PAK ADVANCES ENGINEERING

PAK ADVANCES IN ENGINEERING RESEARCH

ISSN: 3080-2946 (Print) ---- 3080-2954 (Online)

Website: https://pakadvances.com ------ Email: editor@pakadvances.com

Design and Optimization of High-Frequency Power Converters for Enhanced Efficiency and Performance in Electric Vehicle Applications

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Abstract

Article History

Received:
January 10, 2024

Revised:
February 12, 2024

Accepted:
March 20, 2024

Available Online:
June 30, 2024

Keywords:

"High-frequency Converters", "Renewable Energy Systems", "Electric Vehicles", "Systematic Review", "Energy Efficiency" "V2G systems".

The paper reviews high-frequency converter innovations for electric vehicles and renewable power systems with a focus on sustainability and energy system improvement. Using the PRISMA 2020 methodology, 73 excellent research spanning 2014 to 2024 was evaluated for new converter models and advanced materials and control methods and future trends. The research field produced vital findings showing how converter topologies advanced with the invention of LLC resonant designs and dual active bridges enabling soft switching and enhanced scalability and efficiency. Silicon carbide and gallium nitride function as wide-bandgap semiconductors which enable developments in power density while improving compactness along with thermal control capabilities. Efficient operation and stability enhancement in microgrids together with vehicle-to-grid systems result from implementing adaptive and AI-based control techniques. Power conversion along with system reliability improvements become possible through converter applications in wind and solar power systems. The upcoming opportunities align hybrid and multipurpose systems by connecting smart control techniques featuring artificial intelligence platforms with digital twin systems to renewable energy and electric vehicles storage units. These innovative developments establish high-frequency converters as revolutionary energy solutions to address global power issues while advancing environmentally sustainable power generation and locomotion systems. This paper includes essential details about present research along with prospective paths for science advancement. Advanced control methods such as sliding mode control and predictive control together with AI-driven adaptive strategies remain essential for this research because they guarantee stable operation of intricate networks. These approaches deliver three substantial benefits for renewable microgrids including dynamic load control and harmonic reduction with maximum power flow enhancement for V2G systems. The technology behind digital twins positions itself as a major growth opportunity because it delivers live system tracking alongside predictive equipment care and works to spot issues early.

INTRODUCTION

The rise of sustainable technology and energy efficiency needs has led to the development of advanced energy conversion systems for electric cars and renewable systems during the contemporary time period. Since electric car chargers require the integration of renewable energy sources these systems necessitate high-frequency converters. The power density and converter efficiency improved because wide-bandgap materials such as GaN led to significant reduction of magnetic components. Current power systems face two main challenges which include complex control systems for bidirectional charging and high-frequency instability that results in deteriorated power quality and system stability (Alhuwaishel, F.M.; Allehyani, A.K,2020). Energy efficiency together with financial feasibility in these fields require extensive analysis of modern high-frequency converter advancements in design and optimization applications along with their restrictions. The review aims to provide substantial benefits through its proposal of solutions combined with identification of key development areas in power electronics applications for sustainable energy systems (Ditze, S.; Ehrlich, S.,2023).

LITERATURE REVIEW

Milton et al. (2020) created a single approach for representing switching power converters. The control of various PECs through both linear and nonlinear methods can be achieved using the research presented in Habib et al. (2020). Eligibility to control output/load voltage stands as one of the principal responsibilities throughout different PECs. Single-loop control serves as a large-signal nonlinear control technique which enables power converters to perform switching according to Peyghami et al. (2020). To achieve match between the control reference of each cycle and the average controlled variable value requires dynamic modification of the switch duty cycles. The power supply variations cause no interruptions to occur through this method. Many experts remain unfamiliar with the effects of load interruptions on systems. A frequency domain controller for DC-DC switching converter voltage regulation through PWM was presented by Babu et al. in 2020 (Peyghami et al., 2020). The model uses the average tiny signal representation of the converter. The SMC technique has gained a stronger foothold in the power electronics sector after Utkin provided an overview of various PECs which the technique can manage. Professionals have adopted SMCs to regulate numerous PECs and electromechanical systems in the years since their original application (Tan et al., 2022). The output voltage of PECs is controlled by several scientists who utilize SMCs. A review of the prototype development process by Anzola et al. (2020) presents both theoretical and experimental results of a direct-current to alternating-current boost converter controlled by SMC technology. The technique demonstrates effectiveness for designing inverters and uninterruptible power supply (UPS). Visual analysis along with performance examination becomes possible when studying the SMC of a PEC CC-CC. The paper recommends a control system called "fixed frequency hysteresis controller" (FFHC) which combines elements of SMC and FFHC using a hysteresis band according to (İnci et al., 2021). The SMC-based PEC control system is explained through Shah et al. (2021). The research by Mumtaz et al. presented an adaptive terminal SMC solution for DC-DC buck converters which utilized limited time arrival laws and nonlinear sliding surfaces. The research does not specify the region of existence for sliding mode but demonstrates the effects of changing charge on system voltage. Multiple PECs benefit from hybrid modeling-based sliding mode control according to Chang et al (2020). The condition for sliding mode existence was added to the document while incorporating the phrase ROE. Experimental findings proved that high controller parameter values result in prolonged oscillations which mainly affect devices intended for high power usage. Furthermore, steady-state errors in the charging voltage for every reference point plague the SMC of traditional PECs (Xiong et al., 2020). The SWR does not maintain its fixed position within the phase plane since it responds to changes resulting from load disturbances. The continuous observation of charging current should be accompanied by recommended adaptive correction methods according to Chung and Nam (2020). The proposal implements a double-integral sliding mode surface which helps minimize steady-state inaccuracy. The method proposes a new SMC controller to improve system steady-state operation (Sun et al., 2020). The current field remains challenging to reduce. Academic researchers should dedicate their efforts toward investigating steady-state error and oscillation damping with greater intensity. The main goal of this study involves using an updated sliding function to establish the most efficient solution for steady-state oscillation and error damping. The designed SMC controller based on a PI-type sliding function is used to analyze multiple PECs like buck, boost and buck-boost (Zeta converter).

METHODOLOGY FOR STUDY SELECTION

The review process adapted the PRISMA 2020 statement as its foundation because this framework provides transparent and rigorous methods for systematic review and meta-analytic studies. The research team selected this method because it streamlines research analysis by putting findings on high-quality evidence base while eliminating potential judgment distortions. The research selection proceeded through four separate stages including identification and selection and eligibility and inclusion and synthesis. The selection process between stages becomes vital because researchers integrate and analyze evidence which arises from the chosen studies. The set of detailed procedures described in the following sections achieved the objective of selecting appropriate high-quality sources which provided an established basis for the review's conclusions and findings.

Data Quality and Reliability

Quality and reliability of the data presented in the study, including accuracy and consistency. Score scale: 1: Satisfactory, 2: Good, 3: Excellent.

Advancements in High-Frequency Converters

Extent to which the study advances the design, materials, implementation, or applications of high-frequency converters in renewable energy systems and electric vehicle applications. Score scale: 1: Limited, 2: Notable, 3: Highly Impactful.

Identification of Studies

A comprehensive investigation into publications during (2014 to 2024) allowed for systematic literature review research. The research only incorporated English-language scholarly journal articles and conference papers which were completely accessible for review.

The search excluded editorials as well as the remaining listed sources because they lacked academic rigor or scientifically relevant content. This study obtained its bibliographic information from the two prominent academic platforms known as Web of Science and Scopus.

Scopus stands out as a well-known interdisciplinary database platform that serves the applied sciences and engineering disciplines. The peer-reviewed research-based product Scopus brings clarity to high-frequency converters and energy efficiency evaluation through its role as a comprehensive research platform with extensive research depth. The search query utilized for preliminary screening consisted of TITLE-ABS-KEY ((“high frequency” AND “converter”) AND (“renewable energy” OR “electric vehicle charging”)) AND PUBYEAR > 2013 AND PUBYEAR < 2025 AND (LIMIT-TO (DOCTYPE, “cp”) OR LIMIT-TO (DOCTYPE, “ar”)) AND (LIMIT-TO (LANGUAGE, “English”). Web of Science represents an elite database which implements thorough selection protocols while monitoring citations rigorously. This database contains numerous prestigious internationally important research studies from leading publishers IEEE, Elsevier, Springer, Taylor & Francis, Wiley and MDPI which are relevant to this review. The research query used the following strings ((ALL = ("high frequency")) AND ALL = ("converter")) AND (ALL = ("renewable energy") OR ALL = ("electric vehicle charging"). The search sorting includes classifying documents by English language and Article or Procedural Document types within the 2014–2024 time period.

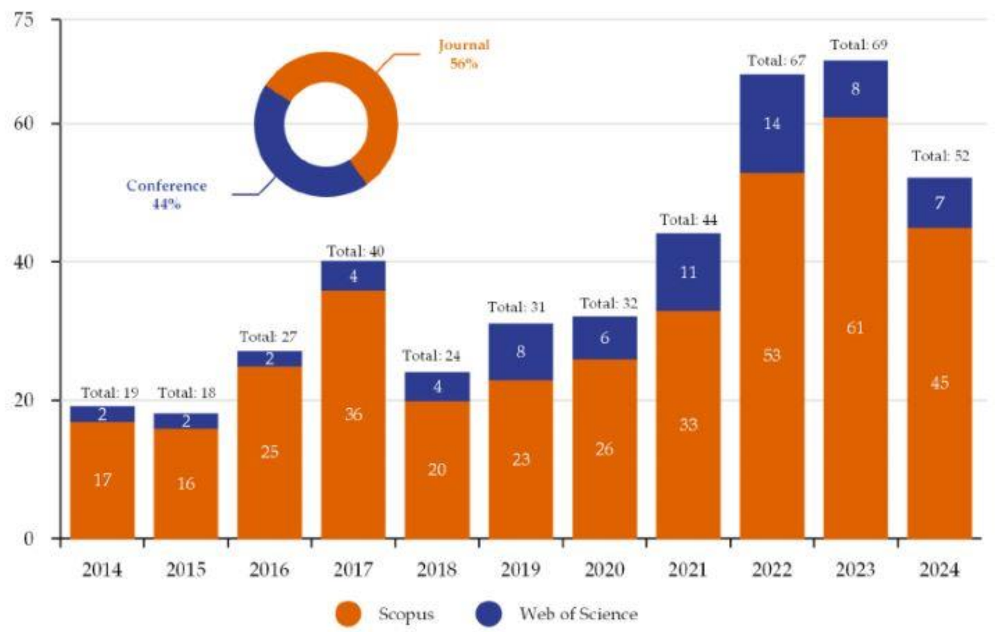

Figure 1. Statistics of the screened studies

The authors zeroed in on 73 scientific papers after checking 423 publications for evaluation categories consistency at a minimum score of 13 out of 15 potential points. The selected cutoff point sealed the review for studies that demonstrated both high relevance along with rigorous methodology and novel findings and substantial impacts. The researchers performed the evaluation distinct from each other to minimize subjective influence at this critical stage. The selection process increased its trustworthiness through the use of debate mechanisms to solve any scores that differed. The Figure 2 chart displays the matrix that researchers used to approve research materials for this study. Application of this exacting procedure allowed us to pick different research findings which fulfilled stringent study demands and showed diverse advancements in electric car high-frequency converters and renewable energy systems. The researchers excluded from evaluation did not fail scientific standards although they were valuable academic works. Utilization of qualifying requirements and established scope and goals determined the selection instead of any additional considerations.

N°	ID	Criterion 1	Criterion 2	Criterion 3	Criterion 4	Criterion 5	Total
1	S-149	3	3	3	3	3	15
2	S-361	3	3	3	3	3	15
3	S-069	2	3	3	3	3	14
4	S-126	2	3	3	3	3	14
5	S-183	2	3	3	3	3	14
6	S-053	3	3	3	2	3	14
7	S-155	3	2	3	3	3	14
8	S-194	3	3	2	3	3	14
9	S-295	3	3	2	3	3	14
10	S-306	3	3	2	3	3	14
11	S-315	3	3	3	3	2	14
12	S-358	3	3	3	2	3	14
13	S-377	3	3	3	2	3	14
14	S-427	3	2	3	3	3	14
15	S-485	3	2	3	3	3	14
16	WoS-079	3	2	3	3	3	14
17	WoS-117	3	2	3	3	3	14
18	WoS-169	3	3	3	3	2	14
19	WoS-195	3	3	3	3	2	14
20	S-046	2	3	3	3	2	13
21	S-066	2	2	3	3	3	13
22	S-136	2	3	3	2	3	13
23	S-269	2	3	2	3	3	13
24	S-333	2	3	3	2	3	13
25	S-339	2	2	3	3	3	13
26	S-372	2	3	2	3	3	13
27	S-409	2	2	3	3	3	13
28	S-437	2	3	3	2	3	13
29	WoS-095	2	3	3	3	2	13
30	WoS-180	2	3	2	3	3	13
31	S-011	3	3	1	3	3	13
32	S-026	3	2	2	3	3	13
33	S-033	3	3	1	3	3	13
34	S-044	3	3	1	3	3	13
35	S-052	3	3	1	3	3	13
36	S-071	3	3	2	2	3	13
37	S-086	3	3	2	2	3	13
38	S-101	3	2	3	2	3	13
39	S-118	3	3	1	3	3	13
40	S-119	3	3	2	2	3	13
41	S-127	3	3	2	3	2	13
42	S-137	3	3	1	3	3	13
43	S-141	3	3	1	3	3	13
44	S-167	3	3	1	3	3	13
45	S-179	3	3	1	3	3	13
46	S-195	3	3	2	2	3	13
47	S-197	3	3	2	2	3	13
48	S-203	3	2	3	2	3	13
49	S-231	3	3	1	3	3	13
50	S-244	3	3	1	3	3	13
51	S-254	3	3	1	3	3	13
52	S-264	3	2	2	3	3	13
53	S-289	3	2	2	3	3	13
54	S-298	3	3	1	3	3	13
55	S-310	3	3	1	3	3	13
56	S-324	3	3	2	2	3	13
57	S-330	3	3	1	3	3	13
58	S-335	3	2	2	3	3	13
59	S-346	3	3	1	3	3	13
60	S-352	3	3	1	3	3	13
61	S-360	3	3	1	3	3	13
62	S-383	3	3	1	3	3	13
63	S-396	3	3	1	3	3	13
64	S-438	3	2	3	2	3	13
65	S-450	3	3	1	3	3	13
66	S-455	3	3	2	3	2	13
67	S-462	3	3	1	3	3	13
68	S-473	3	3	1	3	3	13
69	S-480	3	3	1	3	3	13
70	WoS-151	3	3	3	2	2	13
71	WoS-192	3	2	3	3	2	13
72	WoS-228	3	3	1	3	3	13
73	S-249	3	3	3	3	1	13

Figure 2. Verification matrix for evaluating selected studies: High Score (High contrast color), Medium Score (Medium contrast color), and Low Score (Low contrast color).

We have anonymized the records by source database through the addition of prefixes S-XXX for Scopus entries and WoS-XXX for Web of Science entries to maintain bibliographic resource clarity and respect. The complete metadata information about the identified studies is provided at this link: https://github.com/dannyochoa87/vehicles3379724/archive/refs/heads/main.zip accessible until 27 December 2024. This resource enables readers to check the included articles in the review while upholding the accuracy of article selection.

Synthesis of Selected Studies

This section offers a thorough summary of the current status of research in high-frequency converters for electric cars and renewable energy systems via a bibliometric analysis of the 73 papers chosen during the qualifying and inclusion stages. The annual distribution of the chosen articles is shown in Figure 3. The information reveals a ten-year trend of varying but steady research interest. Because of the growing interest in the topic throughout these years, the number of publications peaks in 2020 and 2021 with 10 and 9 papers, respectively. The number of publications in 2024 (6 articles) is significant since that year was still in progress at the time of the previous update, even though the number of publications in 2023 declines somewhat. This pattern shows that the subject is still relevant and that people are still making contributions to the area, particularly in recent years. 53 of the 73 chosen studies are published in scientific publications, demonstrating the strength of the field's top-notch, peer-reviewed research. With thirteen articles emphasizing its significance in publishing state-of-the-art advancements in the area of power electronics, IEEE Transactions on Power Electronics journal is the most often used source. The IEEE Journal of Emerging and Selected Topics in Power Electronics (4 articles), the IEEE Transactions on Industrial Electronics (3 articles), and the IEEE Transactions on Industrial Applications (8 articles) are other publications that have made noteworthy contributions. The variety of publications demonstrates the field's interdisciplinary character, with studies addressing many facets of high-frequency converters and their uses in electric cars and renewable energy systems. The chosen study includes 20 pieces, including conference papers in addition to scholarly journal articles. With six papers each, the IEEE Energy Conversion Conference and Exposition (ECCE) and IEEE Applied Power Electronics Conference and Exposition (APEC) are two of the most prominent conferences. The worldwide Conference on Circuit Power and Computing Technologies (ICCPCT 2024) and the International Conference on Green Computing, Communications, and Electrical Engineering (ICGCCEE 2014) are two more noteworthy worldwide events. In addition to the more developed research findings reported in the journal papers, these conference publications serve as significant platforms for exhibiting new developments, creative designs, and preliminary studies in high-frequency converters.

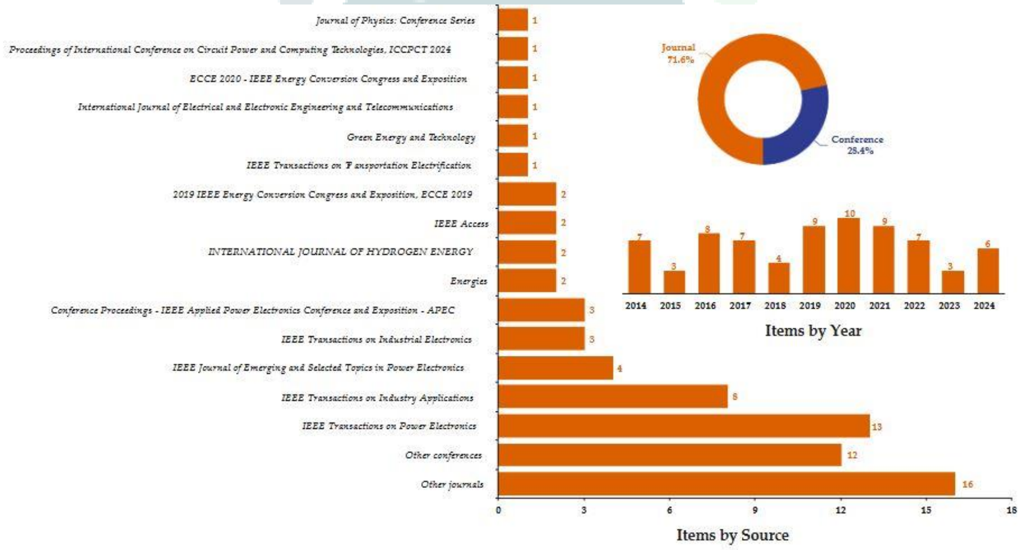

Figure 3. Bibliometric analysis of the selected works

Finally, Figure 4 illustrates a summary of the literature prospecting process followed, presented through a standardized flow diagram as mandated by the PRISMA 2020 Statement.

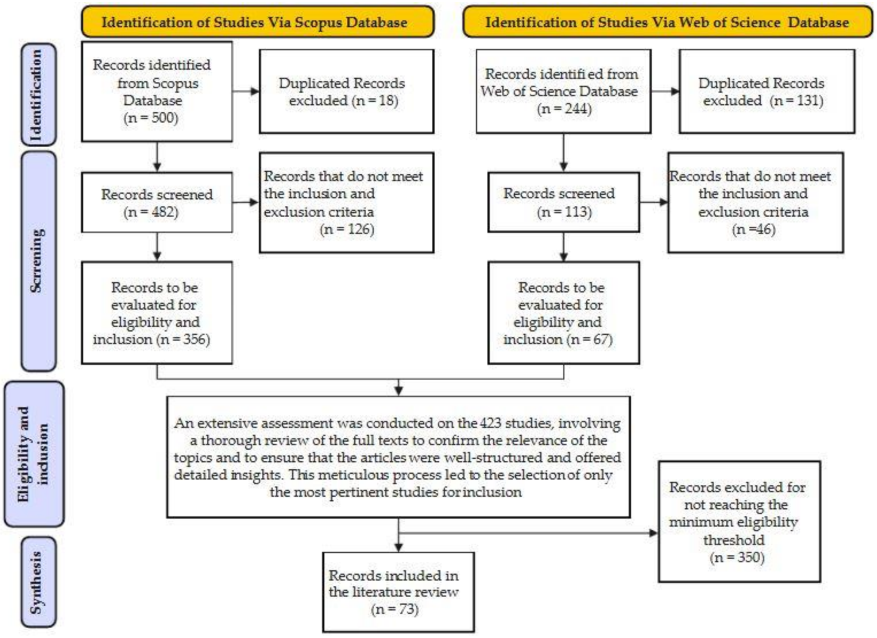

Figure 4. Standardized flow diagram of the PRISMA methodology followed for study selection.

RESULTS AND DISCUSSIONS

High-frequency converter technology witnesses' continuous development through innovative topological improvements aimed at achieving higher flexibility and efficiency and scalability. The dual active bridge (DAB) converter represents a widely recognized example of power transmission equipment because it enables efficient bidirectional power transfer with minimal losses. DAB converters demonstrate exceptional suitability for renewable energy systems and electric vehicles since they provide dependable power management under conditions involving variable loads and stored energy implementation. Organizations rely on these converters to manage energy movement in large systems because they are efficient and adaptable devices. Resonant converters such as Series-parallel resonant converters along with LLC converters maintain specific appeal because they exhibit minimum electromagnetic interference together with high operational efficiency. The higher-frequency operation of these converters achieves minimal power loss through soft-switching methods where zero voltage switching (ZVS) and zero current switching (ZCS) techniques reduce losses. The prevalent change nature of power inputs in photovoltaics makes renewable energy systems respond favorably to resonant designs. Electric car fast-charging systems benefit from these converters because their high efficiency and compactness requirements. Researchers have developed wireless power transfer (WPT) systems as a leading technological innovation. The adoption of WPT technology enables dependable system operations and convenience through elimination of physical connections especially for EV charging needs. High-frequency WPT systems have achieved important developments in power density and efficiency allowing their use in dynamic charging infrastructure that enables moving vehicles to receive charging. High-frequency converters received additional possibilities through the introduction of wide-bandgap (WBG) semiconductors which include silicon carbide (SiC) and gallium nitride (GaN). At higher frequencies these materials drive better thermal conductivity along with faster switching mechanisms and reduced loss performance. Solarion implements revolutionary changes in electric car storage and renewable energy solutions through its solutions for thermal management and power density issues. The current developments show an increasing interest in creating converters that offer greater mobility together with enhanced effectiveness and flexibility. The combination of ZVS and ZCS methods enables DAB converters to transfer power in both directions without significant loss even though traditional converters lose considerable energy during their switching transitions. The implementation of SiC-based DAB systems using comparison techniques results in reduced power dissipations during switching events thus minimizing losses by 30–50%. DAB converters excel in electric car fast charging stations because their adaptable nature allows power transfer efficiency to increase from 92% to above 97%.

Future Perspectives: Hybrid and Multifunctional Designs for High- Efficiency Systems

Future designs of high-frequency converter architectures will develop hybrid multipurpose systems that meet the growing requirements of electric cars along with renewable energy systems. A combination of DAB and resonant and interleaved converter functions enables hybrid designs to achieve maximum power flow with enhanced efficiency across various applications. Rapid charging stations need dependable solutions and high-power density so multiple promising methodology options exist. Power electronics will develop into unified converter systems that enable simultaneous power transfer between battery storage and electric vehicles together with renewable energy generation deployments. These systems use advanced control algorithms and adaptive switching methods to respond dynamically to changing load levels and environmental factors while providing continuous and efficient operation. These ideas make it possible to develop decentralized energy systems together with smart grids. Recent trends indicate that high-frequency converter designs and management systems have started to embrace artificial intelligence (AI) and machine learning (ML) technology (Grasel, B.; Baptista,2014). The real-time modification of operational parameters together with load change prediction through these methods allows maximum converter performance while enhancing both stability and efficiency. Security measures within converter designs will acquire vital importance since power systems become more connected through data integration. High-frequency converters in their next development stage will strongly depend on wide-bandgap materials. The combination of high-power density with minimum thermal loads and extended service lifetime is achievable when SiC and GaN materials integrate with complex topologies. Research teams need to study how these materials age and single out their sustainability factors and adaptive approaches for evolving the energy market landscape. The development of modular converters represents an innovation pathway for electric car technology applications along with renewable energy solutions (Gupta, J.; Kushwaha, R.; Singh,2023). Because of their modular nature these systems can achieve scalability and fault tolerance thus becoming ideal solutions for applications in urban electric car charging networks and offshore wind farms. The implementation of hybrid control techniques alongside DC power sharing methods will enhance system reliability and efficiency for these systems.

Future Perspectives: Sustainability and Emerging Applications

WBG semiconductors show great promise to reshape renewable energy collection and electric vehicle system practices through their sustainable adaptable solutions. The combination of SiC with medium-voltage DC grids enables an effective and consistent link for renewable energy to connect with large-scale energy storage systems (Song, J.; Fu, C.; Zhang, G.2021). Research efforts concentrate on GaN-based converters for electric vehicle ultra-fast charging because they offer small packages that generate high power efficiently and create limited heat during operation. The development process of WBG materials depends strongly on sustainability principles. Our team focuses on improving SiC and GaN production efficiency and product lifecycle length and minimizes environmental consequences during these stages. Grid-connected renewable systems utilize amorphous alloy magnetic materials to replace silicon-based systems in a sustainable way while achieving higher efficiency and recyclability levels (Nachankar, P.; Suryawanshi, H.; Chaturvedi, P.; Atkar,2022). The use of WBG semiconductors develops into hybrid energy storage systems which connect batteries and supercapacitors to maintain grid stability when renewable energy supply reaches high levels. SiC-based converters enable the management of high-frequency transients throughout this system while permitting operation with low-cost microcontroller systems and achieving enhanced reliability. WBG-based converters will achieve better performance thanks to recent developments in AI-driven control algorithms. Real-time system parameter optimization happens with predictive models in order to boost efficiency under varying load situations and environmental factors. Power distribution with improved fault tolerance at medium voltage applications benefits from adaptive control strategies used in modular multilevel converters (Patel, N.; Lopes, L.; Rathore,2023).

CONCLUSIONS

The systematic review adopted the PRISMA 2020 declaration to conduct structured research that allowed the assessment and combination of 73 high-quality papers from 2014 to 2024. The methodical review framework enabled extensive research of high-frequency converter advancements as organizations continue to depend on them for renewable energy system stability and electric vehicle sustainability along with energy efficiency improvements. The examination organizes its research findings across five thematic regions that include high-frequency converter design and advanced semiconductor materials and implementation and control strategies and applications in renewable energy systems and future directions for multifunctional and hybrid systems. The research establishes dual active bridge (DAB) and LLC resonant designs as key converter topologies because they demonstrate superior efficiency potential alongside extensive flexibility and scalability capabilities. These developments work flawlessly within renewable energy projects and electric vehicle fast charging operations because zero voltage and zero current switching strategies can merge together to produce significant power loss reduction and operational efficiency enhancement. This research demonstrates how WBG semiconductors especially SiC and GaN act as disruptive materials which provide compact designs while simultaneously decreasing thermal stress and improving power density. The exceptionally fast switching capabilities of GaN matter most for wireless power transfer applications and mobile electric car charging but SiC performs better with high voltage systems. The materials provide solutions to both heat management problems and electromagnetic interference concerns and enable product designs that are compact and lightweight. Future research should focus on resolving cost limitations and lifetime sustainability problems with wide bandgap materials to enable their wider deployment in future energy system networks.

Advanced control methods such as sliding mode control and predictive control together with AI-driven adaptive strategies remain essential for this research because they guarantee stable operation of intricate networks. These approaches deliver three substantial benefits for renewable microgrids including dynamic load control and harmonic reduction with maximum power flow enhancement for V2G systems. The technology behind digital twins positions itself as a major growth opportunity because it delivers live system tracking alongside predictive equipment care and works to spot issues early. The emerging development will transform how grid networks operate together with hybrid designs and distributed power systems on an industrial scale. Researchers continue to investigate high-frequency converters for renewable energy systems because these converters play an essential role in improving both wind and solar (PV) power system performance and reliability and reduction of system physical size. New modular multilevel converter designs along with multi-input topology innovations are attracting attention because they allow control of variable generation while reducing shading losses and maintaining power grid stability. These systems demonstrate their scale-up capabilities when used for large renewable infrastructure projects such as offshore wind farms and urban electric vehicle charging networks through their capacity to link renewable power sources with next-generation energy storage solutions. Experts have identified the development of combined converter designs into multipurpose units as the fundamental direction for upcoming research work. These systems unite characteristics from multiple designs to achieve maximum power flow and higher efficiency and greater system flexibility across different load conditions. The integration of artificial intelligence and machine learning algorithms enables these converters to automatically adjust operational settings and maximize efficiency while extending lifespan thereby improving their importance in sustainable energy platforms. The report highlights the necessity to develop continuous modular and fault-tolerant technology advances which must focus particularly on high-frequency converters utilized in renewable microgrids and fast-generated electric car infrastructure. A mix of innovative material studies and topology examinations and powerful control algorithms demonstrates potential to address problems in electromagnetic interference and high switching speed operation. High-frequency converters have the potential to transform current methods of achieving energy efficiency and environmental sustainability based on findings from this systematic review. The future global energy transition will heavily rely on high-frequency converters for their ability to connect renewable energy sources to electric cars and their power to build strong intelligent energy networks. Future research estudying the synergy of state-of-the-art materials will be essential for realizing these technology promises that lead to sustainable electrification.

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