LITERATURE REVIEW OF DESIGN AND ANALYSIS OF FPGA CONTROLLED GAN BASED INVERTERS

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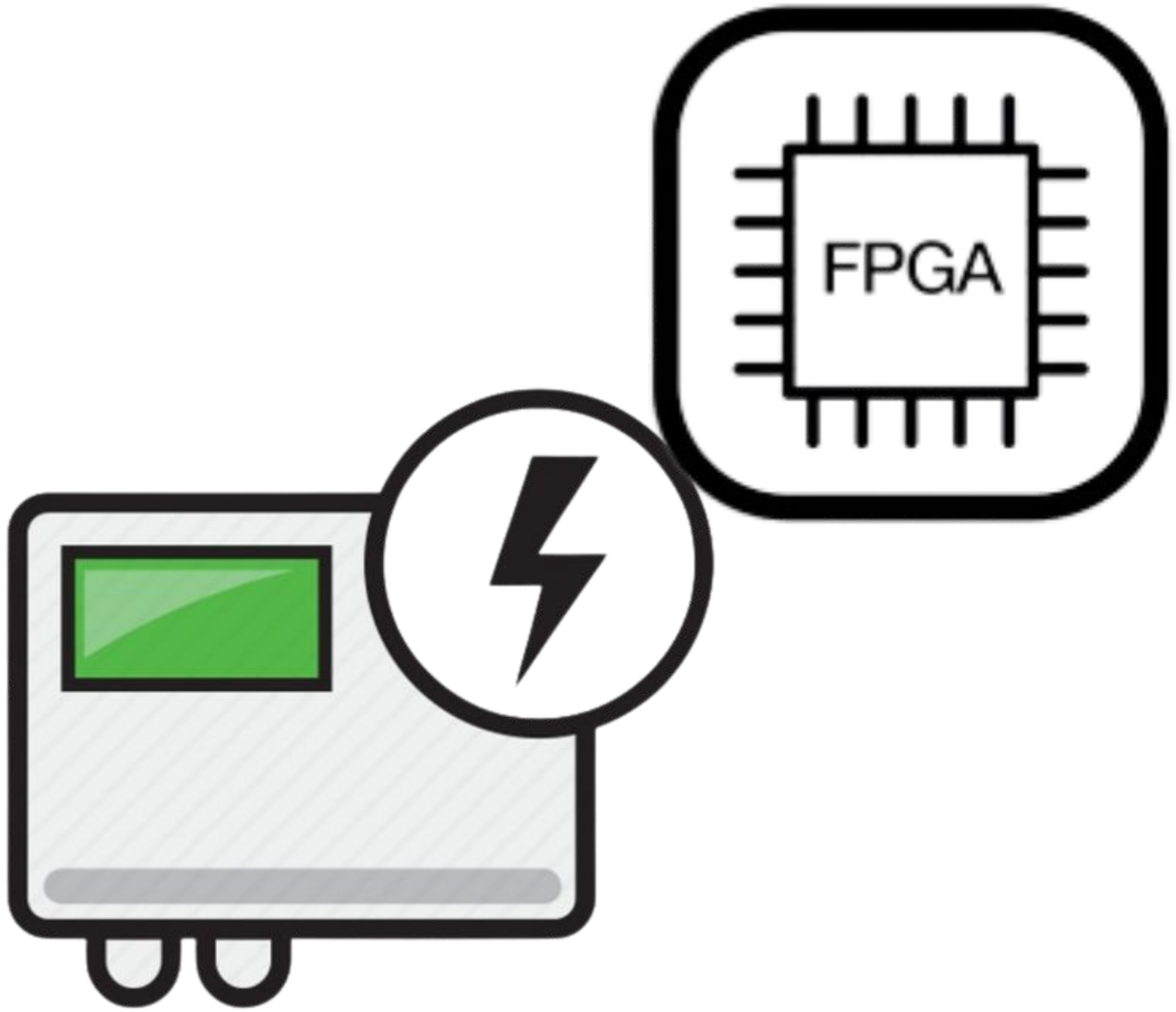


Introduction

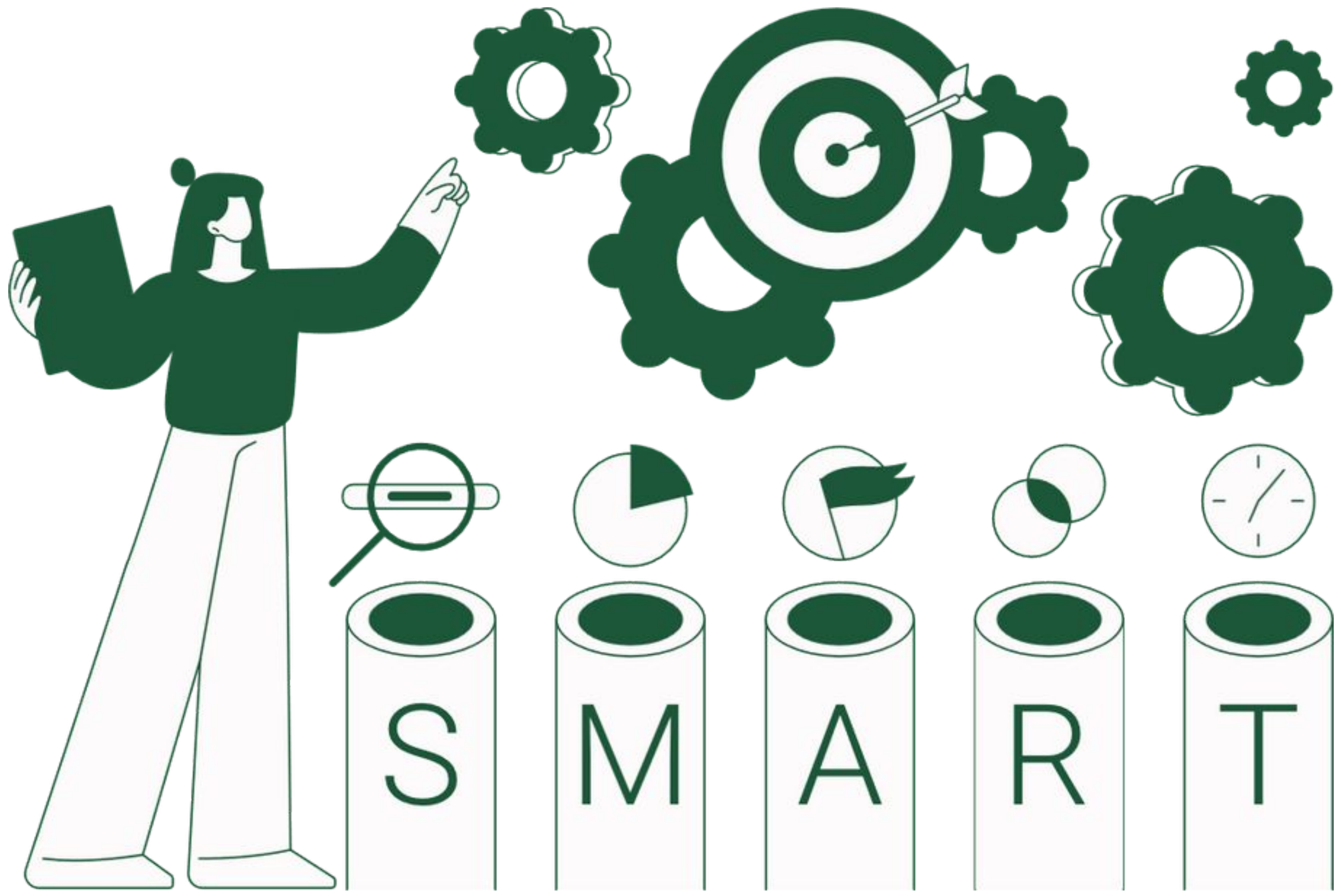
Applications

- Uninterruptible Power Supplies
- Renewable Energy Systems
- Electrical Vehicles
- Industrial Motor Drives
- HVAC systems
- Railway systems

Challenges

- Efficiency
- Thermal Management
- Cost
- Complexity in Design
- Electromagnetic Interference (EMI)

Objectives



Analyze the potential improvements offered by GaN-based inverters compared to traditional silicon-based (Si/SiC) inverters

Explore the use of advanced FPGA-based control mechanisms to handle the high-frequency operation of GaN based inverters

Compare the performance, flexibility, and suitability of FPGA and other microcontrollers for high-frequency GaN power inverters

Why GaN?

- **Higher efficiency**

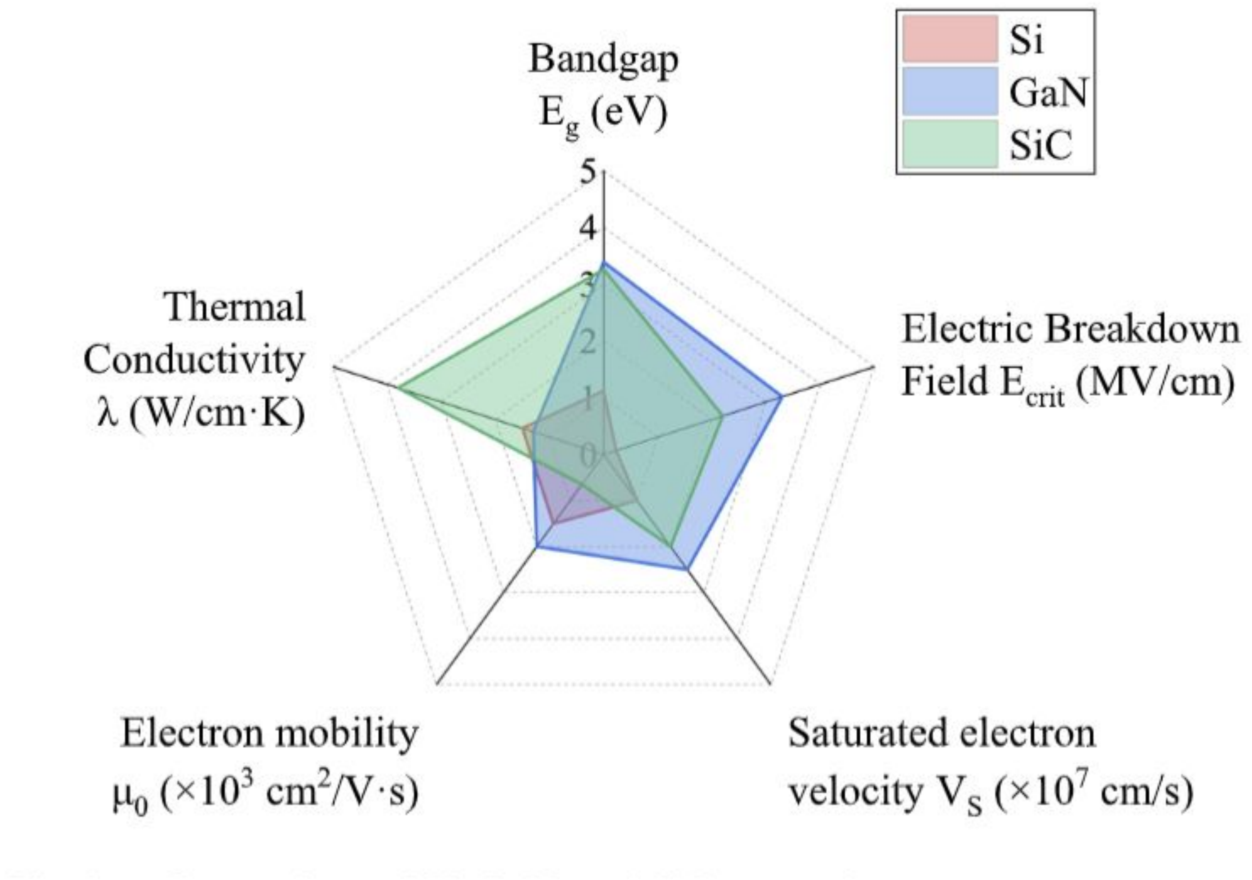
  GaN devices have lower on-resistance and can switch much faster, resulting in reduced conduction losses, lower switching losses, and higher efficiency.

- **Higher frequency operation**

  In some specialized high-frequency power inverter applications, GaN devices can operate at frequencies up to a few MHz, providing further reductions in size and improvements in efficiency.

- **Higher Bandgap and Electric breakdown**

  It allows GaN devices to operate at higher temperatures and voltages, making them more suitable for high-power and high-frequency applications.



Properties	GaN	4H-SiC	Si
Bandgap, E_g(eV)	3.39	3.26	1.12
Breackdown field, E_{on}(MV/cm)	3.3	2.2	0.23
Saturated drift velocity, $V_s(10^7 cm/s)$	2.5	2.0	1.0
lectron mobility, $\mu_n(\mathrm{cm}^2/Vs)$	2000	650	1500
Thermal conductivity, $\sigma(\mathrm{W/cm} \times K)$	1.3	3.8	1.5

Why GaN?

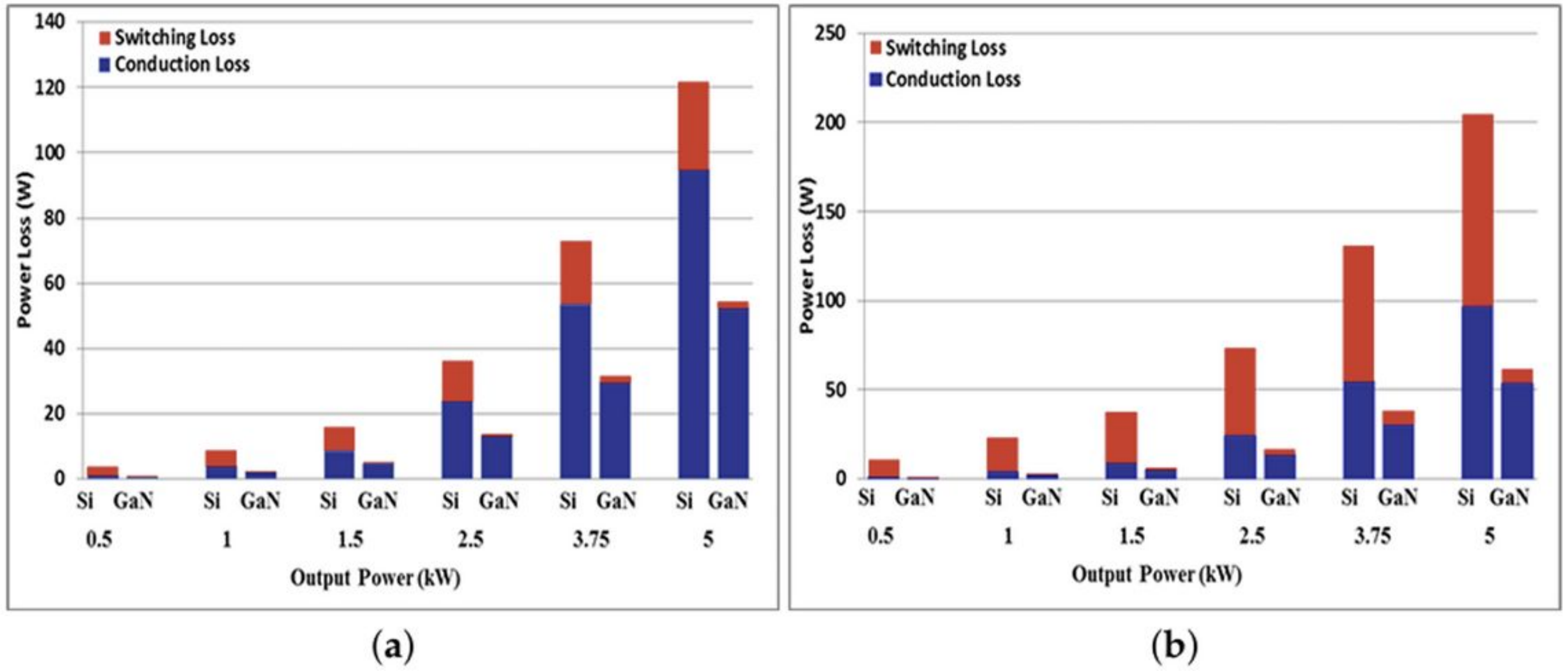
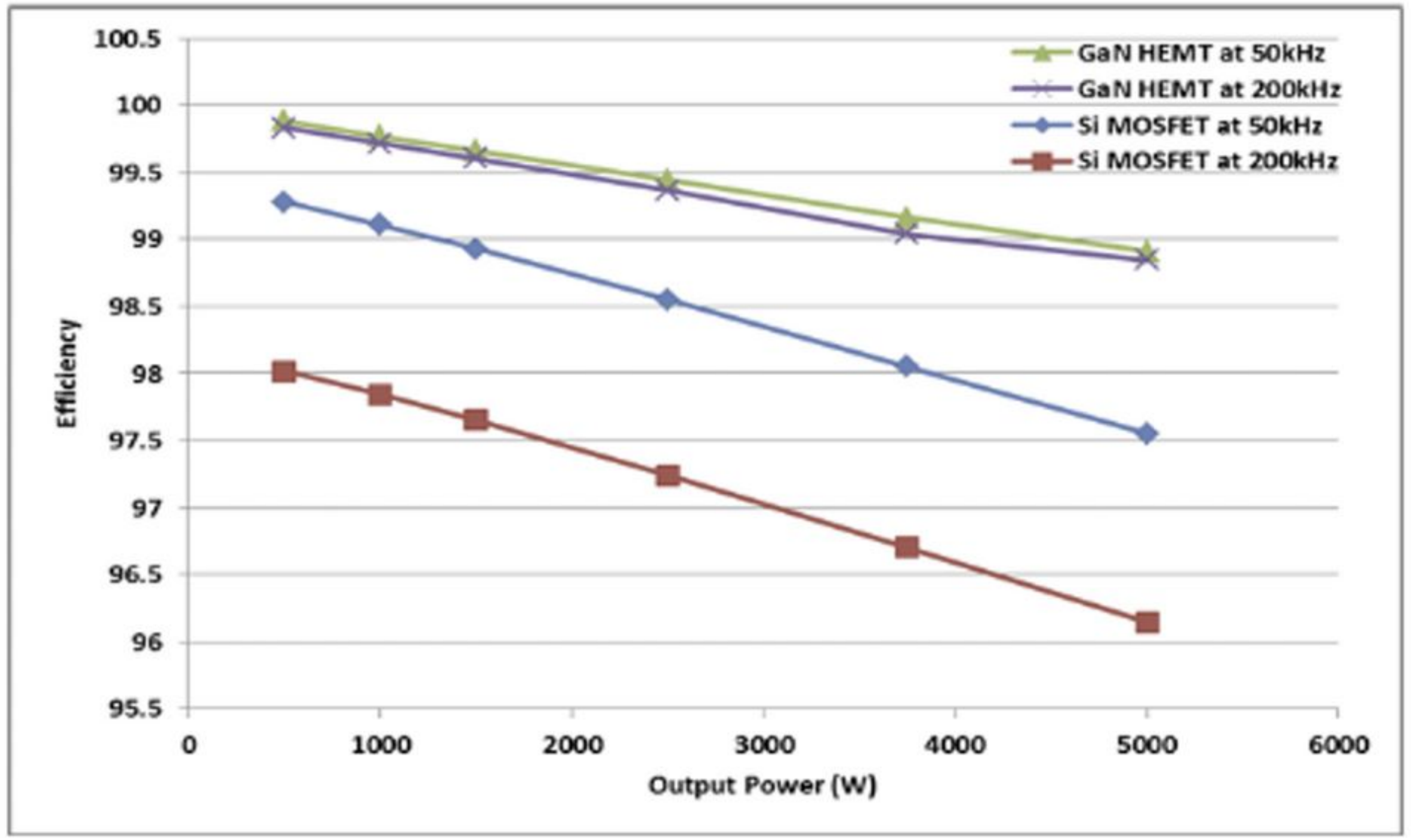


Figure 1 Power losses of Si MOSFET and GaN HEMT: (a) 50 kHz (b) 200 kHz [34]



Challenges

Thermal Management

GaN devices have lower thermal conductivity compared to SiC, posing challenges in high-power and high-temperature applications.

PCB Layout

Designing PCB layouts for GaN transistors involves minimizing parasitic inductance from copper connections on the PCB.

Implementation

The ratio between sampling and switching frequency can complicate control strategies and limit performance in high-frequency applications.

Cost

Although long-term savings in energy efficiency and reduced cooling requirements can offset the initial expense, the initial cost is a barrier to widespread adoption.

FPGA controlled GaN based inverters

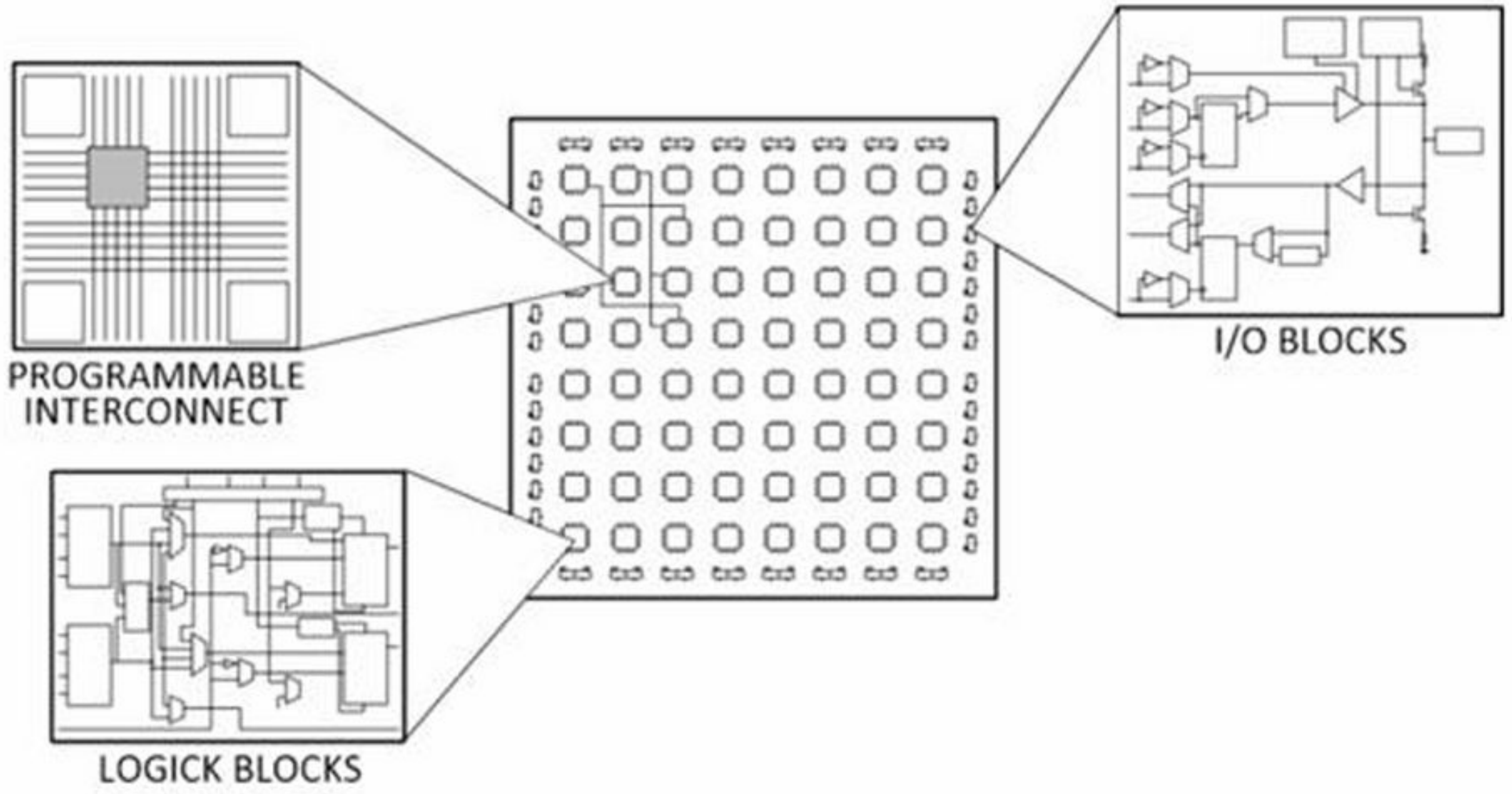
FPGA technology is used in GaN-based inverters due to its ability to handle high-frequency pulse generation, provide precise control over parameters, and execute complex control algorithms in real-time, which enhances performance, efficiency, and reliability. Additionally, FPGAs offer reconfigurability, parallel processing capabilities, and improved thermal management, making them ideal for advanced power electronics applications.

Aspect	**FPGA-Controlled Inverters**	**DSP-Controlled Inverters**	**Microcontroller-Controlled Inverters**
Customization	High	Moderate	Limited
Processing Power	High	High	Low to Moderate
Parallel Processing	Yes	No	No
Power Consumption	Higher	Moderate	Lower
Example Models	Xilinx Virtex Series, Intel Stratix Series	Texas Instruments TMS320 Series	Microchip dsPIC, TI C2000, PIC Family
Controller Processing Time	< 10 ns per operation cycle	< 50 ns per instruction cycle	< 100 ns per instruction cycle
Additional Features	Parallel processing, customizable logic circuits	High-speed real-time processing, specialized for signal processing tasks	Integrated high-speed ADCs, advanced timers
Cost	Higher	Moderate	Lower

- Phase-Locked Loop (PLL)
- Zero-Crossing Detection
- Adaptive Control Algorithms – Model Reference Adaptive Control (MRAC), Sliding Mode Control (SMC), Neural Network-Based Control

FPGA ARCHITECTURE

	Type 1	Type 2	Type 3	Type 4
Architecture	Pure FPGA	FPGA+DSP	SoC	Third party solution
Toolchain	Native	Native	Native	Third party software
Merit	1. Simple one chip solution. 2. Highly customizable.	1. Highly customizable. 2. 28 Abundant peripherals.	1. Simple one chip solution. 2. Highly customizable. 3. Abundant peripherals.	1. High level graphic development tool is easy to learn. 2. No need for low level FPGA design knowledge.
Demerit	1. The lack of peripherals. 2. Require knowledge on low level FPGA design.	1. Hardware design is complicated. 2. Require knowledge on low level FPGA design.	1. Require knowledge on low level FPGA design. 2. Logic resource may be limited.	1. Hardware is not customizable. 2. Performance of the FPGA may be limited by the third party development software.



RELATED WORK

Reference	Key Focus & Contribution	Semiconductor Applications
[63]	Implemented vector control algorithm for a 200 kHz GaN-based motor drive system using an FPGA, achieving precise control unattainable with traditional MCUs.	GaN
[64]	Highlighted the importance of fast response in a 9-level FCML inverter, achieving high effective switching frequencies (up to 4 MHz) and peak efficiency above 99.0%.	GaN
[65]	Discussed the benefits of high switching frequencies supported by FPGAs in improving the efficiency and performance of GaN-based inverters.	GaN
[66]	Introduced FPGA-based speed control using Field Oriented Control (FOC) and Sliding Mode Observer (SMO) design, showing improved back-emf graphics during transitions.	GaN
[67]	Analyzed FPGA-based control for 3-phase BLDC motors, highlighting its power and safety superiority compared to microcontroller-based control.	GaN
[68]	Implemented a 13-level FCML inverter using low-voltage GaN FETs, achieving high switching frequency of 120 kHz, reducing commutation loop inductance, and achieving low total harmonic distortion (THD) of 0.7%.	GaN
[69]	Demonstrated how FPGA-based control generates high-frequency PWM signals for dynamic performance of GaN power devices, ensuring precise control and high-speed switching.	GaN
[70]	Applied Field-Oriented Control (FOC) to an FPGA-controlled GaN-based 3-phase induction motor, achieving higher switching frequencies up to 100 kHz and improving power density.	GaN

Reference	Key Focus & Contribution	Semiconductor Applications
[72]	Designed and implemented a model predictive controller (MPC) on an FPGA for a SiC-based qZSI, achieving high-speed, precise control, and handling high switching frequencies with minimal output current ripple.	SiC
[73]	Developed a CHIL testbed for validating low-level and advanced inverter controls for a SiC-based PV string inverter, achieving peak inverter efficiency of about 99% and validating the FPGA's effectiveness for high-speed, precise control.	SiC
[71]	Examined FPGA-controlled real-time implementation of a 3-phase 3-level VSI for integrating multi-string PV arrays into the power grid, maintaining grid frequency at 50 Hz with a THD of less than 2.5%.	Si
[74]	Presented a control structure for voltage and frequency regulation of VSI using ADALINE-FLL, ensuring stable operation and efficient power control for standalone and grid-connected systems.	Si
[75]	Analyzed a full control system for a grid-connected current-controlled VSI on an FPGA, demonstrating high-speed burst logging, fault detection, and effective management of active and reactive power flows.	Si

CONCLUSION

CHALLENGES

- Complex Design and Programming: Requires specialized knowledge of hardware description languages (HDLs) like VHDL or Verilog, increasing development time and cost.
- Initial Cost: Generally higher than microcontrollers (MCUs) or digital signal processors (DSPs).
- Power Consumption: FPGAs can consume more power compared to optimized microcontroller-based solutions, especially if parallel processing capabilities are underutilized.

FUTURE ASPECTS

- Advanced Control Algorithms: Continued development of more sophisticated control algorithms to further enhance performance and efficiency.
- Integration with Emerging Technologies: Integration with GaN and SiC semiconductors to exploit their high-speed switching capabilities for improved efficiency and performance.
- Reduction in Costs: Economies of scale and technological advancements could reduce the costs associated with FPGA/GaN-based designs, making them more accessible for a wider range of applications.
- Power Optimization: Advances in FPGA design could lead to more power-efficient solutions, minimizing the power consumption challenges.

References

[63] Z. Luo, Y. Li, X. Zhang, and K. Wang, “Vector control implementation in field programmable gate array for 200 kHz GaN-based motor drive systems,” Journal of engineering, vol. 2018, no. https://doi.org/10.1049/joe.2018.0032.

[64] 13, pp. 650–653, Jan. 2018, doi: M. Nitzsche, J. Haarer, V. Ketchedjian and J. Roth-Stielow, "Design of a 9-Level Flying Capacitor Inverter with Very Fast Response of the Controller," IECON 2020 The 46th Annual Conference of the IEEE Industrial Electronics Society, Singapore, 2020, pp. 2424-2429, doi: 10.1109/IECON43393.2020.9254392.

[65] Symposium B. Tufekci, B. Onal, H. Dere and H. F. Ugurdag, "Efficient FPGA Implementation of Field Oriented Control for 3-Phase Machine Drives," 2020 IEEE East-West Design & Test (EWDTS), Varna. Bulgaria, 2020, pp. 1-5, doi: 10.1109/EWDTS50664.2020.9224884

[66] Y. Kung, Hoang Than, Y. Lin, and L. Huang, “FPGA Based Speed Controller Design for a Ceiling Fan Motor,” in Proc. Int. Future Energy Electronics Conference (IFEEC) and ECCE Asia, pp. 30–34, 2017.

[67] S. Suneeta, R. Srinivasan, and R. Sagar, “FPGA Based Control Method for Three Phase BLDC Motor,” Int. Journal of Electrical and Computer Engineering, vol. 6, pp. 1434–1440, 2016.

[68] C. B. Barth et al., "Design and Control of a GaN-Based, 13-Level, Flying Capacitor Multilevel Inverter," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 8, no. 3, pp. 2179-2191, Sept. 2020, doi: 10.1109/JESTPE.2019.2956166.

[69] G. H. M. Tavares, M. L. G. Salmento, W. J. Paula, D. d. C. Pereira and H. A. C. Braga, "Implementation of a high frequency PWM signal in FPGA FOR GaN power devices switching," 2017 Brazilian Power Electronics Conference (COBEP), Juiz de Fora, Brazil, 2017, pp. 1-7, doi: 10.1109/COBEP.2017.8257309.

[70] Tung Duong Do, Nam Duong Le, Vu Hoang Phuong, and Nguyen Tung Lam, “Implementation of FOC algorithm using FPGA for GaN-based three phase induction motor drive,” Bulletin of Electrical Engineering and Informatics, vol. 11, no. 2, pp. 636 645, Apr. 2022, doi: https://doi.org/10.11591/eei.v11i2.3569.

[71] S. Jena, G. Panda and R. Peesapati, "Real-time analysis and simulation of multi string grid connected photovoltaic inverter using FPGA," 2016 IEEE 6th International Conference on Power Systems (ICPS), New Delhi, India, 2016, pp. 1-6, doi: 10.1109/ICPES.2016.7584068.

[72] M. Mosa, G. M. Dousoky and H. Abu-Rub, "A novel FPGA implementation of a model predictive controller for SiC-based Quasi-Z-Source inverters," 2014 IEEE Applied Power Electronics Conference and Exposition - APEC 2014, Fort Worth, TX, USA, 2014, pp. 1293-1298, doi: 10.1109/APEC.2014.6803473.

[73] A. Singh and K. Prabakar, "Controller-Hardware-in-the-Loop Testbed for Fast Switching SiC-Based 50-kW PV Inverter," IECON 2018 - 44th Annual Conference of the IEEE Industrial Electronics Society, Washington, DC, USA, 2018, pp. 1109-1115, doi: 10.1109/IECON.2018.8591991.

[74] C. Guzmán, A. Cardenas and K. Agbossou, "Control of voltage source inverter using FPGA implementation of ADALINE-FLL," IECON 2012 - 38th Annual Conference on IEEE Industrial

THANK YOU

Q&A