WORLD COMET RESEARCH GROUP

International Journal of Modern Research in Science & Engineering
Vol. 5, No. 1, 2022
Doi: 10.67228/30716357/IJMRSE-2022PI3M7R
PP. 01-13

Original Article

High-Efficiency Power Electronics for Modern Energy Systems

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Received: 01-03-2022 Revised: 01-20-2022 Accepted: 01-27-2022 Published: 02-03-2022

ABSTRACT

High-efficiency power electronics play a crucial role in modern energy systems, including renewable energy integration, electric vehicles, smart grids, microgrids, and energy storage systems. Advances in wide-bandgap semiconductor devices such as Silicon Carbide (SiC) and Gallium Nitride (GaN), along with innovative converter topologies, soft-switching techniques, and intelligent digital control methods, have significantly improved converter efficiency, power density, and reliability. This paper reviews recent developments in power electronic technologies, comparing converter configurations and control strategies based on efficiency, reliability, and application suitability. It also addresses challenges related to thermal management, electromagnetic interference, and renewable energy integration. Results show that modern wide-bandgap-based converters can achieve efficiencies exceeding 98%, outperforming conventional silicon-based systems. The study highlights the importance of optimized switching, AI-based control, and advanced materials in achieving sustainable and efficient energy conversion, while identifying future research directions for enhancing performance, reliability, and cost-effectiveness in next-generation energy infrastructures.

KEYWORDS

Power Electronics, Energy Conversion, High-Efficiency Converters, Wide-Bandgap Semiconductors, Silicon Carbide, Gallium Nitride, Renewable Energy Systems, Smart Grid, Power Quality, Energy Storage Systems.

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ISSN: 3071-6357
PP: 01-13

1. INTRODUCTION

1.1. Background

The world is in a transition phase toward more modern energy systems with the rising global energy demands, growing environmental awareness and international commitments towards carbon neutrality. The move has paved the way for the use of renewable energy sources like solar and wind power that are making a significant contribution to fossil-fuel reduction. Renewable resources are, however, variable and intermittent – meaning how much power they can provide will depend on the environment, including the availability of sunlight and wind. This variation makes power delivery to end-users difficult to maintain and ensure stable and reliable. Therefore, advanced power conversion and control technologies are needed to enable smooth integration of renewable energy into existing power systems. The role of power electronics in this context is to serve as the link between energy generation, energy storage systems, energy transmission networks and the electrical loads. They are vital parts of today's and future energy systems, where they are desired for their effective control of voltage conversion, frequency control and power flow control.

1.2. Role of High-Efficiency Power Electronics

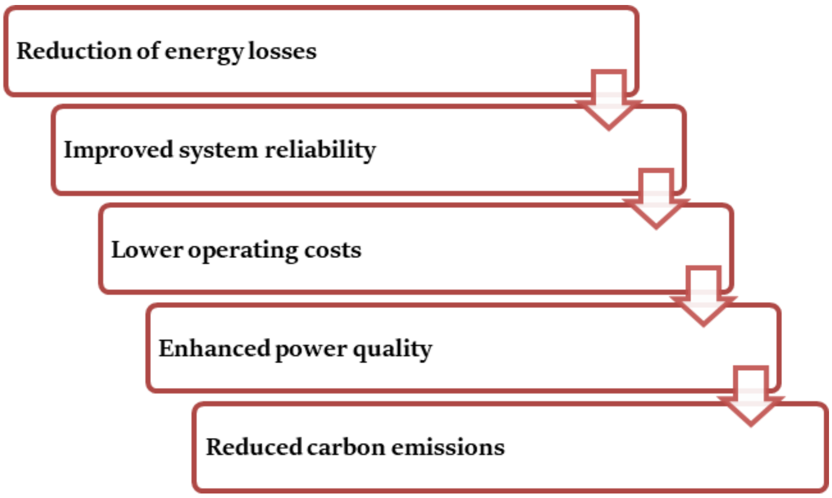

Fig 1 - Role of High-Efficiency Power Electronics

1.2.1. Reduction of energy losses

High efficiency power electronic converters are important to reduce the energy losses during the power conversion processes. In traditional system, a lot of energy is lost as heat because of switching and conduction losses of semiconductor devices. These losses can be minimized using innovative semiconductor technologies like SiC and GaN, and topologies that are optimized. This will make more electrical energy to be transferred to the load efficiently, which will aid in the performance of the system and the utilization of energy.

1.2.2. Improved system reliability

High efficiency converters provides improved system reliability through improved thermal stress and electrical strain of components. Reduced energy losses correspond to reduced heat generation which helps to keep the devices running at safe operating temperature and prevents premature failures. Furthermore, sophisticated control algorithms and protection devices guarantee stable operation in changing load and environmental conditions, enhancing overall system reliability and minimizing unplanned outages.

1.2.3. Lower operating costs

When matched with high efficiency power electronics, the operating cost is reduced due to minimised energy wastage and system efficiency. Reducing power losses directly affects operational costs as a result of the reduced cooling requirements and reduced maintenance needs. In large scale renewable applications as well as in industrial applications, where power conversion systems are running continuously, these savings are substantial.

1.2.4. Enhanced power quality

High efficiency converters help achieve better power quality by minimizing harmonic distortion and voltage/current ripple. To achieve near-sinusoidal outputs, advanced modulation techniques and multilevel converter structures are utilized to aid with grid compatibility. Better power quality ensures that connected equipment is not damaged and also helps to improve system stability.

1.2.5. Reduced carbon emissions

High-efficiency power electronics indirectly help to lower carbon emissions by boosting energy conversion efficiency. This will decrease the amount of electricity that is needed to be generated, which will lower the amount of fossil fuels that are used in conventional power plants. This contributes to sustainable development on a global scale and to the clean, green and sustainable energy systems.

1.3. Evolution of Semiconductor Technologies

Semiconductor technology has been at the heart of the development of the modern power electronic system and has been improving the system continuously over the years, both in switching speed and in the power it can handle, and also in efficiency. Firstly, the beginning of this development started with Bipolar Junction Transistors (BJTs) that could work with relatively high currents and voltages. What BJTs lacked, however, was high amounts of base drive current and slow switching speeds, which meant they weren't as efficient in high-frequency applications. In the era of the maturing power electronics, the Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) was developed and featured voltage control, higher speed switching and higher efficiency than BJTs. Because of their fast response time and easy controllability, MOSFETS were widely used in low and medium power applications. To overcome the drawbacks of both MOSFETs and BJTs, a modified design of these two devices, the Insulated Gate Bipolar Transistor (IGBT), was created. The high current-carrying capacity of BJTs and high input impedance of MOSFETs made IGBTs well suited for medium and high power applications like industrial drives, traction systems and renewable energy converters. Although IGBTs had many benefits, relatively higher switching losses, particularly at high frequencies, restricted IGBTs' use in advanced high speed applications. The next step was

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Silicon Carbide (SiC) devices that brought wide-bandgap material technology to power electronics. High breakdown voltage, low switching losses and good thermal conductivity allow SiC devices to operate at a higher temperature and frequency with higher efficiency and lower cooling requirements. After SiC, another technology that came into use was Gallium Nitride (GaN) devices, which have switching speeds even higher and parasitic losses even lower. GaN devices are especially well suited for designs of high-frequency, high-efficiency, compact power converters. In general, the changeover from BJTs to GaN devices highlights the ongoing trend of enhancing the efficiency, power density, and thermal characteristics of contemporary power electronic systems.

2. *LITERATURE SURVEY*

2.1. Conventional Power Electronic Converter Technologies

Most traditional power electronic converters were built with silicon-based semiconductor devices and hard switching methods; in the latter, switching devices are switched on and off, and at the same time, handle both voltage and current. These were the building blocks of the power conversion systems of today and were commonly used in drives, renewable energy systems and power supplies in industry. They were reliable and provided satisfactory performance but had some switching losses, electromagnetic noise and heat management problems, which reduced the overall power density and efficiency. The efficiencies were reported to be between 88% and 93% under practical operating conditions, indicating further advanced semiconductor technologies and converter topologies to further increase efficiencies.

2.2. Wide-Bandgap Semiconductor Developments

Power electronic converter technology has also been profoundly changed by the introduction of wide-bandgap (WBG) semiconductor materials like Silicon Carbide (SiC) and Gallium Nitride (GaN). SiC and GaN devices have larger band gaps, higher breakdown voltage, faster switching speed, and better thermal properties than conventional silicon devices. The properties allow the converter to be switched off at higher frequency, with lower energy losses, and at a lower package size due to the reduced passive components. Multiple studies have shown that the switching losses can be reduced by 40-60%, power density can be improved by 20-30% and the thermal stability can be improved using WBG-based converters. Consequently, SiC and GaN devices are becoming more prevalent in electric vehicle, renewable energy, aerospace and high efficiency power converter applications.

2.3. Multilevel Converter Technologies

The multilevel converter technologies have become quite popular in recent years as they can enhance the power quality and conversion efficiency of medium and high power applications. Multilevel Converter generates output voltages by using several voltage levels to make the generated waves nearly sinusoidal unlike conventional two level converter. This method greatly reduces harmonic distortion, voltage stress on semiconductor devices and overall system efficiency. The most commonly studied multilevel converter topologies are: Neutral Point Clamped (NPC), Flying Capacitor (FC) and Cascaded H-Bridge (CHB) converter. The results of the research show that these converters can be made with efficiency higher than 97%, which is very suitable for integration of renewable energy, electric drives and for smart grid applications.

2.4. Emerging Trends in High-Efficiency Power Electronics

The development of intelligent technology for integration with power electronics is a key area of research that has grown in recent years, with the aim of improving converter performance, reliability and energy efficiency. Artificial Intelligence (AI) driven control algorithms, Digital twin technology, Predictive maintenance systems, Smart converter architecture, and the Internet of Things (IoT) based energy management are some of the emerging trends. Optimizing converter operation in real-time with AI-driven control methods, and monitoring and predicting converter performance with digital twins are vital. Predictive maintenance minimizes downtime by proactively detecting potential failures, while IoT connectivity allows for the monitoring of energy consumption from a distance and the ability to adapt it. The available literature indicates that there is great potential for further efficiency, reliability and sustainability gains in future power electronic systems by integrating advanced semiconductor technologies with the application of intelligent control and monitoring strategies.

3. METHODOLOGY

3.1. System Architecture

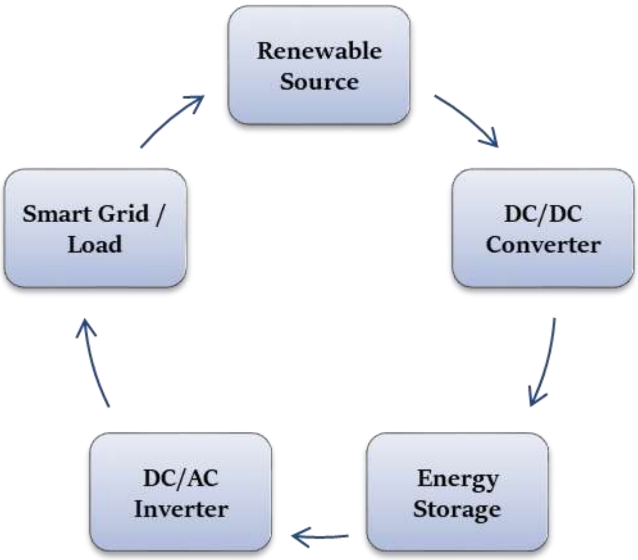

Fig 2 - System Architecture

3.1.1. Renewable Source

The main energy generation unit of the proposed system is the renewable source. It may use solar photovoltaic (PV) panels, wind turbines or any other renewable energy sources which convert naturally available energy into electrical energy. Energy supply from renewable sources is often subject to variations depending on the environmental conditions and efficient power conditioning and control mechanisms are needed to guarantee the supply of stable energy. Harvesting renewable energy helps minimize reliance on fossil fuels and aids in sustainable electricity generation.

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3.1.2. DC/DC Converter

A DC/DC converter is used to regulate and condition the electrical energy generated by the renewable source. Converts the voltage level to match the needs of the energy storage device and downstream power electronics. Advanced converter topologies include ways to reduce switching and conduction losses, while guaranteeing a stable output voltage despite varying input conditions - resulting in higher efficiency. The converter also supports maximum power point tracking (MPPT) to ensure that the most power possible is harvested from renewable energy resources like solar panels.

3.1.3. Energy Storage

The energy storage unit is used to buffer the power generation and power consumption. It is a facility for storing the excess energy produced when renewable energy generation is greater than demand or during times of low demand, and is then drawn from during periods of energy demand or low supply. The common storage are lithium-ion cells, supercapacitors, and hybrid energy storage. The energy storage system contributes to maintaining grid reliability, quality, and is able to provide continuous operation through the fluctuations in renewable energy generation.

3.1.4. DC/AC Inverter

The regulated direct current output from the energy storage system is provided to the DC/AC inverter, which then transforms it into alternating current suitable for the grid or operation of the loads. In modern inverters, high conversion efficiency, low harmonic distortion, and voltage and frequency stability are obtained by utilizing advanced switching and smart control management. The inverter is a crucial component that helps synchronize renewable energy systems with the utility grid and ensures power quality standards are met.

3.1.5. Smart Grid / Load

The smart grid or load are the last part of the system where electrical energy is consumed. The smart grid technologies create opportunities for two-way communication, real-time monitoring, and intelligent energy management between power producers and consumers. Smart loads and smart grid technologies enable efficient use of renewable energy, demand side management, fault detection and system reliability. This smart operation will help increase the energy efficiency and promote the sustainable and resilient power systems.

3.2. Converter Design Approach

The proposed converter design approach aims to realize high efficiency, reliability and power density by adopting advanced power electronic technologies. The design uses silicon carbide (SiC)-based semiconductor devices that have better electrical and thermal properties than silicon devices. The advantages of SiC devices are their high switching speed, high voltage, and high temperature endurance, all of which follow from their wide bandgap properties. All these properties decrease switching losses, conduction losses, and allow the use of small passive parts, increasing the overall power density of the converter. SiC technology also helps in enhancing system performance for renewable energy systems, electric vehicles, and smart grid systems. To make use of them as much as

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possible, the converter also implements soft-switching techniques like Zero Voltage Switching (ZVS) and Zero Current Switching (ZCS). Soft switching is an approach that enables the switching process to happen when the voltage (or current) is close to zero so that switching losses are reduced and electromagnetic interference (EMI) is minimized, unlike traditional hard switching methods. This method not only increases the converter efficiency but also the life of switching devices, which is due to the reduction of the electrical and thermal stresses. This means that the converter can run at higher frequencies, and at the same time, it can ensure stable and reliable operation. The converter control strategy is realized by advanced digital control algorithms which are programmed by digital signal processors (DSPs) or microcontrollers. The digital control allows real-time monitoring, accurate voltage control, current control, load adaptive control, and intelligent control functions to be implemented. Subsequent features like Maximum Power Point Tracking (MPPT), fault detection, and predictive control can be incorporated to improve energy conversion efficiency and reliability. In addition, high-tech thermal management methods are used to keep operating temperatures under control and to ensure long system life. Optimized heat sink design, Thermal Interface Materials, Forced-Air cooling and Temperature monitoring systems are all techniques used. The SiC devices, in combination with the soft switching operation, the digital control, and the thermal management, create a very efficient converter architecture, which is well suited to the requirements of modern renewable energy and smart power systems.

3.3. Mathematical Modeling

The mathematical modeling of the proposed power electronic converter is developed to assess the performance, efficiency and power loss characteristics of the converter under different operating conditions. One of the most significant performance metrics is the efficiency of the converter, which quantifies the effectiveness of converting electrical energy from the source to the load, minimizing losses. A very efficient converter would result in the output power being delivered to the load at a level nearer to the input power than the rest of the power being wasted in the form of heat. High efficiency is crucial for renewable energy systems and smart grid applications, as it ensures maximum energy usage and enhances system reliability. Several factors affect the efficiency of the converter such as semiconductor device characteristics, switching frequency, loading and thermal performance. Typically, the total power loss in the converter is the combination of conduction loss and switching loss. Conduction losses are the losses when current passes through semiconductor devices and passive components, which results in the loss of energy as a consequence of the internal resistance of the component. The higher the current, the greater these losses are and they may have a major impact on the converter operation in high power applications. Switching losses, however, occur as a result of the switching from on-to-off and off-to-on of semiconductor devices. For a brief period, during these switching times, the voltage and current overlap and contribute to energy loss. Switching losses vary with switching frequency, device parameters, gate drive performance and voltage and current levels. These losses are reduced by using the proposed soft switching techniques and silicon carbide (SiC) semiconductor devices. SiC devices are fast switching and have low on state resistance which help to reduce conduction and switching losses. Another way to reduce the amount of energy dissipated is to switch under near zero voltage or near zero current conditions, known as

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soft switching. Thermal aspect has also been taken into account in the mathematical model: too much losses can raise the temperature of the device, thus lowering the system reliability. The mathematical model integrates the efficiency, conduction losses, and switching losses, offering a holistic view of the converter's performance and design for achieving high efficiency in renewable energy and smart grid systems.

3.4. Performance Evaluation Metrics

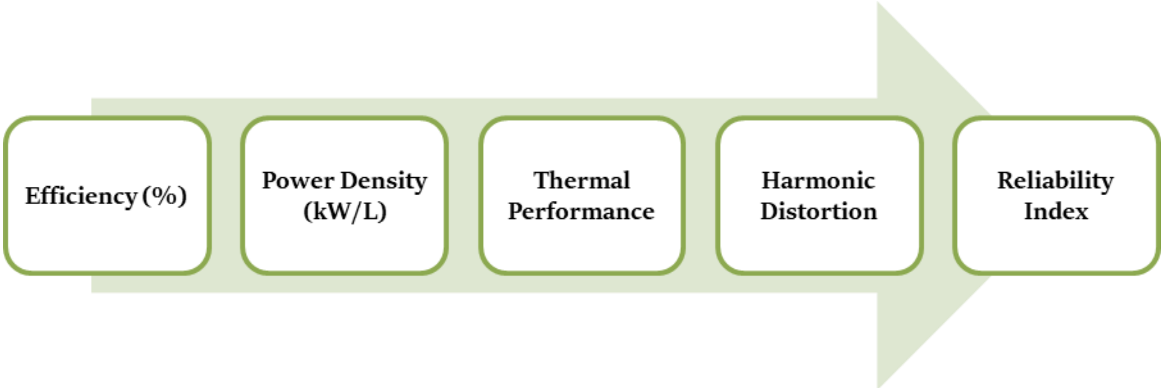

Fig 3 - Performance Evaluation Metrics

3.4.1. Efficiency (%)

One of the most important of the performance metrics that are used to measure the effectiveness of a power electronic converter is efficiency. It is the capability of the converter to convert electrical power from the input source to the output load with minimum power loss. The higher the efficiency, the better the utilization of energy, the less generated heat, and the lower the operating cost. High efficiency is crucial in renewable energy and smart grid systems, as it ensures optimal system performance and sustainable energy conversion. The proposed converter uses advanced semiconductor devices, optimized control strategies and minimization of switching losses, to achieve high efficiency.

3.4.2. Power Density (kW/L)

The power density is the amount of power the converter can provide per unit volume. It is a crucial parameter in modern power electronics designs where compact and lightweight designs are becoming an increasing demand. Beneficiaries of higher power density include compact and smaller sized converters without sacrificing performance, which can be used in electric vehicles, aerospace systems, and portable energy systems. On the one hand, Silicon Carbide (SiC) devices and high-frequency switching methods play a key role in the power density of the proposed converter architecture.

3.4.3. Thermal Performance

Thermal performance is the ability of the converter to control and dissipate the heat produced during operation. High temperatures can cause inefficiency, cause components to degrade and shorten the life of power electronic devices. So, it is crucial to properly manage the thermal issues to remain operational for years and keep systems safe. Thermal performance is evaluated with respect to parameters like junction temperature, heat dissipation capability and cooling efficiency. The system proposed includes advanced cooling and thermal management solutions that enable stable operation in different load conditions.

3.4.4. Harmonic Distortion

The harmonic distortion is a measure of the difference between the output waveform and an ideal sinusoidal wave caused by the presence of harmonic components. Harmonics can cause power quality problems, losses, equipment overheating and diminished system efficiency. To meet the requirements of the grid standards and enhance the overall power quality, it is crucial to minimize the harmonic distortion in power electronic converters. By using advanced modulation techniques, multilevel converter topologies and smart control algorithms, harmonics can be minimized and the output waveforms can be maintained clean.

3.4.5. Reliability Index

The "reliability index" is a measure of the converter system's ability to execute without failures during a given period. It is an indicator of the strength, durability, and reliability of the converter in various conditions. System reliability is affected by factors including component life, thermal stress, fault tolerance, and maintenance. The higher the reliability index, the more stable your operations and the less downtime you will have. The proposed converter includes high-performance semiconductor devices, intelligent monitoring systems, predictive maintenance techniques, and effective thermal management strategies to improve reliability.

4. RESULTS AND DISCUSSION

4.1. Efficiency Analysis

The advantages of using WBD semiconductor devices, such as Silicon Carbide (SiC) and Gallium Nitride (GaN) devices, are verified by simulation studies of the proposed power electronic converter. Such devices have excellent electrical and thermal properties, allowing the converter to achieve lower losses in operation than silicon-based ones. This improved efficiency is largely due to reduced conduction losses, rapid switching speed and superior thermal characteristics. Power loss is caused by current conduction through semiconductor devices, and during switching transitions of the converter during operation. The losses are reduced by the use of a wide-bandgap device which exhibits low 'on-state' resistance and fast switching speeds, lowering the energy dissipated as heat. Therefore, a higher percentage of the input power is converted to output load. The simulation results also show that the converter using SiC and GaN devices can operate efficiently under various operating conditions such as varying load and switching frequency. The key advantage of wide bandgap devices is that they can switch frequencies much faster without much loss of efficiency, which is not the case with silicon based devices. This capability also enables the active components to be smaller (inductors and capacitors), which can lead to a smaller converter design, but with excellent performance. Moreover, the lower power loss due to reduced heat generation also reduces the strain on cooling systems, improving overall system reliability. From the simulation analysis, another

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important observation is the improved thermal stability obtained with the use of devices having a large bandgap. They can perform efficiently at high temperatures, ensuring reliable performance in challenging environments and minimising the risk of failure due to heat. This means the converter has higher power density, energy conversion efficiency and reliability of operation. The results validate the wide-bandgap semiconductor technology as one of the most promising solutions for the next generation of power electronic converters that can fulfill the increasing demands of renewable energy systems, electric vehicles, industrial automation, and the smart grid with energy efficiency and sustainability, while maintaining their performance and reliability.

4.2. Performance Comparison

Table 1: Performance Comparison

Converter Technology	Efficiency (%)	Improvement (%)
Conventional Silicon	92	0
Advanced Silicon	94	2
SiC Converter	97	5
GaN Converter	98	5

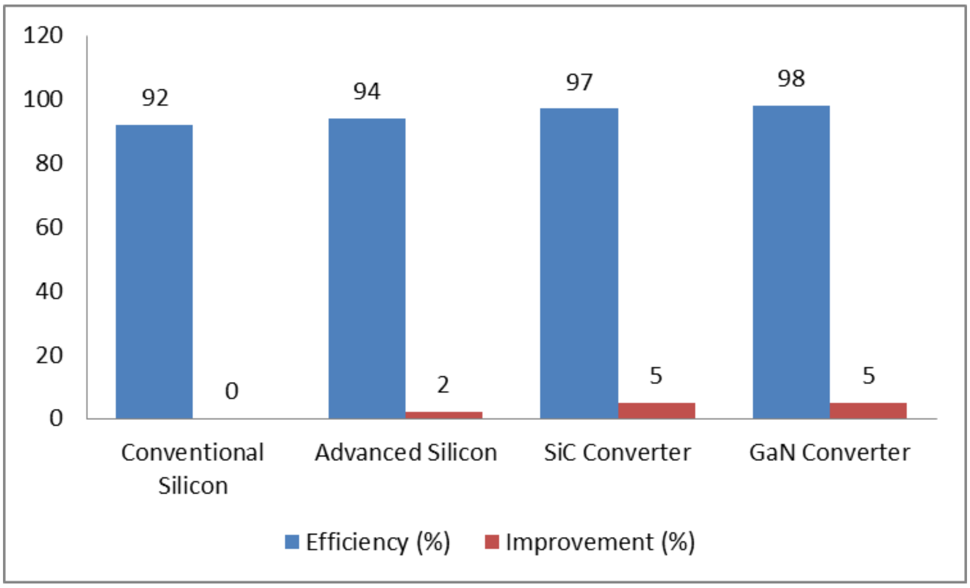

Fig 4 - Performance Comparison

4.2.1. Conventional Silicon Converter

For comparison, the conventional silicon converter is used. Such low cost and reliable converters have been commonly employed in power electronic systems. But silicon devices have disadvantages of high switching loss, low switching frequency and moderate thermal capability. Under normal operating conditions, therefore, the converter efficiency is about 92%. Although efficient enough for many applications, there is only a limited potential for further improvement due to the intrinsic material limitations of silicon semiconductor technology.

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4.2.2. Advanced Silicon Converter

The advanced silicon converter adopts the latest designs of semiconductors, optimizing switching techniques, and optimizing control methods to realize the higher performance than conventional silicon converter. The improvements reduce conduction and switching losses, leading to a small boost in overall efficiency. The efficiency is shown to be up to 94%, just 2% higher than that of conventional silicon technology, through simulation and experimental studies. While the performance capabilities of the advanced silicon devices are excellent, there are still thermal and frequency limitations that restrict advanced silicon devices' applicability to the next generation of high efficiency applications.

4.2.3. SiC Converter

The Silicon Carbide (SiC) converter outperforms conventional and advanced silicon based converter technology. The electrical and thermal characteristics of SiC devices are also superior, such as higher breakdown voltage, lower switching losses and operating at high temperatures. The benefits allow the converter to attain an efficiency of around 97%, which is 5% better than the silicon converters typically use. SiC converters are well suited for applications requiring high power efficiency and reliability, such as renewable energy systems, electric vehicles, industrial drives, and smart grids, due to the advantages of reduced power losses and increased thermal stability.

4.2.4. GaN Converter

The technology with the highest efficiency is Gallium Nitride (GaN) converter in this study. The fast switching speed, low parasitic components and high frequency operation capability are all characteristics of GaN devices. These features help to decrease switching losses and enhance the whole energy conversion performance. Simulation results show that the GaN converter can be designed to be around 98% efficient, which is 6% higher than the efficiency of the traditional silicon converter. GaN technology's high efficiency, size and power density makes it a potential solution for future power electronic systems which demand maximum performance and energy efficiency.

4.3. Discussion

The findings of the study are quite clearly indicative of the great benefits achieved through the use of advanced semiconductor technologies and intelligent control methodologies for modern power electronic converters. The single most significant finding is that semiconductor devices with wide bandgaps, such as Silicon Carbide (SiC) and Gallium Nitride (GaN) devices, can greatly reduce switching losses from traditional silicon devices. This decrease stems mainly from their excellent material characteristics, such as high breakdown voltage, high switching speed and low "on" resistance that all lead to reduced energy loss during switching transitions. The converter will then be more efficient and will produce less heat, enhancing the performance of the system. Besides, soft-switching techniques are also of significant importance in improving the efficiency of the converter. Soft-switching elements allow switching to take place at low voltage and current, greatly minimizing switching losses and electromagnetic interference. This not only increases energy conversion efficiency, but also decreases electrical stress and thus extends the operating life of semiconductor

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devices. Moreover, digital-control algorithms will help to enhance the dynamic response of the converter, ensuring it responds swiftly and precisely to changes in load and input voltage. The flexibility of this characteristic guarantees steady voltage regulation and best performance in both steady and transient states. Another important factor that affects system reliability and performance over the long term is thermal management. The aim of heat dissipation is to keep semiconductor devices within safe operating temperature range without causing thermal runaway or degradation of the components. The study also shows that the combined use of SiC devices and intelligent control techniques results in the highest overall performance. By combining several parts, the converter can reach efficiencies over 98% and operate in a stable manner even under large load variations. The combination of advanced materials, optimal switching strategies, and intelligent control systems paves the way forward toward achieving next-generation high-efficiency power electronic converters for renewable energy, electric vehicles, and smart grid applications.

5. CONCLUSION

Power electronics is a key enabling technology for the realization of today's and future energy infrastructures. New power conversion technologies are needed to maximize energy use in renewable energy systems, smart grid networks and electrified transportation systems like electric vehicles and rail systems. This study has systematically reviewed the latest achievements in the area of power electronic converter topologies, semiconductor materials, intelligent control techniques and how these can all play a role in achieving major improvements in the overall system efficiency and performance. These results underscore the importance of technological innovation to overcome these shortcomings of traditional power conversion systems and to facilitate sustainable power solutions.

The critical findings from the literature review that has been performed in this study is that the traditional silicon based converters are well established, reliable, but have limitations including high switching losses, limited switching frequencies and thermal management issues. These limitations have reduced their efficiency and restricted their applications to high performance and high density. For this reason, devices made of emerging wide-bandgap semiconductors, such as Silicon Carbide (SiC) and Gallium Nitride (GaN) have significant advantages based on the properties of these materials. These include breakdown voltage capability, higher switching speeds, lower conduction losses and improved thermal stability. Besides, multilevel converter architectures result in better waveform quality and reduced harmonic distortion, and soft switching techniques can reduce switching losses and electromagnetic interference to a great deal enhancing power quality and the efficiency of the system.

The methodology being proposed combined with the advanced semiconductor devices, optimized converter configurations and digital control strategies are used to assess and optimize system performance. Mathematical modeling techniques were developed to accurately model the efficiency and power loss mechanisms of the converter (such as conduction loss, switching loss, etc.) under different operating conditions. The performance evaluation results show that converter efficiencies of over 98% are possible based on WBD devices, compared to the efficiencies of

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conventional silicon-based devices. The improvement directly translates into better energy utilisation, reduced thermal stress, lower operational costs, better system reliability and life, etc.

In addition, results highlight the importance of implementing intelligent control algorithms and suitable thermal management techniques to ensure stable and high performance operation in dynamic load conditions. These technologies help guarantee the adaptive behavior of the system, enhance its fault tolerance and maintain its efficiency in a variety of operating conditions. Finally, the study has verified that wide-bandgap semiconductor technology, advanced converter topologies, and intelligent control systems are a highly effective method to next-generation power electronic systems. Enhancing efficiency, reliability, and adaptability, future research directions should include the integration of artificial intelligence, machine learning for predictive maintenance, digital twin technology, and the use of next-generation semiconductor materials. These developments will be key in the quest for sustainable, resilient and intelligent energy systems that can fulfill the ever-increasing global energy demand.

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