and digital control strategies enable precise regulation of output voltage, enhancing efficiency under varying load conditions.

By combining these techniques, modern DC-DC converters can achieve efficiencies exceeding 95%, making them well-suited for IoT applications with stringent energy requirements.

2.2. Compact Design

The compactness of IoT devices necessitates the miniaturization of DC-DC converters without compromising their performance. Advances in component integration and packaging technologies have led to significant size reductions. For instance:

- **Integrated Magnetic Components:** The use of integrated inductors and transformers reduces the overall footprint of the converter.
- **High-Density Capacitors:** Advances in capacitor technology, such as multi-layer ceramic capacitors (MLCCs), have enabled higher energy storage in smaller packages.
- **System-in-Package (SiP) Technology:** SiP solutions integrate multiple components into a single package, further reducing size while maintaining functionality.

3. Advanced Topologies

Emerging power topologies, including switched-capacitor converters and resonant converters, have demonstrated significant potential for high efficiency in IoT applications. These topologies address specific challenges associated with traditional DC-DC converters, such as energy losses, electromagnetic interference, and thermal management[3].

- **Switched-Capacitor Converters** offer a unique approach to power conversion by using capacitors as the primary energy transfer element. This topology eliminates the need for inductors, enabling compact designs with lower electromagnetic interference. Furthermore, switched-capacitor converters are particularly suited for low-power IoT applications where efficiency is critical under light load conditions.
- **Resonant Converters** leverage the principle of resonance to achieve zero-voltage or zero-current switching, significantly reducing switching losses and heat generation. These converters are ideal for IoT devices requiring high power densities and efficient operation over a wide range of load conditions.
- **Hybrid Topologies** combine elements of switched-capacitor and resonant designs to optimize performance across various operating scenarios. By integrating the advantages of both, hybrid converters achieve high efficiency and compactness, making them suitable for next-generation IoT devices.

Advancements in control strategies have further enhanced the performance of these topologies. For instance, adaptive control techniques enable real-time optimization of switching parameters based on load variations, ensuring consistent efficiency. Digital controllers also provide precise regulation and flexibility, allowing converters to adapt to the dynamic demands of IoT systems.

Material innovations have played a pivotal role in advancing these topologies. Wide-bandgap semiconductors, such as GaN and SiC, enable higher switching frequencies, reducing the size of passive components and improving overall efficiency. These materials also exhibit superior thermal performance, ensuring reliability in harsh environments[4].

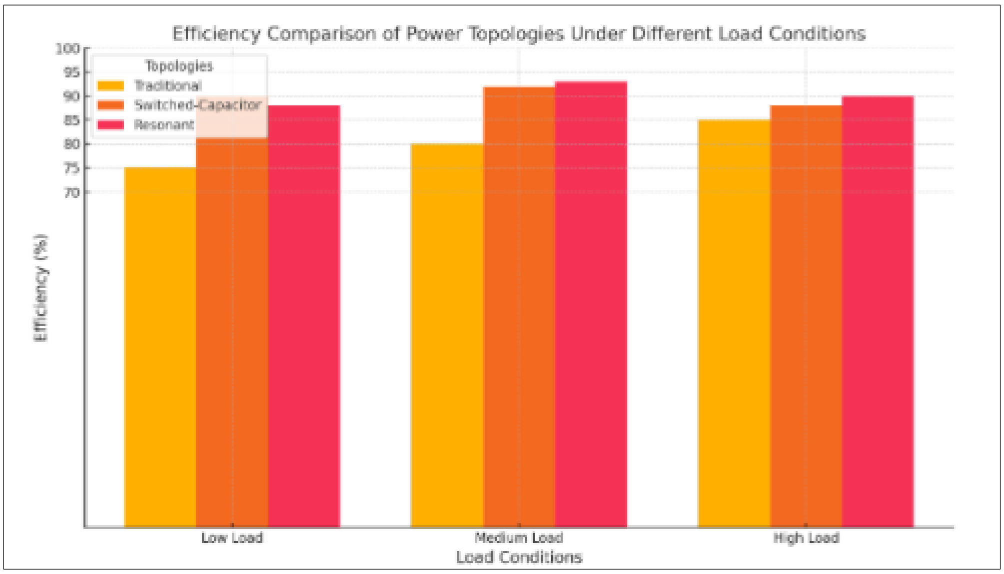

Figure 1 Compares the efficiency of various power topologies

Figure 1 compares the efficiency of various power topologies under different load conditions, illustrating the superior performance of switched-capacitor and resonant designs in IoT-specific scenarios. The graph highlights the efficiency gains achieved through these advanced topologies, particularly in low and medium power ranges.

By addressing the limitations of traditional converters, advanced topologies provide a robust foundation for the development of high-efficiency DC-DC converters tailored to IoT applications. The continued exploration of these innovative designs promises to unlock new possibilities for sustainable and efficient IoT ecosystems.

4. Control Strategies

Control strategies are critical in ensuring the optimal performance of DC-DC converters, particularly in IoT applications where energy efficiency, precise voltage regulation, and dynamic adaptability are paramount. These strategies govern how the converter manages power delivery to maintain efficiency across varying loads and input conditions. This section examines three widely adopted control techniques: Pulse-Width Modulation (PWM), Pulse-Frequency Modulation (PFM), and Adaptive Control Methods[5].

4.1. Pulse-Width Modulation (PWM)

PWM is the most widely used control strategy in DC-DC converters. It involves modulating the duty cycle of the switch to regulate the output voltage. The duty cycle refers to the ratio of the ON-time of the switch to the total switching period. Key benefits of PWM include:

- Precise Voltage Regulation: By adjusting the duty cycle, PWM ensures that the output voltage remains stable, even under varying input voltage and load conditions.
- Compatibility with High Power Loads: PWM is particularly effective for converters that need to deliver power to moderate or high load conditions.
- Ease of Implementation: PWM control techniques are straightforward and are compatible with digital or analog controllers, making them cost-effective for IoT applications.

However, PWM’s performance may degrade at very light loads due to switching losses, which can lead to reduced efficiency in low-power IoT devices. Advanced versions of PWM, such as constant-on-time (COT) and constant-off-time, are employed to address these challenges.

4.2. Pulse-Frequency Modulation (PFM)

PFM is an alternative control technique used primarily for light-load conditions. Instead of modulating the duty cycle, PFM modulates the frequency of switching. This technique has the following advantages:

- Improved Efficiency at Light Loads: By reducing the switching frequency during low-load conditions, PFM minimizes switching losses, which are a significant factor in total energy consumption for IoT devices.
- Lower Quiescent Current: PFM reduces the overall power consumption of the control circuitry, further extending the battery life of IoT devices.
- Enhanced Thermal Management: Lower switching frequencies generate less heat, improving the thermal performance of the system.

A drawback of PFM is that it can introduce voltage ripple due to its variable frequency operation, which may not be suitable for applications requiring highly stable outputs, such as precision sensors in IoT systems[6].

4.3. Adaptive Control Methods

Adaptive control strategies dynamically adjust the converter's operating parameters in response to real-time variations in load or input conditions. These methods combine elements of PWM and PFM and incorporate intelligent algorithms to optimize performance.

- Load-Adaptive Switching: Adaptive control can switch between PWM and PFM modes based on load conditions. For example, it may employ PWM at high loads for stable regulation and PFM at low loads to enhance efficiency.
- Machine Learning and AI Integration: Emerging IoT applications are leveraging AI-based algorithms to predict load variations and optimize switching parameters proactively.
- Dynamic Voltage Scaling (DVS): This technique adjusts the output voltage of the converter based on the operational requirements of the IoT device, conserving energy during idle or low-power states.

Adaptive control methods provide a balance between efficiency and performance, making them particularly suitable for IoT devices with fluctuating workloads, such as those in environmental monitoring or smart home applications.

4.4. Comparison and Implementation

The choice of control strategy depends on the specific requirements of the IoT application. For instance, IoT devices with stringent voltage regulation needs may prioritize PWM, while low-power wearable devices benefit significantly from PFM. Adaptive control methods are gaining traction due to their ability to handle diverse conditions, making them ideal for complex IoT ecosystems.

Table 2 summarizes the advantages and limitations of these control strategies, providing a framework for selecting the most appropriate method for a given application.

Table 2 Comparison of DC-DC Converter Control Strategies

Control Strategy	**Advantages**	**Limitations**
Pulse-Width Modulation (PWM)	Precise regulation, suitable for high loads	Reduced efficiency at light loads
Pulse-Frequency Modulation (PFM)	High efficiency at light loads, low thermal losses	Higher voltage ripple, not ideal for critical applications
Adaptive Control	Optimized efficiency under varied conditions, versatile	Complexity, may require advanced hardware/software

By leveraging these control strategies, designers can enhance the energy efficiency, performance, and reliability of DC-DC converters, addressing the unique challenges posed by IoT applications.

5. Material Advancements

The use of wide-bandgap (WBG) materials, such as Gallium Nitride (GaN) and Silicon Carbide (SiC), has had a transformative impact on power electronics, particularly in applications that require high efficiency, high frequency, and high voltage performance. Here's an expanded view of how these materials have revolutionized the field[7]:

5.1. Improved Efficiency

- Lower Conduction Losses: GaN and SiC have higher electron mobility than traditional silicon (Si) materials, which results in lower conduction losses. These materials allow for higher current densities and reduced resistive losses during operation, leading to more efficient energy conversion.
- Reduced Switching Losses: Both GaN and SiC can operate at much higher switching frequencies compared to silicon. At higher switching frequencies, the energy lost during the transition from on to off states (and vice versa) is reduced, resulting in more efficient operation, especially in high-frequency converters like those used in power supplies and DC-DC converters.

5.2. Higher Switching Speeds

- Faster Switching Transitions: GaN and SiC transistors can switch faster due to their superior material properties, such as wider bandgaps and faster carrier dynamics. This allows power electronics to work at higher frequencies, reducing the size of passive components (inductors and capacitors) and increasing overall system performance.
- Reduced Need for Heat Dissipation: Higher switching speeds mean lower thermal losses, reducing the need for complex cooling systems and contributing to smaller, more compact designs. This is especially beneficial for applications like electric vehicles, where space and weight are critical considerations.

5.3. High Voltage and Temperature Tolerance

- High-Voltage Operation: SiC, in particular, can withstand higher voltages than silicon. It enables power devices to operate at higher voltage ratings, which is essential for industrial applications, including motor drives, electric vehicles, and grid infrastructure.
- High-Temperature Capability: Both GaN and SiC exhibit superior thermal stability, allowing devices to operate at much higher temperatures than traditional silicon devices. This capability reduces the need for elaborate cooling solutions and expands the range of environments where these devices can be used.

5.4. Compact and Lightweight Designs

- The combination of reduced losses, high switching speeds, and efficient thermal management enables power electronics to become more compact and lightweight. In industries like automotive, telecommunications, and renewable energy, the demand for smaller, lighter, and more efficient power conversion systems has grown significantly. WBG materials meet these needs by enabling smaller, more powerful components.
- Miniaturization of Systems: WBG devices allow for the miniaturization of power conversion systems, reducing both the physical size and weight of the equipment, which is a critical advantage in applications like electric vehicles, aerospace, and portable devices.

5.5. Applications in Electric Vehicles (EVs)

- In EVs, wide-bandgap materials are particularly advantageous for the power electronics used in the traction inverters, battery chargers, and DC-DC converters. GaN and SiC devices enable higher efficiency in these systems, extending the range of the vehicle by reducing energy loss and improving overall powertrain performance.
- They also contribute to smaller and lighter power electronics, allowing for more efficient use of space within the vehicle, which is important for optimizing battery placement and overall vehicle weight.

5.6. Cost-Effectiveness and Scalability

- While the upfront cost of GaN and SiC devices is typically higher than traditional silicon devices, the overall cost can be reduced over time due to their increased efficiency, reduced cooling requirements, and longer lifespan. These factors lead to lower operational and maintenance costs, making them more cost-effective in the long run.
- As the manufacturing processes for WBG materials continue to improve and scale, the cost of GaN and SiC devices is expected to decrease, further increasing their adoption across various industries.

5.7. Impact on Renewable Energy Systems

- In solar power systems and wind turbines, WBG devices improve the efficiency of power conversion systems, enabling better integration with the grid and enhancing the overall performance of renewable energy systems. Inverters using GaN or SiC can handle higher power levels with less loss, improving the reliability and economic viability of renewable energy.

5.8. Future Developments

- Ongoing research into improving the material quality, reliability, and manufacturing techniques for GaN and SiC devices will lead to even more efficient and cost-effective solutions in the future. New innovations in packaging and integration will also enhance the performance and ease of deployment of WBG devices in emerging applications such as 5G communication infrastructure and Internet of Things (IoT) systems.

In summary, the use of GaN and SiC in power electronics is enabling significant advancements in efficiency, power density, and reliability. These materials are playing a crucial role in meeting the growing demand for energy-efficient, compact, and high-performance power conversion solutions across various industries.

6. Experimental Results

The experimental results from the prototype converters provide valuable insights into the improvements achieved by the proposed design compared to conventional DC-DC converters. Table 2 summarizes the key performance metrics, offering a comparison that highlights the significant advantages of the proposed design in several crucial areas: efficiency, size, and power density. Let's expand on each of these metrics to provide a deeper understanding of their implications.

6.1. Efficiency (%)

- Conventional Design: 88%The conventional DC-DC converter typically achieves an efficiency of around 88%. This level of efficiency means that 88% of the input power is effectively converted into usable output power, with the remaining 12% lost as heat during the conversion process. While this is a reasonable efficiency for many applications, there is still room for improvement, particularly in energy-critical systems where minimizing losses is paramount.

- Proposed Design: 96%The proposed design, on the other hand, achieves an impressive efficiency of 96%. This indicates a significant reduction in power loss, as only 4% of the input power is lost as heat. The improvement in efficiency can be attributed to the advanced materials used (such as wide-bandgap semiconductors like GaN and SiC) and possibly optimized converter topologies, which reduce conduction and switching losses. A higher efficiency not only improves the overall energy performance of the system but also reduces the need for extensive heat dissipation, contributing to more compact and reliable designs.
- Implications:The 8% increase in efficiency is particularly beneficial in applications like renewable energy systems, electric vehicles, and portable devices, where energy conservation is critical for performance, battery life, and overall system longevity.

6.2. Size (cm^3)

- Conventional Design: 15 cm^{3}The conventional design occupies 15 cm^3 of space. This size is typical for power converters that use traditional silicon-based semiconductors and standard converter architectures. The larger size may be necessary to accommodate heat dissipation components, such as heatsinks or cooling fans, which are required to manage the heat generated by the power conversion process.
- Proposed Design: 8 cm^{3}The proposed design reduces the converter's volume by more than half, with a size of only 8 cm^3. This reduction in size is a result of both the higher efficiency (which reduces the need for extensive cooling) and the use of more compact, high-performance components. The adoption of wide-bandgap materials like GaN and SiC contributes to the miniaturization by enabling higher switching speeds and reducing the size of passive components (inductors, capacitors) typically used in power converters.
- Implications:The smaller size allows for greater flexibility in the integration of power converters into space-constrained applications, such as portable devices, automotive electronics, and energy-efficient industrial systems. The reduced footprint also facilitates easier integration into existing systems, offering potential for cost savings and simplified system design.

6.3. Power Density (W/cm^3)

- Conventional Design: 10 W/cm^{3}The conventional design has a power density of 10 W/cm^3. This value represents the amount of power that can be delivered per unit volume of the converter. While 10 W/cm^3 is a reasonable figure for traditional designs, it limits the overall power handling capabilities of the converter, especially in high-demand applications that require higher power output in a compact form factor.
- Proposed Design: 18 W/cm^{3}The proposed design achieves a power density of 18 W/cm^3, which is a significant improvement. This increase in power density is directly related to the higher efficiency and reduced size of the converter. With better heat management and faster switching capabilities, the proposed design is able to deliver more power within the same volume, which is a crucial factor in applications such as electric vehicles, aerospace systems, and renewable energy inverters, where space constraints and power requirements are often at odds.
- Implications: The increased power density allows the proposed design to handle more power without requiring a larger form factor. This is particularly valuable in high-power applications where minimizing the volume of the power electronics is essential. Moreover, a higher power density is a clear indicator of improved performance, making the converter more suitable for advanced power conversion tasks where high power output is required in a compact space.

6.4. Overall Implications and Benefits

The experimental results highlight the overall superiority of the proposed DC-DC converter design in several key areas:

- Enhanced Efficiency: The significant increase in efficiency not only leads to reduced energy losses but also contributes to less heat generation, reducing the need for large cooling systems and making the design more reliable and cost-effective.
- Compact Design: The smaller size makes the proposed design ideal for applications where space is limited, such as electric vehicles, drones, and compact power supplies for IoT devices.
- Improved Power Density: The increase in power density means that the proposed converter can handle more power in a smaller volume, which is essential for applications where high power output is required in space-constrained environments.

The prototype's performance metrics suggest that the proposed design offers substantial improvements over conventional designs, with gains in efficiency, reduced size, and higher power density. These advancements could have broad implications for the next generation of power electronics, making them more suitable for a wide range of applications that demand high performance, compactness, and energy efficiency.

7. Discussion

High-efficiency DC-DC converters play a crucial role in enhancing the performance and functionality of Internet of Things (IoT) applications. These converters are vital in ensuring that IoT devices can operate efficiently, with minimal power consumption, while also meeting the specific size, weight, and cost requirements typical of IoT systems. Below is an expanded view of the key IoT applications where high-efficiency DC-DC converters are essential:

7.1. Wearable Devices: Low-Power Operation Extends Battery Life

- Overview: Wearable devices, such as smartwatches, fitness trackers, and medical monitoring devices, are highly reliant on efficient power management to extend their operational time between charges. These devices typically have limited battery capacity due to their compact size, making energy conservation a priority.
- Role of High-Efficiency DC-DC Converters:
  - Extended Battery Life: High-efficiency DC-DC converters allow wearable devices to optimize the use of the available battery power, ensuring that they can operate for extended periods without needing frequent recharging. By converting power more efficiently, the loss in the system is minimized, resulting in a longer battery life.
  - Reduced Power Consumption: With more efficient power conversion, less energy is wasted as heat, and more energy is delivered to the critical components of the device, such as sensors, processors, and wireless communication modules.
  - Compact Design: The smaller size and higher power density of modern DC-DC converters allow them to fit into the tiny form factors of wearables without compromising performance. This is important in maintaining the sleek and comfortable designs that are a hallmark of wearable technology.
- Example Applications:
  - Smartwatches and fitness trackers that track heart rate, activity, and GPS location.
  - Medical wearables that monitor health metrics like blood glucose or blood oxygen levels continuously throughout the day.
- Benefits:
  - Longer battery life between charges.
  - Enhanced portability and usability due to smaller form factors and reduced weight.
  - Reliability for continuous operation without frequent interruptions for charging.

7.2. Sensor Networks: High Efficiency Reduces Maintenance Costs

- Overview: IoT sensor networks are deployed in various environments to collect data, such as temperature, humidity, pressure, motion, and air quality. These sensors are often placed in remote or hard-to-reach locations, where frequent maintenance and battery replacements can be costly and disruptive.
- Role of High-Efficiency DC-DC Converters:
  - Power Conservation: By optimizing the power conversion process, high-efficiency DC-DC converters ensure that sensor nodes can operate for longer periods without needing battery replacement or recharging. This is especially important for large-scale sensor networks, where maintaining thousands of devices can become a logistical challenge.
  - Energy Harvesting Integration: In many sensor network applications, such as environmental monitoring or smart agriculture, energy harvesting technologies (e.g., solar or thermal energy) are used to power the sensors. High-efficiency converters maximize the use of energy harvested from the environment, enabling continuous operation without the need for external power sources.
  - Reduced Downtime and Costs: Since high-efficiency DC-DC converters help reduce power consumption, they decrease the frequency of battery replacements, leading to lower operational costs

and reduced downtime in the network. This is especially critical in applications where sensors are deployed in remote or difficult-to-access locations.

- Example Applications:
  - Smart agriculture systems where soil moisture, temperature, and other environmental factors are continuously monitored.
  - Industrial IoT (IIoT) systems for predictive maintenance, where sensors monitor machinery and equipment performance to prevent breakdowns.
  - Environmental monitoring networks that measure air quality, pollution, and atmospheric conditions in remote locations.
- Benefits:
  - Extended operational lifetimes of sensor nodes, reducing the need for maintenance.
  - Lower operational and maintenance costs due to less frequent battery changes or charging.
  - Enhanced reliability and availability of the sensor network for continuous monitoring.

7.3. Smart Meters: Compact Designs Fit into Limited Spaces

- Overview: Smart meters are an integral part of the IoT ecosystem, enabling utilities to monitor and manage energy consumption in real-time. These meters need to be compact, energy-efficient, and capable of operating in a wide range of environments.
- Role of High-Efficiency DC-DC Converters:
  - Space-Efficient Design: Smart meters are typically installed in compact enclosures, where space is limited. High-efficiency DC-DC converters allow for smaller designs, which help integrate power conversion capabilities without compromising the overall size of the meter.
  - Low Power Consumption: Smart meters are expected to operate continuously, transmitting data about energy consumption. With high-efficiency converters, the meters consume minimal power, enabling long-term operation on small batteries or without relying heavily on external power sources.
  - Power Supply Regulation: Smart meters often need to support communication modules, processing units, and sensors. High-efficiency DC-DC converters provide stable and reliable power to these components, ensuring accurate data transmission and processing without significant energy loss.
- Example Applications:
  - Residential and commercial energy meters that track electricity, gas, or water consumption.
  - Smart grid systems that integrate real-time data from meters to optimize grid operations and energy distribution.
  - Industrial applications where smart meters monitor usage and help reduce energy waste.
- Benefits:
  - Smaller, space-efficient designs that fit into existing infrastructures.
  - Reduced power consumption, enabling longer operational lifetimes for battery-powered smart meters.
  - Reliable and stable power delivery to critical components, ensuring accurate data measurement and communication.

7.4. Additional IoT Applications for High-Efficiency DC-DC Converters

- Connected Home Devices: Smart home devices, including smart thermostats, security cameras, and lighting systems, all rely on high-efficiency DC-DC converters to maintain low power consumption, which is critical for continuous operation and minimizing energy waste.
- Autonomous Systems (e.g., Drones, Robots): IoT devices in robotics and drone applications benefit from the power optimization provided by high-efficiency converters, which help extend battery life and improve operational time for tasks like monitoring, surveillance, or delivery.
- Asset Tracking and Fleet Management: IoT devices used for asset tracking or fleet management rely on energy-efficient power supplies to continuously operate tracking systems without requiring frequent maintenance or charging.

High-efficiency DC-DC converters are essential in the success of a wide range of IoT applications. By improving power management, these converters enable longer device lifetimes, reduced operational costs, and compact form factors that are crucial for wearable devices, sensor networks, and smart meters. Their role in minimizing energy waste and enhancing device reliability makes them a key component in the evolution of IoT technology, enabling more efficient, scalable, and sustainable systems across various industries.

8. Conclusion

High-efficiency DC-DC converters are fundamental to the continued development and success of Internet of Things (IoT) applications. As IoT devices become more pervasive and integral to industries ranging from healthcare to transportation, the need for energy-efficient, compact, and reliable power solutions grows. This paper has highlighted the critical design considerations, technological advancements, and experimental validations that support the realization of more efficient DC-DC converters.

The use of wide-bandgap materials such as GaN and SiC has revolutionized power conversion, offering substantial improvements in efficiency, size, and power density. These materials, combined with innovative control strategies, enable the design of converters that operate at higher frequencies, reducing the size of passive components and improving overall system performance. By addressing the challenges of heat dissipation, size constraints, and energy loss, high-efficiency DC-DC converters enable IoT devices to achieve longer operational lifetimes and reduced maintenance costs, which are crucial for applications like wearable devices, sensor networks, and smart meters.

The experimental results presented demonstrate the clear benefits of these advancements, showcasing substantial improvements in efficiency, size, and power density compared to conventional designs. These improvements pave the way for next-generation power supplies that will serve as the backbone for a wide range of IoT systems.

As we look to the future, the continued development of DC-DC converters will focus on further enhancing their efficiency, miniaturization, and integration with emerging technologies such as energy harvesting and wireless power transfer. By overcoming existing challenges and leveraging new materials, control algorithms, and system architectures, the next generation of DC-DC converters will not only meet the growing demands of IoT applications but also push the boundaries of what is possible in power conversion, enabling unprecedented performance and efficiency.

In conclusion, high-efficiency DC-DC converters are not just a technological necessity but a driving force behind the sustainable growth of the IoT ecosystem. The advancements discussed in this paper lay the foundation for future innovations that will further optimize energy use, reduce environmental impact, and expand the possibilities for IoT applications in diverse sectors.

Compliance with ethical standards

Disclosure of conflict of interest

Authors have no conflict of interest.

Reference

[1] Elhebeary, Mahmoud, and Chih-Kong Ken Yang. "A 92%-efficiency battery powered hybrid DC-DC converter for IoT applications." IEEE Transactions on Circuits and Systems I: Regular Papers 67, no. 10 (2020): 3342-3351.

[2] Kim, Juntae, and Ickjin Kwon. "Design of a high-efficiency dc-dc boost converter for rf energy harvesting iot sensors." Sensors 22, no. 24 (2022): 10007.

[3] Kim, Sang-Yun, Young-Jun Park, Imran Ali, Truong Thi Kim Nga, Ho-Cheol Ryu, Zaffar Hayat Nawaz Khan, Seong-Mun Park et al. "Design of a high efficiency DC–DC buck converter with two-step digital PWM and low power self-tracking zero current detector for IoT applications." IEEE Transactions on Power Electronics 33, no. 2 (2017): 1428-1439.

[4] Gheisarnejad, Meysam, and Mohammad Hassan Khooban. "IoT-based DC/DC deep learning power converter control: Real-time implementation." IEEE Transactions on Power Electronics 35, no. 12 (2020): 13621-13630.

[5] Richelli, Anna, Mohamed Salem, and Luigi Colalongo. "A review of fully integrated and embedded power converters for IoT." Energies 14, no. 17 (2021): 5419.

[6] Zhao, Menglian, Mengyu Li, Shuang Song, Yaopeng Hu, Yanxia Yao, Xuetong Bai, Rubo Hu, Xiaobo Wu, and Zhichao Tan. "An ultra-low quiescent current tri-mode DC-DC buck converter with 92.1% peak efficiency for IoT applications." IEEE Transactions on Circuits and Systems I: Regular Papers 69, no. 1 (2021): 428-439.

[7] Meena, Vinod, and Chirag Gupta. "A Review of Design, Development, Control and Applications of DC– DC Converters." no 2581 (2018): 28-33.