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Research on the Latest Technological Advances and Trends in High-Frequency and High-Efficiency Power Electronic Converters

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Abstract:

Power electronic converters play a vital role in modern power systems. To meet the surging demand for more efficient and compact devices for these applications, high frequency and high efficiency have become two main areas of development in power electronics. Increasing switching frequency in power electronics allows for a significant size reduction in passive components, thus enhancing the power density and reducing overall system size. However, high-frequency operation also causes higher switching losses and poses several design and efficiency challenges. These are further compounded by constraints arising from the harsh operating environment, which dictates the need to pursue new and better materials and circuit approaches to maximize converter efficiency. This study has explored the application of latest wide-bandgap semiconductor materials, including gallium nitride (GaN) and silicon carbide (SiC), as well as ultra-wide-bandgap semiconductor materials such as Ga2O3 and AlN. They present new opportunities for the development of high-frequency and high-efficiency power electronic converters that significantly allow for higher frequency operation, reducing most of the switching losses to achieve overall efficiency. Additionally, vital advancements in soft-switching techniques such as zero-voltage switching (ZVS) and zero-current switching (ZCS), also the development of new circuit topologies like LLC and DAB converters, are evaluated. Further, various gate driver designs, and their comparison are considered key strategies toward minimal energy losses at high frequencies. The review is based on a novel perspective of the bottlenecks left unchallenged so far in power conversion systems, considering some critical technological deficiencies and showing pathways to more efficient, compact, and reliable future solutions.

Keywords: High-frequency; power electronic converters; soft-switching technology; zero-voltage switching (ZVS); zero-current switching (ZCS)

1. Introduction

As power electronic converter technology witnessed surging development within the past several years, characteristics of high efficiency, high power density, small volume and handy manufacturing are urgently expected, especially in the field of electric vehicles, light emitting diode (LED) drivers and energy storage & distribution systems. To cope with these issues, an elementary solution is to increase the frequency of operation. Since high operating frequency greatly reduces the value and volume of components in converters, the energy stored during a certain period of operation diminishes, effectively boosting power density and efficiency.

Nevertheless, switching frequency increment also leads to challenges such as high switching loss, high magnetic loss, influence of parasitic components, etc. To tackle the conflict between those problems and operating frequency, improvements in component material and characteristics, circuit topology, and driver strategy are three conventional solutions.

For component material, wide-bandgap (WBG) semiconductors with significantly lower output capacitance, higher breakdown voltage and lower ON resistance like gallium nitride (GaN) and silicon carbide (SiC) have been elected as effective solutions. Despite steady progress in the research of those materials, the long-term reliability and stability of WBG devices, especially under high-temperature and high-voltage operation conditions, remain a deep concern. Therefore, further thermal management and EMI control in WBG device management require more profound research.

For circuit topology, advancements in high-frequency power converters have focused on developing new topologies, including LLC resonant converters, CLCL converters and dual active bridge (DAB) converters, etc. These designs possess the capability to attain enhanced efficiency and power density, especially when integrated with wide-bandgap semiconductors. LLC converters have gained popularity for their ability to achieve soft-switching, which minimises switching losses in high-frequency applications. Nevertheless, there are still obstacles to optimizing these topologies for broader applications, especially regarding the complexity of the control mechanisms and the stability of the system under varying load conditions. The integration of these topologies into compact, high-power modules while maintaining thermal efficiency also requires further research.

For driver strategy, recent advancements have centered on developing gate drivers which are state-of-the-art with most advanced technologies, particularly for wide-bandgap devices such as SiC and GaN. Resonant gate drivers aim to recover energy and minimize switching losses in high-frequency applications. However, additional challenges remain in managing conduction losses during resonance. The utilization of current source drivers has been demonstrated to facilitate enhanced switching speeds and reduced losses, particularly in scenarios characterized by hard switching. However, the deployment of continuous current drivers can potentially engender elevated overall losses. Future research will seek to optimize these strategies, particularly by integrating intermittent current source drivers for variable frequency applications, to fully harness the potential of wide-bandgap semiconductors.

Given the significant challenges in high-frequency power converter design—ranging from increased switching losses to complex thermal management—the motivation for this review stems from the need to address these critical issues through a comprehensive exploration of the latest developments in the three areas mentioned above. By doing so, this work provides new insights into how these innovations can overcome existing limitations in high-frequency power converters, offering pathways for future research and practical applications.

The following sections are organized around three key components: materials, topology, and driver techniques. Section 2 discusses the application of WBG and UWBG semiconductors in power electronic converters, including their characteristics and challenges. Section 3 covers advancements in converter topologies and driver strategies, emphasizing the critical role of soft-switching techniques in achieving efficiency and reliability. Section 4 provides an in-depth analysis of gate driver design, focusing on the utilization of voltage-source, current-source, and resonant gate drivers in high-frequency power converters. Their efficiency, challenges, and trade-offs in modern applications are also evaluated further.

2. Application of WBG semiconductors in power electronic converters

2.1 Material Characteristics

As an indispensable part of power electronics converters, innovations in power semiconductor devices and semiconductor technology have made the onward and upward progress of the whole power electronics industry possible. Since the thyristor came into being in the 1950s, Si-based semiconductor devices have held important positions for a long period because of the abundant material resources, low production costs, and simple manufacturing processes.[1] Nevertheless, Si shows some significant disadvantages regarding voltage blocking capability, normal operation temperature and maximum blocking capability.[1] Specifically, using Si-based power devices becomes infeasible when the voltage exceeds 6.5 kV, the current exceeds 2 kA, or the temperature exceeds 250℃[2]. In contrast, WBG semiconductors, signified by GaN and SiC, offer significant advantages in these areas due to their physical properties, as summarized in Table 1 summarizes the critical parameters of standard WBG counterparts to replace Si components.

Table 1. Material Properties For Si and Conventional WBG semiconductors [1]

Material	E_g (eV) @ 300K	μ_n (10^3cm^2/V·s)	μ_p (100cm^2/V·s)	V_{sat} (10^7cm/s)	E_c (10^7V/cm)	λ (W/cm·K)	ϵ_r
Si	1.12	1.45	4.5	1	0.03	1.3	11.7
GaAs	1.4	8.5	4	2	0.04	0.54	12.9
3C–SiC	2.3	1	0.45	2.5	0.2	5	9.6
6H–SiC	2.9	0.415	0.9	2	0.25	5	9.7
4H–SiC	3.2	0.95	1.15	2	0.3	5	10
GaN	3.39	1	0.35	0.5	0.5	1.3	8.9
Diamond	5.6	2.2	18	3	5.6	20	5.7

In the past thirty years, the applications of wide bandgap semiconductors have advanced towards maturity, resulting in successful commercialization in various domains, including light-emitting diodes, radio frequency devices, and power switches. [5-6]. While GaN and SiC still have been the most widely adopted in power electronic devices, as analyzed before, the performance of WBG semiconductor-based devices is nearing theoretical limits. Consequently, the semiconductor community is currently exploring next-frontier devices based on ultra-wide bandgap (UWBG) semiconductors, including diamond, Ga2O3, Hexagonal boron nitride (h-BN), and AlN, to prepare for future demanding electrical and photonic applications. These UWBG materials have attracted significant research attention across various research fields regarding power electronics due to their distinctive material characteristics, including ultra-high critical electric field and chemical inertness.[7] Table 2 illustrates the major properties and the parameters of selected WBG and UWBG materials.

Table 2. Physical Properties selected WBG and UWBG Materials [7-9]

	WBG		UWBG		
Material	GaN	4H-SiC	AlGaN/AlN	β-Ga_2O_3	Diamond
Bandgap (eV)	3.4	3.3	Up to 6.0	4.9	5.5
Thermal Conductivity (W/m·K)	253	370	253–319	11–27	2290–3450
Cutting-edge substrate quality (dislocations per cm^2)	≈10^4	≈10^2	≈10^4	≈10^4	≈10^5
Cutting-edge substrate diameter (inches)	8 (on Si)	8	2	4	1
Proven capability for p-type doping	Good	Good	Poor	No	Good
Proven capability for n-type doping	Good	Good	Moderate	Good	Moderate

As shown in Table 2, Ga2O3 possesses remarkable characteristics from the standpoint of the electronic industry. Firstly, it possesses a bandgap that exceeds 4.5 eV, resulting in a formidable breakdown electric field of around 9 MV cm1. Furthermore, its estimated Baliga figure of merit (BFOM) surpasses that of WBG SiC and GaN (albeit having a comparatively lower mobility), but falls short of UWBG values. This has generated significant impetus for the advancement of Ga2O3 power semiconductors. [10-11]

From the optoelectronics point of view, Ga2O3 has a bandgap in the deep-ultraviolet region, making it useful for solar-blind DUV photodetectors and flame detectors. However, its complexity and inability to dope p-type hinder its application in bipolar devices. [10]

Also, according to Table 2, from an electronic perspective, it possesses a direct bandgap of approximately 6.0 eV, along with a high breakdown field exceeding 10 MV/cm and saturation velocities over 10^7 cm/s. Regarding optoelectronic properties, AlN offers wide spectral transparency ranging from the ultraviolet to the mid-infrared region, along with a 12 MV/cm high critical electric field.

2.2 Applications in Power Electronic Converters

Gallium oxide (Ga2O3) is becoming a promising option for some categories of power electronics, solar blind UV photodetectors, solar cells, and sensors surpassing current technology capabilities.

Beyond electronics or optoelectronics, Ga2O3 finds appealing uses in signal processing under harsh thermal conditions, electronics operating in demanding environments, and designated wireless communication systems. Regarding operation in complex environments, the intrinsic stability of Ga2O3 against oxidation and its broad bandgap are crucial characteristics.

Generally, as mentioned above, AlN exhibits very favorable fundamental physical characteristics. These exceptional properties of AlN mentioned make it an excellent choice for an extensive variety of high-performance applications, especially in challenging conditions that demand high temperature, high frequency, and high-power demands. Its thermal conductivity and large breakdown field enable it to function in high-power devices, particularly those running in challenging ambient circumstances. For instance, AlN is increasingly being utilized in power transistors and amplifiers specifically engineered for microwave and RF systems. Furthermore, AlN's large bandgap and UV transparency make it particularly well-suited for deep-UV LEDs and laser diodes, which play a crucial role in applications such as disinfection, water purification, biomedical analytics, and even sensors and optical detectors.

2.3 Technical Challenges and Future Prospects

For WBG and UWBG semiconductors, a major challenge is that these materials, despite their superior physical properties, generate high power densities during operation, leading to substantial self-heating causing severe influence on the reliability and performance of the devices.[21] The thermal conductivity of some UWBG materials, such as Ga_2O_3, is relatively low compared to conventional semiconductors like SiC, exacerbating the thermal management problem. Also, measuring the materials' thermal conductivity features is challenging. Many WBG and UWBG materials are transparent to light at energies below their bandgap, making direct thermal measurements difficult without using a thin metal film layer.[22]

Another difficulty that threatens the future development of those materials is the fabrication techniques. For instance, manufacturing high-performance vertical GaN transistors encounters challenges like refining epitaxial growth techniques and minimizing defect concentrations. For UWBG materials like Ga_2O_3, the challenges are even greater due to their relatively nascent state of development. These materials require advancements in material quality, doping techniques, and thermal management strategies to handle the high power densities and extreme thermal conditions they are designed to operate under.[23]

Looking forward, the co-design of devices and packaging with an emphasis on electrothermal properties is a crucial area of research, aiming to optimize electrical performance and thermal stability. Advanced thermoreflectance techniques such as pump-probe thermoreflectance (TR) and thermoreflectance thermal imaging (TTI) offer potential solutions for overcoming the current challenges in characterizing these materials. Another promising direction is the development of high-temperature packages that can withstand the extreme conditions expected in wide band gap and ultra-wide bandgapdevices.

If the challenges related to material quality and heat management can be addressed, these technologies can potentially revolutionize power-switching applications across a wide range of industries even further.

3. Topologies and Design Optimization

3.1 Soft-Switching Converters Overview

Upon selecting the correct semiconductor material, minimizing the switching losses brought by the surged switch frequency is the next challenge to overcome. The most instinctive and effective way is to improve the topology and the converter circuit design.

The conventional low-frequency power electronic converters usually operate in the hard-switching mode, detonating the phenomenon where the power switch's current and voltage overlap significantly during turning on or off as shown in Figure 1. This is exactly the primary cause of losses in power electronic converters. At elevated switching frequencies —a trend in modern power electronics— the efficiency of converters operating in hard-switching mode diminishes while switching losses and associated stress markedly escalate. This hampers the progress of high-frequency power electronics and introduces issues such as substantial current spikes, oscillations during switching events, additional losses during the diode's reverse recovery period, and severe electromagnetic interference.

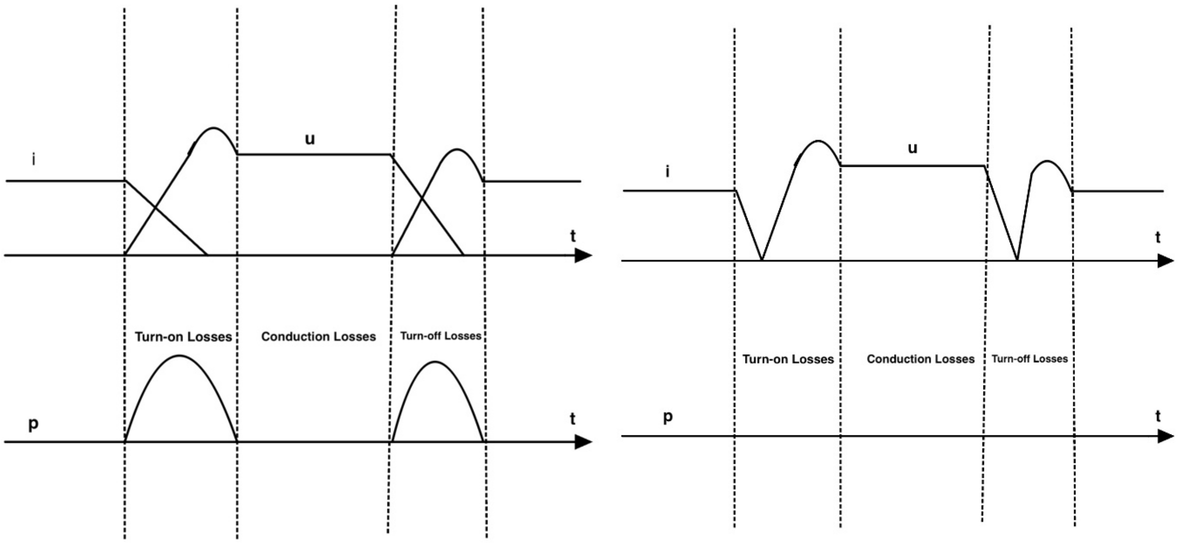

Fig. 1 Comparison of Losses in Soft-Switching (Left) and Hard-Switching (Right)

Soft-switching techniques are employed to overcome these challenges. Soft switching involves using passive components in series or parallel with the switching device to generate resonance, resulting in the current or voltage during turn-off resembling a sine waveform. This approach does not eliminate switching losses but transfers them to the resonant circuit, where they are dissipated. Under soft-switching conditions, the switch is deactivated when the current reaches zero and activated when the voltage reaches zero. Consequently, circuits utilizing soft-switching technology exhibit reduced device stress, negligible switching losses, and lower di/dt and du/dt, significantly enhancing the operating frequency and efficiency of the converter.

Achieving soft switching requires appropriate circuit topologies that realize zero-voltage switching (ZVS), zero-current switching (ZCS), or ideally both.

3.2 Topology Classification Methods

Several classification methods are utilized to analyze these soft-switching converter topologies systematically. Some classify them based on operating principles [12], where resonant converters rely on resonant components to achieve ZVS or ZCS, and non-resonant converters employ other control strategies. Others categorize soft-switching techniques based on converter type and switching methods, such as dividing soft-switching techniques for DC-DC converters into QR-based, SR/PR/SPR-based, MR-based, and RT-based techniques [13].

However, these methods either provide a high-level understanding lacking specificity or offer detailed distinctions without explicitly considering the resonant and non-resonant nature of the techniques.

To address these limitations, we propose a new classification scheme. As depicted in Figure 2, soft-switching converters are first categorized into four essential types (DC-DC, DC-AC, AC-DC, AC-AC) and then further classified into resonant and non-resonant converters based on their operating principles. Finally, they are detailed based on different technical soft-switching methods. This proposed classification system combines the advantages of both approaches, providing a more precise and structured framework for analyzing soft-switching converters.

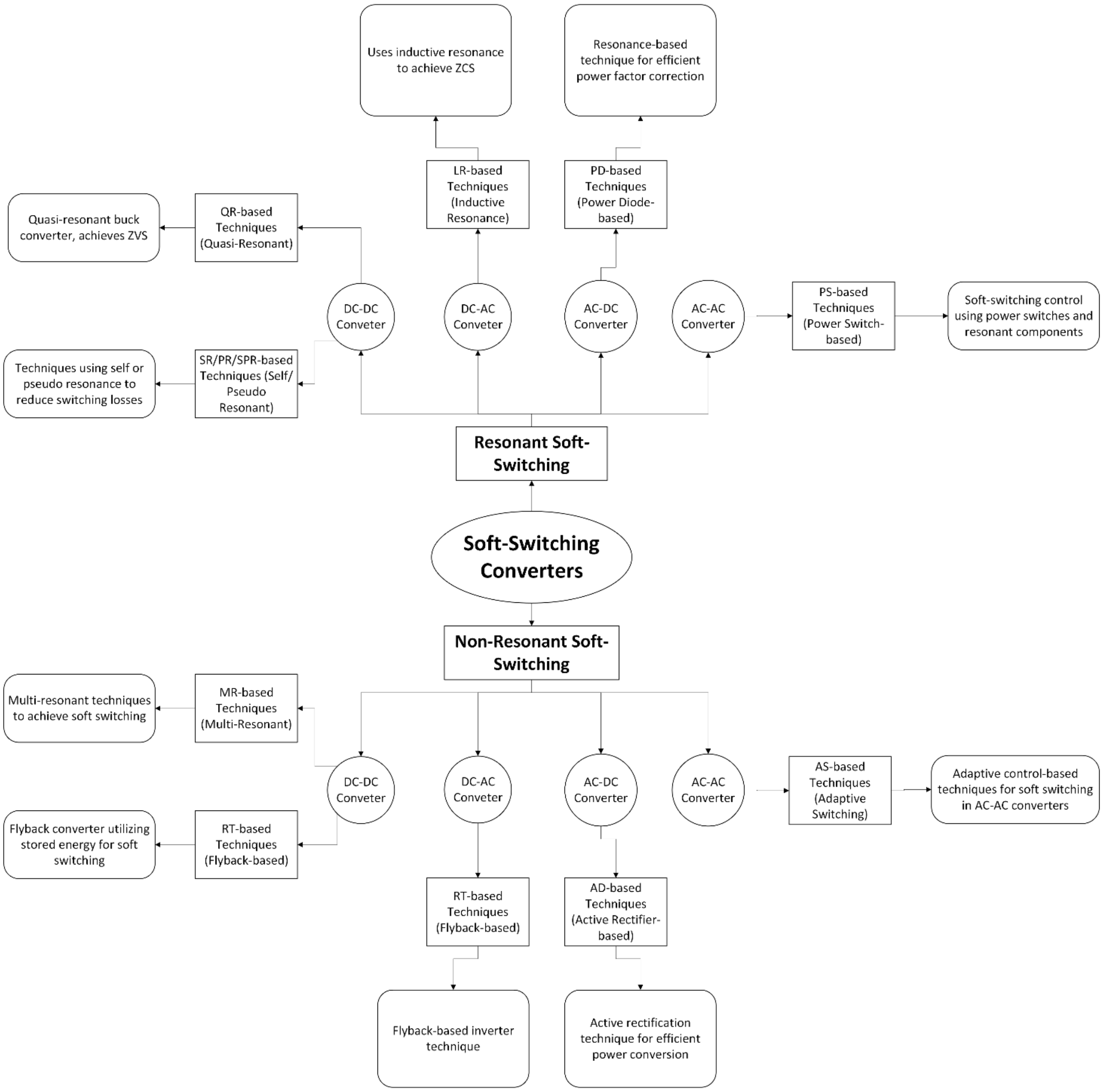

Fig. 2 A New Classification Scheme of Soft-Switching Converters

For a more digested and focused analysis of design specifications, the following sections will elaborate on two primary categories, resonant and non-resonant converters.

3.3 Topology Design Methods

3.3.1 Resonant Converters

Resonant converters utilize resonance phenomena in their circuit design to achieve high-efficiency power conversion. Their design can usually be split into four blocks: power switches, a resonance tank, a transformer and a rectifier. Further, resonant converters can be classified into series resonant, parallel resonant and series-parallel resonance converters.[12] The series and parallel resonant converters are foundational types that serve specific applications. However, for higher efficiency and performance, the focus often shifts to series-parallel (LLC) ones.

The primary circuit topology for LLC converters are shown in Figure 3. Its ability to enable zero-voltage switching (ZVS) for all devices over the whole spectrum of loads and zero-current switching (ZCS) while operating at or below resonance for the secondary-side rectification circuit is highly welcomed in various fields of applications. However, In high-frequency (HF) applications, the design of LLC resonant converters faces several significant challenges, particularly when combined with wide-bandgap (WBG) devices. However, LLC converters come with certain inherent disadvantages. One notable issue is that they are typically designed to operate around the resonant frequency for optimal system efficiency. Thus, the transformer turns ratio must be adequately elevated to get the requisite input-to-output voltage ratio.

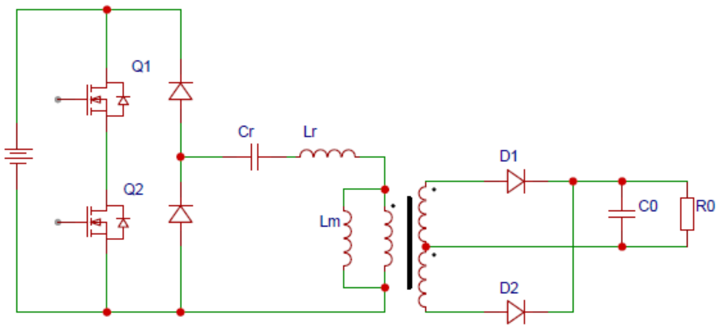

Fig. 3 The topology for LLC Converters

To deal with the inborn demerits of LLC converters, alternative topologies such as Class-E converters, CLCL converters and Dual Active Bridge (DAB) (as shown in Figure 4) converters, etc.

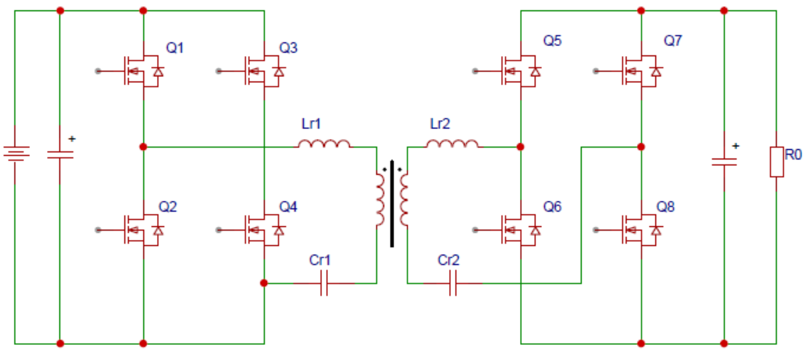

Fig. 4 The topology for DAB Converters

Class-E converters achieve zero-voltage switching (ZVS), significantly reducing switching losses and improving efficiency, particularly in high-frequency applications.

CLCL converters enhance voltage gain flexibility and mitigate wide frequency variations, thereby enabling superior output control without the necessity for excessively high transformer turn ratios.

DAB converters enable bidirectional power flow and offer effective performance across a range of load conditions, thus further enhancing efficiency and adaptability in power electronics systems.

3.3.2 Non-Resonant Converters

Traditional soft-switching techniques often rely purely on resonance to achieve ZVS or ZCS. In contrast, quasi-resonant converters use a combination of resonant and PWM control, allowing for more flexible operation across a broader range of load conditions.

Non-resonant converters are not born with the capability of soft-switching. They often utilize resonant components but not in the same manner as complete resonant converters, achieving soft-switching on the foundation of hard-switching using different technical approaches.

A typical example is the Quasi-Resonant converters, hard-switching circuits added by some extra resonant elements. They also realize ZVS and ZCS just as resonant converters do. Quasi-Resonant converters may present greater complexity in design and control compared to basic hard-switching converters; yet, they provide enhanced performance benefits.

Paper [14] first proposes a systematic approach to synthesizing and analyzing Quasi-Resonant (QR) converters by adding resonant elements to traditional PWM topologies. The study introduces six classes of QR converters and highlights the advantages of smoother waveforms, which reduce switching losses and improve efficiency. The study also compares zero-voltage switching (ZVS) and zero-current switching (ZCS), favoring ZVS for most applications. However, it notes that QR converters can place higher stress on switches and involve more complex designs, requiring advanced modeling and more robust components, leaving open challenges in the practical implementation of highly complex QR systems.

To solve this, Paper [15] focuses on high-frequency quasi-resonant converter technologies, addressing key issues such as reducing switching losses and stresses through zero-voltage switching (ZVS) and zero-current switching (ZCS) techniques. This study also explores topological innovations and high-frequency performance, which help mitigate switch stress and efficiency challenges raised in the Paper [14]. Additionally, it highlights advanced gate drive designs and control techniques, providing potential solutions for reducing design complexity and ensuring stable operation in quasi-resonant converters.

The choice of converter topology is crucial for optimizing high-frequency power electronic systems by reducing switching losses. Resonant converters, such as series, parallel, and LLC configurations, use resonance for soft-switching, improving efficiency and minimizing interference. However, they face challenges in high-frequency applications, particularly for WBG devices. Non-resonant methods, like quasi-resonant converters, combine resonant components with hard-switching architectures, enhancing performance and efficiency.

4. Gate Driver Design

4.1 Introduction and Classification of the Gate Driver

Considering the further design optimization of power converters, careful and sufficient attention should be paid to the design of gate drivers for switch components. In high-frequency power converters, gate driver design becomes even more critical, particularly when dealing with wide-bandgap (WBG) semiconductors. As frequencies increase, several challenges arise. For instance, parasitic elements such as gate resistance and gate-source capacitance significantly affect switching performance, leading to issues like voltage ringing and electromagnetic interference (EMI), which degrade overall efficiency. Additionally, high switching frequencies exacerbate switching losses, especially during the overlap of current and voltage in the power switches, resulting in heat generation and reduced system efficiency. WBG devices, with their high rate of change in voltage and current, are particularly sensitive to these parasitic components, requiring careful gate driver design to avoid overstressing the switches.[16]

Specifically, gate drivers can be categorized based on their design and functionality. Typical classifications include resonant gate drivers, which recycle switching energy to minimize losses; current-source gate drivers, which provide better control over switching transitions; and voltage-source drivers, widely used for general applications but may require further adaptation for high-speed WBG devices.

4.2 Voltage-Source Gate Driver (VSD)

Figure 5 gives a simplified topology of the traditional voltage-source gate driver. As shown in the figure, the gate capacitor Cg is charged by a supply voltage through a parasitic resistance Rv, which mitigates the oscillation brought by the parasitic inductor and input capacitance (omitted from the figure). Paper [12] gives specific formulations for switching losses and a total gate driving loss, indicating that increasing frequency, especially super high-frequency scenario, decreases the efficiency of the conventional Voltage-Source gate driver circuit, leading to significant energy losses and thermal challenges (large energy dissipation without recovery). It also confirms an elementary upper-frequency threshold and insufficient anti-interference capability for VSD circuits, so these circuits are not ideally fit for high-frequency operation.

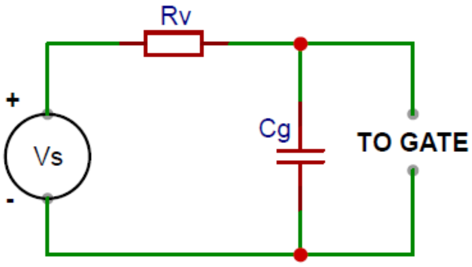

Fig. 5 Simplified Topology for VSD[16]

4.3 Current-Source Gate Driver (CSD)

In order to mitigate the losses brought by VSD topologies under high-frequency working scenarios, Current-Source Gate Drivers (CSD) are first introduced, and a typical topology for them is depicted in Figure 6. In contrast to VSDs, which provide a voltage pulse to the gate of the switching device, CSDs deliver a continuous current for gate charging and discharging. Also, the existing current source inductor enables the recovery of energy stored in the gate capacitance. Paper [16] gives the detailed calculation of dissipated energy and operation efficiency of CSDs, reflecting a significant improvement in adaptability in high-frequency conditions.

Nonetheless, whereas CSDs provide enhanced regulation of switching transitions and diminish the related losses during charging, they still possess constraints. A notable disadvantage is the continuous current flow demanded by the driver, even while the switch is not undergoing active

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transition. This results in circulation losses, especially when the gate is fully charged or drained, rendering CSDs less efficient at marginally lower frequencies or under light loads.

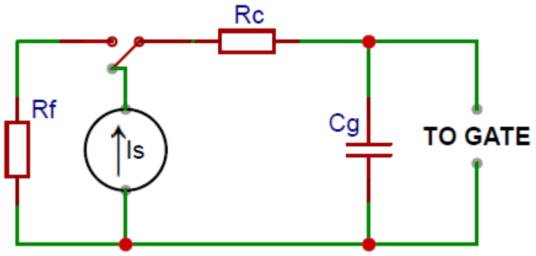

Fig. 6 Simplified Topology for CSD[16]

4.4 Resonant Gate Driver (RSD)

To rectify this inefficiency mentioned, Resonant Gate Drivers (RGD) were designed as a superior alternative for high-frequency applications. Resonant Gate Drivers can be classified into different operation modes: Full resonance and Stamped resonance.[16]

Under full resonance mode, the resonant inductor Lr transfers all its energy to the gate capacitance Cg during the switching cycle. Once the gate is charged, the current in the resonant circuit drops to zero, ensuring the switch operates under either zero-voltage switching (ZVS) or zero-current switching (ZCS) conditions.

The gate voltage or current is restricted for clamped resonance mode once it attains a specified threshold. Instead of permitting the energy to oscillate among the resonant components completely, clamped resonance diverts or recycles surplus energy once the gate is sufficiently charged. Like the elementary gate driver circuit, the RSDs can also be classified into Voltage Source Gate Driver and Current Source Gate Driver based on their supply source variations.

4.4.1 Voltage Source Resonant Gate Driver

In this type of gate drivers, the gate capacitance is charged up by a fixed voltage source. The primary feature of these drivers is their dependence on a constant voltage to activate the gate, whereas the resonant circuit, which is made up of inductors and capacitors, regulates the energy transfer.

The basic topology is shown in Figure 7. By adding an inductor in the VSD circuit, the excessive energy stored in gate capacitor Cg can be restored by transmitting to resonant inductor L, which works in full resonance mode. However, these so-called conventional RSDs obtain inherited disadvantages. Given that the resonant inductor and gate capacitance are connected in series with the supply voltage, the inductor is charged earlier than the capacitor, resulting in an exceeding energy supply compared to the actual gate requirement. Even if some of this energy may get recycled, it brings further conduction losses.

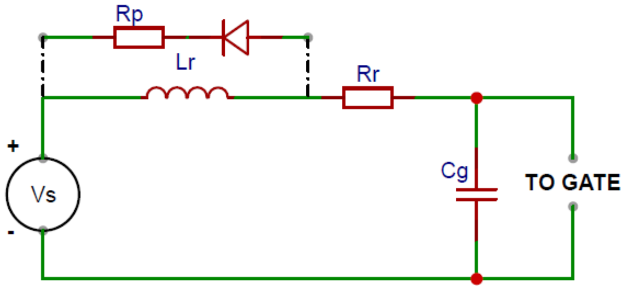

Fig. 7 Simplified Topology for conventional RSD (clamped)[16]

The other two most utilized topologies are the H-bridge and half-bridge gate drivers, which works under clamped resonance mode; both offer unique benefits and trade-offs, especially in high-frequency applications.

Figures 8 and 9 illustrate that the half-bridge circuit requires two additional diodes compared to the H-bridge configuration. However, controlling the MOSFETs at the end of each resonant period in the H-bridge is more complex due to the Miller Effect. On the other hand, the diodes in the half-bridge design effectively block reverse resonant currents, thereby simplifying the control process.

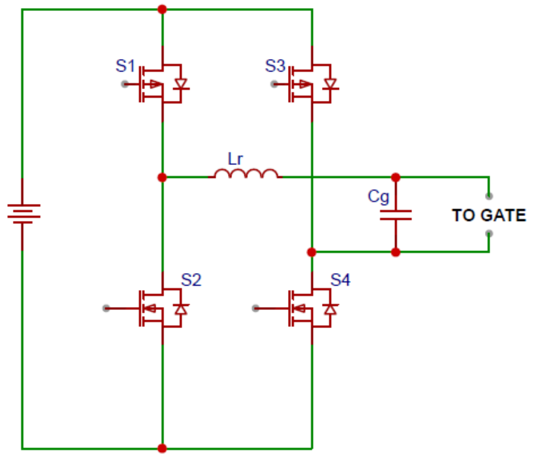

Fig. 8 Topology for H-bridge RSD[12]

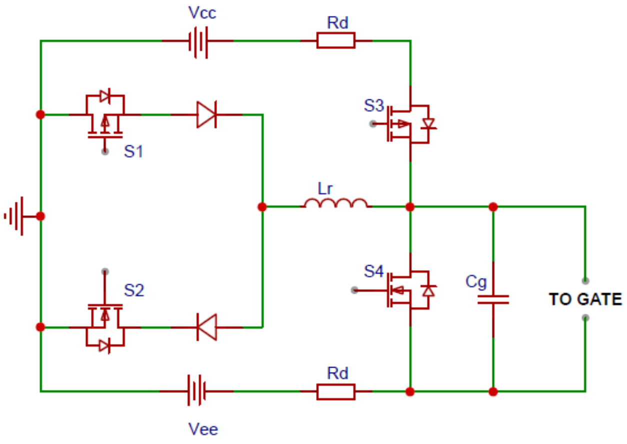

Fig. 9 Topology for half bridge RSD[12]

In the half-bridge circuit, a low-resistance resistor is applied to regulate the switch gate, unlike the inductor-based clamping technique utilized in the H-bridge configuration. The resistor mitigates gate voltage fluctuation during rapid fluctuations in the drain-source voltage. This function, however, leads to increased energy losses from power dissipation in the resistor. This approach, albeit simple, compromises efficiency for improved noise management.

4.4.2 Current Source Resonant Gate Driver

Like CSDs, in Current Source Resonant Gate Drivers (CSD), a constant current source is employed to charge the gate capacitance. This facilitates enhanced management of the gate's switching characteristics, particularly in high-frequency operations, where accurate control over switching transitions is essential to reduce losses.

Current Source Resonant Gate Drivers are widely used in various high-frequency power applications. In high-frequency DC-DC converters, such as synchronous buck converters, CSDs enhance switching speed and reduce the impact of parasitic inductance, leading to better performance than traditional gate drivers.[18] They are also effective in driving GaN power devices, where they significantly lower hard-switching losses by providing a constant gate current, making them ideal for high-power, high-frequency applications.[19] Additionally, CSDs are used in Silicon Carbide (SiC) MOSFETs to reduce switching losses in high-voltage environments, achieving up to 55% power loss reduction compared to conventional gate drivers.[20]

5. Conclusion

This review has examined developments in wide-bandgap (WBG) and ultra-wide-bandgap (UWBG) semiconductor materials and resonant and non-resonant converter topologies and gate driver designs for high-frequency power electronic converters. Incorporating WBG materials such as GaN and SiC, along with UWBG materials like Ga2O3 and AlN, greatly improves power density and efficiency. Additionally, soft-switching techniques (ZVS/ZCS) effectively reduce switching losses. Innovations in circuit topologies, including LLC and DAB converters and advanced gate driver designs (voltage and current source resonant drivers), showcase enhanced performance in high-frequency applications. The recent developments lead to enhanced efficiency, compactness, and superior performance in power converters, particularly for use in electric vehicles, renewable energy systems, and telecommunications. Future investigations should concentrate on enhancing the integration of UWBG materials and further fine-tuning gate driver topologies to tackle the new challenges that higher-frequency, high-power applications present.

References

[1] J. Millán, "A review of WBG power semiconductor devices," CAS 2012 (International Semiconductor Conference), Sinaia, Romania, 2012, pp. 57-66, doi: 10.1109/SMICND.2012.6400696.Fangfang. Research on power load forecasting based on Improved BP neural network. Harbin Institute of Technology, 2011.

[2] J. Hornberger, A. B. Lostetter, K. J. Olejniczak, T. McNutt, S. M. Lal and A. Mantooth, "Silicon-carbide (SiC) semiconductor power electronics for extreme high-temperature environments," 2004 IEEE Aerospace Conference Proceedings (IEEE Cat. No.04TH8720), Big Sky, MT, USA, 2004, pp. 2538-2555 Vol.4

[3] E. A. Jones, F. F. Wang and D. Costinett, "Review of Commercial GaN Power Devices and GaN-Based Converter Design Challenges," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 4, no. 3, pp. 707-719, Sept. 2016

[4] F. C. Lee and Q. Li, "High-Frequency Integrated Point-of-Load Converters: Overview," in IEEE Transactions on Power Electronics, vol. 28, no. 9, pp. 4127-4136, Sept. 2013

[5] R. R. Duarte, G. F. Ferreira, M. A. Dalla Costa and J. M. Alonso, "Performance comparison of Si and GaN transistors in a family of synchronous buck converters for LED lighting applications," 2016 IEEE Industry Applications Society Annual Meeting, Portland, OR, USA, 2016, pp. 1-7

[6] M. Rosker, "The wide and the narrow: DARPA/MTO programs for RF applications in wide bandgap and antimonide-based semiconductors," IEEE Compound Semiconductor Integrated Circuit Symposium, 2005. CSIC '05., Palm Springs, CA, USA, 2005, pp. 4 pp.

[7] Mingfei Xu, Dawei Wang, Kai Fu, Dinusha Herath Mudiyanselage, Houqiang Fu, Yuji Zhao, A review of ultrawide bandgap materials: properties, synthesis and devices, Oxford

Open Materials Science, Volume 2, Issue 1, 2022, itac004

[8] J. Y. Tsao, S. Chowdhury, M. A. Hollis, D. Jena, N. M. Johnson, K. A. Jones, R. J. Kaplar, S. Rajan, C. G. Van de Walle, E. Bellotti, C. L. Chua, R. Collazo, M. E. Coltrin, J. A. Cooper, K. R. Evans, S. Graham, T. A. Grotjohn, E. R. Heller, M. Higashiwaki, M. S. Islam, P. W. Juodawlkis, M. A. Khan, A. D. Koehler, J. H. Leach, U. K. Mishra, R. J. Nemanich, R. C. N. Pilawa-Podgurski, J. B. Shealy, Z. Sitar, M. J. Tadjer, A. F. Witulski, M. Wraback, J. A. Simmons, Adv. Electron. Mater. 2018, 4, 1600501.

[9] S. Roy, X. Zhang, A. B. Puthirath, A. Meiyazhagan, S. Bhattacharyya, M. M. Rahman, G. Babu, S. Susarla, S. K. Saju, M. K. Tran, L. M. Sassi, M. A. S. R. Saadi, J. Lai, O. Sahin, S. M. Sajadi, B. Dharmarajan, D. Salpekar, N. Chakingal, A. Baburaj, X. Shuai, A. Adumbumkulath, K. A. Miller, J. M. Gayle, A. Ajnsztajn, T. Prasankumar, V. V. J. Harikrishnan, V. Ojha, H. Kannan, A. Z. Khater, Z. Zhu, S. A. Iyengar, P. A. d. S. Autreto, E. F. Oliveira, G. Gao, A. G. Birdwell, M. R. Neupane, T. G. Ivanov, J. Taha-Tijerina, R. M. Yadav, S. Arepalli, R. Vajtai, P. M. Ajayan, Structure, Properties and Applications of Two-Dimensional Hexagonal Boron Nitride. Adv. Mater. 2021, 33, 2101589

[10] Zbigniew Galazka 2018 *Semicond. Sci. Technol.* 33 113001

[11] S. J. Pearton, Jiancheng Yang, Patrick H. Cary, F. Ren, Jihyun Kim, Marko J. Tadjer, Michael A. Mastro; A review of Ga2O3 materials, processing, and devices. Appl. Phys. Rev. 1 March 2018; 5 (1): 011301.

[12] Y. Wang, O. Lucia, Z. Zhang, S. Gao, Y. Guan and D. Xu, “A Review of High Frequency Power Converters and Related Technologies,” in IEEE Open Journal of the Industrial Electronics Society, vol. 1, pp. 247-260, 2020

[13] S. A. Q. Mohammed and J. -W. Jung, “A State-of-the-Art Review on Soft-Switching Techniques for DC–DC, DC–AC, AC–DC, and AC–AC Power Converters,” in IEEE Transactions on Industrial Informatics, vol. 17, no. 10, pp. 6569-6582, Oct. 2021

[14] D. Maksimovic and S. Cuk, “A general approach to synthesis and analysis of quasi-resonant converters,” in IEEE Transactions on Power Electronics, vol. 6, no. 1, pp. 127-140, Jan. 1991, doi: 10.1109/63.65011.

[15] F. C. Lee, “High-frequency quasi-resonant converter technologies,” in Proceedings of the IEEE, vol. 76, no. 4, pp. 377-390, April 1988

[16] Strydom, J. T., M. A. De Rooij, and J. D. Van Wyk. “A comparison of fundamental gate-driver topologies for high frequency applications.” Nineteenth Annual IEEE Applied Power Electronics Conference and Exposition, 2004. APEC’04.. Vol. 2. IEEE, 2004.

[17] L. Cohen, Joseph B. Bernstein, Ilan Aharon. Gate Driver for High-Frequency High Power Electronics. TechRxiv. July 09, 2024.

[18] Liu, Y., Ge, L., & Zheng, S. (2008). Dual channel current-source gate drivers for high-frequency dc-dc converters. 2008 3rd IEEE Conference on Industrial Electronics and Applications, 613-618.

[19] Moradpour, M., Franke, W., Pirino, P., & Gatto, G. (2020). Current Source Gate Driver for GaN E-HEMT in Hard-Switched High Power Applications. 2020 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM), 408-413.

[20] Kumar, A., Losito, M., Moradpour, M., & Gatto, G. (2022). Current Source Gate Driver for SiC MOSFETs in Power Electronics Applications. 2022 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM), 523-527.

[21] Qin, Y., Albano, B., Spencer, J., Lundh, J., Wang, B., Buttay, C., Tadjer, M., Dimarino, C., & Zhang, Y. (2023). Thermal management and packaging of wide and ultra-wide bandgap power devices: a review and perspective. Journal of Physics D: Applied Physics, 56.

[22] Yuan, C., Hanus, R., & Graham, S. (2022). A review of thermoreflectance techniques for characterizing wide bandgap semiconductors’ thermal properties and devices’ temperatures. Journal of Applied Physics.

[23] Gupta, C., & Pasayat, S. (2022). Vertical GaN and Vertical Ga2O3 Power Transistors: Status and Challenges. physica status solidi (a), 219.