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DESIGN AND ANALYSIS OF A FPGA-BASED CONTROLLER FOR GAN-BASED THREE-PHASE INVERTERS: EFFICIENCY, PERFORMANCE, AND RELIABILITY OPTIMIZATION

LITERATURE REVIEW REPORT

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INTRODUCTION

Inverters play a vital role in contemporary electrical systems by converting direct current (DC) into alternating current (AC) for a variety of uses. They are fundamental in renewable energy systems, such as those utilizing solar or wind power, because they facilitate the integration of these renewable sources into the electrical grid. In electric vehicles, inverters are key to transforming the DC power stored in batteries into AC power required by the electric motors. Moreover, inverters are integral to the functioning of industrial motor drives, uninterruptible power supplies (UPS), heating, ventilation, and air conditioning (HVAC) systems, as well as railway systems. Their efficiency and reliability in power conversion are critical to the performance and stability of these applications.

The development of power electronics has been significantly enhanced by the incorporation of advanced materials and control technologies, particularly the use of Gallium Nitride (GaN) devices and Field-Programmable Gate Arrays (FPGAs). GaN-based inverters, recognized for their superior efficiency, high switching frequency, and excellent thermal performance, are leading the innovation in power conversion systems. These inverters are pivotal in applications that span from renewable energy systems to electric vehicles and industrial motor drives. However, the complicated nature of controlling GaN devices, especially at elevated frequencies, necessitates sophisticated control solutions.

FPGAs, with their flexible architecture, rapid cycle times, and capability for parallel processing, provide an optimal solution for this complexity. This study focuses on the design and analysis of FPGA-controlled GaN-based inverters, evaluating their efficiency, performance, and reliability. By reviewing current research and advancements, this study aims to offer a thorough understanding of the potential and challenges of integrating FPGA control with GaN technology in inverter applications.

Recognizing the synergy between GaN devices and FPGA technology is crucial as it addresses fundamental issues in power electronics, such as enhancing energy efficiency, minimizing system size, and improving reliability. This study aims using of the continuous advancement in power electronics and contributing valuable insights to the ongoing development of sustainable energy systems, electric mobility, and industrial automation. The outcomes and insights derived from this review are essential for creating next-generation power conversion systems that fulfill the growing need for efficient and reliable power solutions.

LITERATURE REVIEW

1. Inverters

An inverter, also referred to as a DC-AC converter, is used to generate an alternating current (AC) output from a direct current (DC) source. Inverters are essential components in modern power electronics, playing a critical role in various applications ranging from renewable energy systems to electric vehicles and industrial motor drives. They can be broadly classified into voltage-source inverters (VSIs) and current-source inverters (CSIs). A VSI operates with a DC voltage source, typically involving a large capacitor connected across the DC bus, whereas a CSI uses a DC current source with a large inductor in series.

Inverters utilize pulse-width modulation (PWM) techniques to regulate the output voltage and frequency. PWM allows the control of switches within the inverter to create an AC output with the desired characteristics. This modulation converts a signal with potentially varying amplitude into a series of pulses with varying widths, which can effectively control the performance of the inverter. Various PWM methods, such as sinusoidal PWM (SPWM) and space vector PWM (SVPWM), are employed to optimize inverter operation, reducing harmonic content and improving overall efficiency. Several PWM approaches are analyzed in the papers [1-9].

In the referenced paper [10], it is highlighted that while the control methodologies for voltage source inverters (VSIs) and current source inverters (CSIs) differ, both are essential for converting DC to AC, supporting a diverse range of applications. CSIs are generally employed in scenarios that involve inductive loads, including motors and transformers. These inverters can deliver high-quality AC with adjustable voltage and frequency by modulating the current. Typical uses for CSIs encompass inverter air conditioning systems, motor drives, and electromagnet control. Conversely, VSIs are predominantly utilized for driving capacitive loads, such as electronic devices and lighting systems. VSIs offer a stable output voltage that can be controlled by adjusting the voltage and frequency, making them suitable for applications like uninterruptible power supplies (UPS), solar inverters, and household appliances.

In renewable energy applications, inverters are essential for converting DC power generated by solar panels and wind turbines into AC power suitable for grid integration or local consumption. The implementation of inverters using advanced semiconductor materials like Gallium Nitride (GaN) and Silicon Carbide (SiC) has been shown to enhance efficiency and performance. The literature highlights various advancements in this field. The study [11] examines the design of a 2-stage, grid-connected and single-phase GaN-based micro-inverter, emphasizing its effectiveness in tracking the maximum power point and maintaining power continuity even in the event of converter failures. Similarly, the paper [28] demonstrate that SiC and GaN devices in inverters achieve high efficiencies and reduced cooling and filter requirements, with SiC devices offering robust performance under varying conditions and GaN devices excelling in high-frequency operations. These advancements underscore the pivotal role of inverters in maximizing energy yield and reliability in renewable energy applications.

In electric vehicles, three-phase inverters are essential for managing power conversion between batteries and motors. Various inverter designs enhance efficiency, reduce size, and improve thermal management, as seen in different studies. For instance, Naoufel Bouraoui's work on Silicon Carbide (SiC) MOSFET inverters emphasizes their ability to achieve higher switching frequencies and efficiency, improving the overall performance of EV traction systems [12]. Similarly, the study on a hybrid GaN-Si T-Type three-level inverter configuration showcases advancements in reducing switching losses and enhancing power density, crucial for EV applications [13]. Furthermore, the use of a 9-switch Z-source power inverter with Maximum Constant Boost Control (MCBC) in EVs demonstrates the potential to reduce component count, switching losses, and system cost, while providing independent control of dual motors [14]. These innovations collectively contribute to the development of more efficient, compact, and cost-effective inverters for electric vehicles, highlighting the continuous progress in this field.

In industrial motor drives, inverters play a critical role, particularly in applications requiring precise speed and torque control. In the literature, various inverter topologies are explored for their suitability in integrated modular motor drive (IMMD) applications, highlighting the importance of efficiency, fault tolerance, and size reduction. The paper [15] provide a comprehensive comparison of inverter topologies such as two-level voltage source inverters (2L-VSI) and three-level voltage source inverters (3L-VSI), emphasizing their efficiency improvements when utilizing GaN power semiconductors over conventional IGBT motor drives. Meanwhile, the reference [16] focuses on current-source inverters (CSI), noting their advantages like motor-friendly waveforms and power reversal capabilities, which are beneficial for medium-voltage drives. Their proposed modified indirect vector control (IVC) technique for CSI drives ensures superior decoupling and field orientation, addressing the limitations of conventional IVC systems. These studies generally underscore the evolving landscape of inverter technology in enhancing motor drive performance and reliability.

In summary, inverters are essential for the effective operation of renewable energy systems, enabling the conversion of DC power from renewable sources into stable AC power for grid integration or local use. The advancements in inverter technology, particularly with the use of wide-bandgap semiconductors like SiC and GaN, are driving improvements in efficiency, reliability, and performance across various applications.

2. GaN-based devices

2.1. Why GaN

Progress in applied science frequently arises from changes in materials science. Transistors, introduced by Bell Labs in 1948, rapidly evolved alongside first-generation semiconductor materials such as silicon (Si) and germanium (Ge). Silicon technology sparked the third industrial revolution and has remained the most widely used semiconductor material since. The second generation of semiconductors saw the introduction of compound materials like gallium arsenide (GaAs), which were extensively used for high-speed and high-power transistors. Currently, research in power electronics is focused on transistors made from third-generation semiconductor materials, particularly silicon carbide (SiC) and gallium nitride (GaN) [17, 18]. These materials are characterized by their wide semiconductor bandgap, which allows them to exceed the physical limits of silicon semiconductors and provide more efficient switching. The utilization of wide bandgap semiconductors holds the potential to revolutionize the design of power converters by enhancing efficiency and power density [19-23]. Compared to SiC transistors, GaN transistors offer a superior figure of merit (FOM), making them highly suitable for high-frequency applications. The fabrication of GaN transistors requires innovative packaging techniques to achieve low parasitic inductance connections. For example, the ball grid array (BGA) package by EPC, the quad flat no-lead (QFN) package by Nivatas, and the GaNPX package by GaN Systems are all chip-scale surface mount packages designed for high-frequency applications.

In addition, emerging GaN power devices have been extensively studied and applied to power converters due to their low specific on-state resistance (Rdson), high switching speed, low junction capacitance (Coss), and zero reverse recovery [24, 25]. These attributes allow for high switching frequencies and minimal losses, which in turn not only decrease the size or the weight of converters but also enhance their efficiency. Previous research has highlighted the benefits of GaN-based power converters. For instance, compared to Si devices, GaN devices exhibit lower conduction, switching, and driving losses, and they reduce transformer winding losses because less total device charge is required during soft-switching transients [26]. Studies have shown that GaN devices improve the efficiency of buck and LLC converters due to their zero reverse recovery and low junction capacitance [27]. Additionally, GaN-based single-phase T-type inverters have been shown to reduce power loss and heatsink volume compared to their silicon carbide (SiC) and silicon (Si) counterparts [28].

2.2. Advantages & Disadvantages

Gallium Nitride (GaN) devices present a unique set of advantages and disadvantages in power electronics applications.

Advantages

1. Efficiency and Performance:

- GaN devices demonstrate significantly lower total losses and higher efficiency, particularly in high-frequency applications. The comparative analysis highlights that GaN technology is preferred for applications requiring high efficiency and power density due to its superior electron mobility, which reduces switching times and output capacitance. [29-31] Silicon Carbide (SiC) devices constitute a competitive alternative due to their exceptional thermal conductivity, robust electric field, and wide energy gap. These characteristics make SiC devices particularly suitable for applications requiring operation at elevated temperatures, high frequencies, substantial power levels, and high drain-source voltages [29, 30, 32].
- The study [33] underscores GaN superior on-state resistance and faster switching capabilities, leading to 17% lower total power losses compared to SiC-MOSFETs and 61% lower than Si-IGBTs.
- Utilizing GaN HEMTs in inverter applications significantly reduces power losses in semiconductors by up to 60% when compared to Si MOSFETs, leading to a 3% improvement in overall system efficiency. This increase in efficiency also allows for a 60% boost in power rating without any additional power losses, resulting in a decrease in the volume of the heat sink and a reduction in overall system costs.

2. Thermal Management:

- Gallium Nitride (GaN) devices have a lower thermal conductivity than Silicon Carbide (SiC) devices. However, GaN devices still require less thermal management due to their superior efficiency and lower power losses. This is crucial for compact and high-density power electronics designs where thermal constraints are a significant concern.
- The reduction in heatsink volume by more than 30% due to lower power losses translates to a decrease in the overall system volume and cost, making GaN-based designs more appealing for high-frequency and high-power applications [34].

3. Switching Frequency:

- Gallium Nitride (GaN) devices have the capability to function at significantly greater switching frequencies compared to their Silicon (Si) counterparts. It is found that GaN based HEMTs may have a switching frequency that is almost 10 times higher than that of Si based MOSFETs. This feature enables a decrease in the dimensions and mass of inactive components, leading to a reduction in both cost and volume.
- Higher switching frequencies enable more efficient power conversion and improved performance in various power electronics applications, such as photovoltaic inverters and motor drives.

The study [34] further analyzes the benefits of GaN devices. Figure 1 illustrates a drop in total loss of over 60% at 50 kHz and an even higher reduction at 200 kHz. Figure 2 depicts the enhancement in efficiency achieved by employing GaN HEMTs, with a more than 2% improvement at 50 kHz and a more than 3% improvement at 200 kHz. Furthermore, Figure 3 presents the concept of increasing output power from 2500 W using Si MOSFETs to 3750 W using GaN HEMTs at the same power losses and 50 kHz switching frequency, achieving over a 60% increase in power rating without additional cooling.

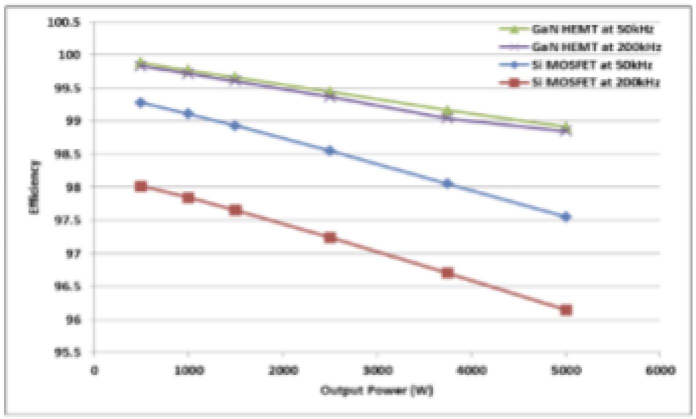


*Figure SEQ Figure * ARABIC 2 Efficiency comparison [34]*

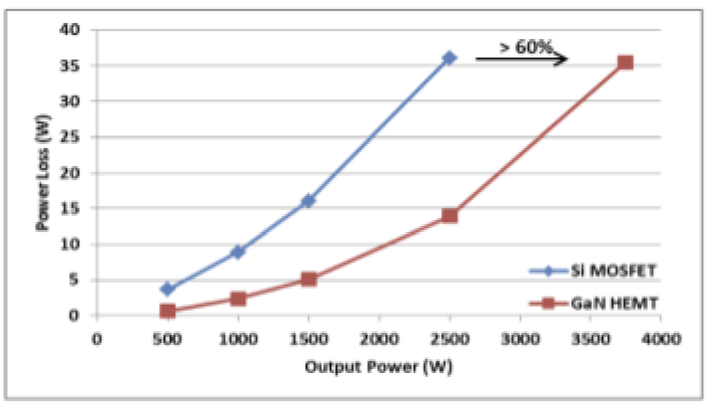
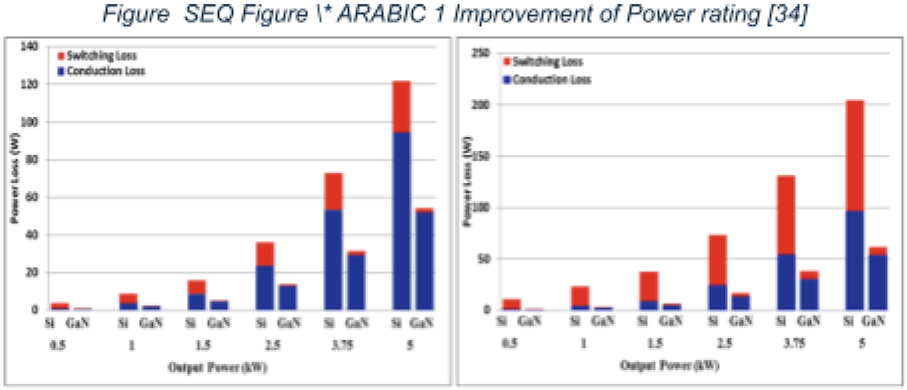


*Figure SEQ Figure * ARABIC 1 Improvement of Power rating [34]*



(a) (b)

*Figure SEQ Figure * ARABIC 3 Power losses of Si MOSFET and GaN HEMT: (a) 50 kHz (b) 200 kHz [34]*

Disadvantages

1. Thermal Conductivity:

- Despite their efficiency benefits, GaN devices have lower thermal conductivity compared to SiC, which can be a disadvantage in high-power and high-temperature applications. The studies point out that this limitation may pose challenges in scenarios where devices need to operate at elevated temperatures and power levels [30, 31, 35, 36].

2. Cost:

- Initial costs of GaN devices are higher compared to traditional Si-based devices. Although the overall system cost can be reduced by 10% due to smaller passive components and heatsinks, the upfront expense of GaN technology remains a barrier to widespread adoption [37].
- The cost-effectiveness of GaN devices improves over time with long-term savings in energy efficiency and reduced cooling requirements. However, the initial investment may deter some applications from transitioning to GaN technology.

3. Complexity of Implementation:

- Integrating GaN devices into existing systems can be complex due to their unique characteristics and the need for optimized gate drive circuits. The higher switching speeds require careful design considerations to minimize issues such as electromagnetic interference (EMI) and to fully leverage the advantages of GaN technology.
- One critical limitation in GaN inverter projects is managing the ratio between sampling and switching frequency. This ratio can complicate control strategies and limit performance in high-frequency applications. Effective high-frequency control is crucial for operations at MHz frequencies, particularly in soft-switching applications. It is essential to quickly identify soft-switching conditions and produce precise PWM signals accordingly.

4. PCB Layout Challenges:

- The PCB layout poses a considerable problem in applications with high slew-rate and high switching frequency. Si and SiC transistors commonly utilize through-hole packages, with the key concern being the presence of shared source inductance. On the other hand, GaN transistors mostly experience power loop inductance caused by parasitic inductance from the copper connections on the PCB. The power loop inductance can be greatly affected by the strategies used for component placement and arrangement. Due to the GaN transistors' low gate threshold voltage, restricted blocking voltage, and absence of avalanche breakdown, it is crucial to rigorously design PCB layouts for such devices in order to prevent parasitic inductance [38-40].

3. FPGA controlled GaN-based Inverters

The advancement of semiconductor technology utilizing GaN material enables operation at switching frequencies ranging from 50 to MHz, significantly higher than the 2 to 20 kHz range typical of IGBT transistors. GaN-based devices offer numerous advantages, including reduced switching losses and the ability to operate at high temperatures. Numerous studies, as discussed in previous chapters, have demonstrated their practical effectiveness in power electronic converters.

However, these benefits come with notable challenges, such as managing thermal issues, electromagnetic interference (EMI), and controlling complexity at high frequencies. One critical limitation in GaN inverter projects is the ratio between sampling and switching frequency. Most platforms currently used for generating PWM signals, such as dedicated PWM controllers and microcontrollers, are limited to applications within the tens of kHz range. Consequently, these analog and digital solutions may not be suitable for applications requiring GaN devices to operate in the MHz frequency range. To address this limitation, the use of FPGA (Field-Programmable Gate Array) devices presents a viable alternative. FPGAs, with their exceptional architecture, can generate high-frequency pulses, enabling precise control over key parameters such as duty cycle, frequency, and phase difference between PWM signals, even at operating frequencies in the tens of MHz. Additionally, FPGA manufacturers offer a system-on-chip (SoC) environment, which has led to their increasing use in power electronics and electrical drive systems [41-48].

3.1. How FPGA works

With the advancements in integrated circuit technology, field-programmable gate arrays (FPGAs) are becoming more accessible and powerful, making them increasingly popular in power electronics applications. The inherent parallelism and substantial computational capabilities of FPGAs make them more suitable for specific applications compared to traditional microcontrollers and digital signal processors (DSPs). A comprehensive comparison between DSPs, microcontrollers, and FPGAs can be found in [49]. Furthermore, FPGAs have been used to implement computationally demanding control methods such as model predictive control (MPC) [50-54]. Their numerous I/O pins and extensive logic resources make FPGAs ideal for applications that require intricate modulation strategies [55, 56].

FPGAs are defined by their reprogrammable silicon architecture, enabling the synthesis of any digital function. It differs them from conventional processor architectures, which are constrained by their fixed architectures, the number of cores, and the serial nature of instruction processing [57]. The inherent properties of FPGAs allow for real-time execution and genuine parallel processing of tasks. Consequently, different processes do not have to compete for the same resources, allowing each task to be programmed into a dedicated section of the chip to operate independently without interference from other logical blocks. This isolation ensures that the performance of individual application segments remains unaffected by the addition of more tasks. Additionally, FPGA architecture offers hardware-timed speed and high reliability [58].

Figure 4 depicts a generic structure consisting of FPGA components. FPGA devices consist of a limited number of I/O (Input/Output) blocks and logical blocks organized in a matrix structure. These blocks communicate with each other by programmable hardware-based connections [59].

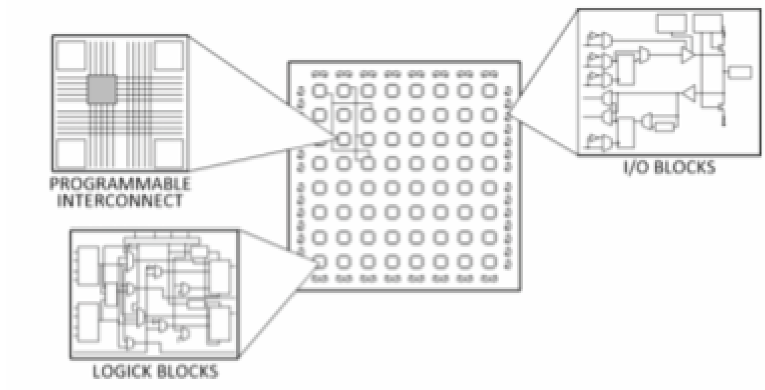


*Figure SEQ Figure * ARABIC 4 Structure of FPGA [58]*

Various programming languages and development platforms are utilized in FPGA programming to enhance design efficiency and implementation. Among the primary hardware description languages (HDLs) used are VHDL, Verilog, High-Level Synthesis (HLS) and SystemVerilog, which allow for the detailed specification of digital circuit behavior and structure at multiple levels of abstraction. Verilog, in particular, has been extensively employed in FPGA programming, as demonstrated in generating Pulse Width Modulation (PWM) signals and implementing reversible logic gate-based Arithmetic Logic Units (ALUs) [60].

These HDLs are supported by various development platforms and software tools that facilitate the design, simulation, synthesis, and implementation of FPGA-based systems, including Xilinx ISE Design Suite, LabVIEW FPGA, Matlab/Simulink, Intel Quartus Prime and so on. These platforms and tools enable the development of complex FPGA-based systems, leveraging the full potential of FPGAs in various applications, including digital signal processing, embedded systems, and communications [61, 62].

3.2. Impacts of FPGA on Inverters

Field Programmable Gate Arrays (FPGAs) have significantly impacted the design and operation of inverters, particularly in the context of high-performance and high-efficiency applications. Their reconfigurable nature and parallel processing capabilities make them ideal for implementing complex control algorithms and handling the high switching frequencies required in modern inverter designs.

One of the primary advantages of FPGAs is their ability to implement intricate control algorithms that operate at high frequencies. This capability is crucial for applications such as motor drives and power converters, where precision and speed are paramount. The reference [63] which implements a vector control algorithm for a 200 kHz GaN-based motor drive system using an FPGA, is a good example to demonstrate achieving a level of precise control unattainable with traditional microcontroller units (MCUs). The reconfigurability of FPGAs also allows for the easy modification and upgrading of control algorithms without the need to change the hardware, providing a flexible solution for evolving application needs.

Another significant advantage of FPGAs is their parallel processing capabilities [64]. FPGAs can handle multiple tasks simultaneously, thanks to their parallel architecture. This feature is particularly beneficial in inverter applications where real-time processing of multiple signals is required. Additionally, the ability of FPGAs to support high switching frequencies improves the efficiency and performance of inverters. GaN-based inverters, in particular, benefit from the high switching frequencies that FPGAs can achieve, leading to enhanced performance in power electronics systems [65].

However, the use of FPGAs is not without its challenges. Designing and programming FPGAs can be complex and requires specialized knowledge of hardware description languages (HDLs) like VHDL or Verilog. This complexity can increase development time and cost compared to traditional microcontroller-based designs. Furthermore, the initial cost of FPGAs is generally higher than that of microcontrollers or digital signal processors (DSPs). While this cost can be offset by the performance benefits and flexibility that FPGAs provide, it remains a consideration for many applications. Additionally, FPGAs can consume more power compared to some optimized microcontroller-based solutions, particularly in applications that do not fully exploit their parallel processing capabilities.

3.3. State of Art of FPGA controlled Inverters

Current research has demonstrated the successful implementation of FPGAs in various inverter, renewable energy systems and motor drive applications.

In the literature, the paper [66] introduced an FPGA-based method for speed control using Field-Oriented Control (FOC). Their work incorporates a Sliding Mode Observer (SMO) design with a sensorless FOC and a phase-locked loop. The NIOS II processor was used to generate speed information, while all other topologies were implemented on the FPGA. The results indicate that their approach smooths the back-emf graphics during the transition from stop to acceleration. Similarly, the research analyzed FPGA-based control for 3-phase BLDC motors, highlighting its superiority in power and safety compared to microcontroller-based control, due to the flexibility of FPGA designs [67]. However, microcontroller-based control offers faster development and lower costs, making it a preferable choice depending on specific system requirements.

The integration of FPGA-based control systems with GaN-based inverters addresses several critical challenges in modern power electronics, enhancing efficiency, compactness, and response times. The paper [64] highlights the importance of fast response in their 9-level FCML inverter, achieved through an FPGA-based control system. The FPGA enables extremely high effective switching frequencies (up to 4 MHz) and precise modulation schemes, resulting in a peak efficiency above 99.0%. The study [68] expands on this by implementing a 13-level FCML inverter using low-voltage GaN FETs (Figure 5). The FPGA's role in this design is pivotal, allowing for the reduction of commutation loop inductance and supporting a high switching frequency of 120 kHz, which minimizes the size of passive components and achieves a low total harmonic distortion (THD) of 0.7%. Designed inverter is depicted in the figure below. Furthermore, the paper [69] demonstrates how FPGA-based control can generate high-frequency PWM signals essential for the dynamic performance of GaN power devices. This capability ensures precise control and high-speed switching, which are crucial for the optimal performance of GaN-based inverters.

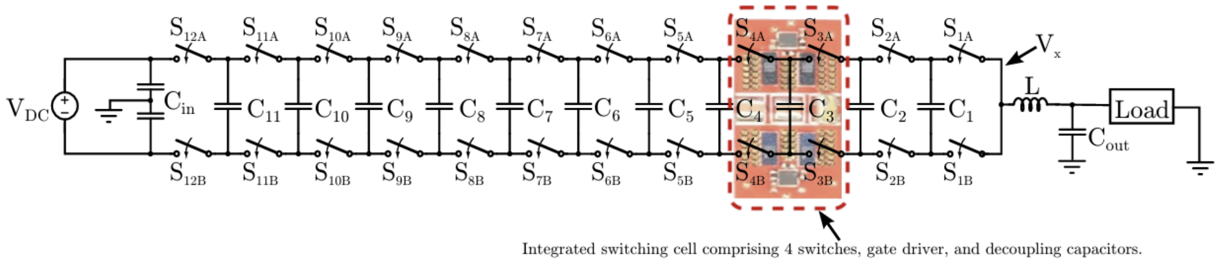


Figure 5 Inverter schematic [68]

The study [63] achieved notable improvements by implementing a vector control algorithm for a GaN-based motor drive system on an FPGA platform. The key objective was to leverage GaN devices' high switching frequency capabilities, attaining a 200 kHz switching frequency. This advancement significantly enhanced power density and reduced switching losses. The technical implementation involved the Xilinx ZYNQ-7000 controller, which integrated motor vector control algorithms into the FPGA, facilitating high-speed, precise control. Experimental validation demonstrated the system's capability to achieve precise single-cycle control of the motor at high switching frequencies, highlighting the algorithm's efficiency and reliability.

Similarly, the study [70] focused on applying a Field-Oriented Control (FOC) algorithm to an FPGA-controlled GaN-based 3-phase induction motor. The primary objective was to leverage the

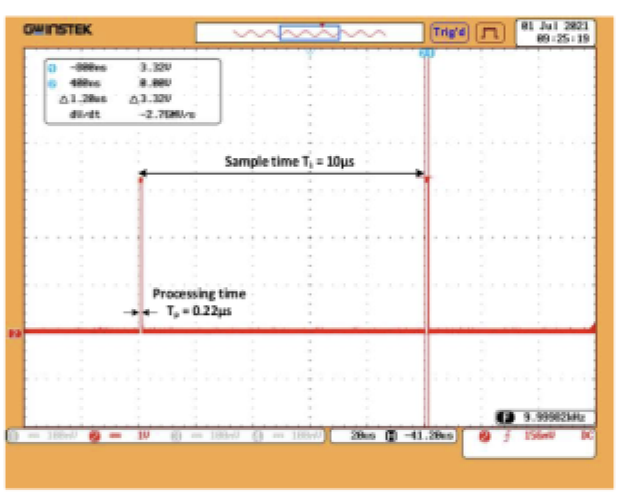


Figure 6 Processing time [70]

benefits of GaN technology, enabling higher switching frequencies up to 100 kHz, compared to the typical 2-20 kHz range of conventional IGBT transistors. The control system was rigorously implemented using VHDL on a Xilinx Zybo Z7010 FPGA board, leading to a decrease in switching losses and an improvement in power density. Figure 7 illustrates the schematic for

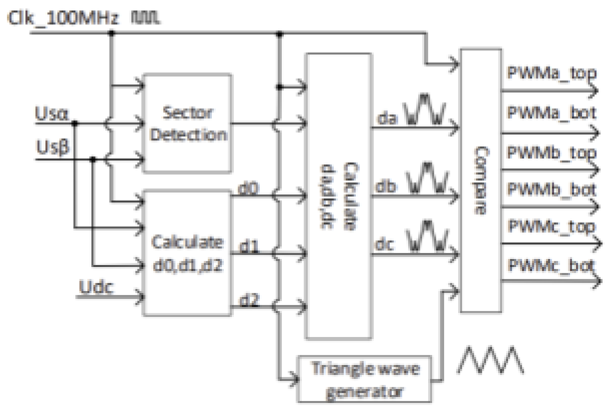
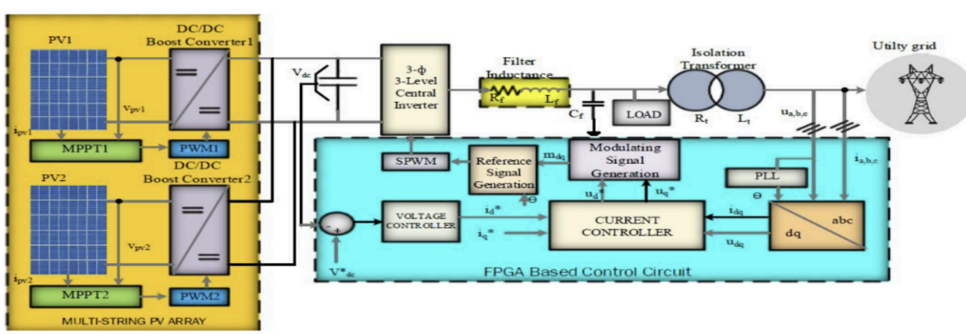


Figure 7 Implementation of SVPWM in FPGA [70]

implementing SVPWM in an FPGA. The study confirmed the validity of the approach by conducting hardware-in-the-loop (HIL) simulations, which showcased the system's efficiency in functioning effectively at high frequencies. As can be seen from figure 6, the processing time of FPGA is 0.22 muS, which is calculated by setting the flag at beginning & end points of computation cycle. It is quite fast for the systems with higher switching frequencies.

The study [71] examines the efficiency of a FPGA controlled real-time implementation of a 3-phase 3-level VSI. This inverter is designed for integrating multi-string Photovoltaic (PV)



arrays into the power grid, as depicted in Figure 8. The objective of the study was to enable efficient DC to AC conversion for grid connection while maintaining system reliability and performance under various conditions. The system included a centralized multilevel inverter, Maximum Power Point Tracking (MPPT) for each PV string, and a decoupled current controller for grid synchronization. Virtex-6 ML605 Evaluation Kit with Xilinx System Generator was used for control algorithm implementation, enabling precise control and high-speed processing.

Simulations and hardware co-simulations validated the system's effectiveness, showing it maintained grid frequency at 50 Hz with a Total Harmonic Distortion (THD) of less than 2.5%.

Figure 8 Proposed system structure [71]

In addition to GaN-based inverters, numerous papers have analyzed the use of FPGA controllers and their impact on SiC-based inverters. The paper [72] aimed to enhance computational speed and control accuracy by designing and implementing a model predictive controller (MPC) on an FPGA for a SiC-based Inverters (qZSI). The FPGA's parallel processing capabilities allowed for a significantly reduced computation time, achieving a sampling time of just 1 µs. This enabled the system to handle high switching frequencies, which are characteristic of SiC devices. The proposed MPC algorithm was tested both in simulation using MATLAB Simulink and experimentally validated with a three-phase SiC-based qZSI, which is shown in Figure 9, demonstrating stable control with minimal output current ripple. The study highlighted the effectiveness of FPGAs in providing high-speed, precise control for SiC-based power converters, emphasizing their role in improving dynamic performance and computational efficiency.

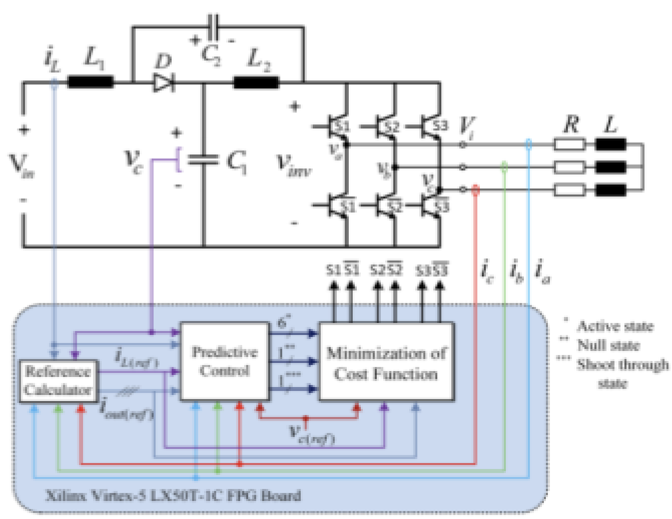


Figure 9 Structure of FPGA controlled SiC based qZSI [72]

In another paper [73], a CHIL testbed was developed to validate both low-level and advanced inverter controls (Figure 10) for a SiC-based PV string inverter. The primary objective was to create a cost-effective and precise method for testing fast-switching inverter controls without the risk of hardware damage. The testbed utilized an FPGA real-time simulator, specifically the Opal-RT OP5607 FPGA expansion unit, enabling simulations at a high switching frequency of 20 kHz with a time step of 500 ns. The results showed that the CHIL testbed accurately mirrored experimental setups, with the peak inverter efficiency reaching about 99%, closely matching the experimental efficiency of 98.2%. This study demonstrates the significant advantages of using FPGAs for high-speed, precise control in power electronics, validating the CHIL approach as an effective tool for developing and testing complex inverter controls.

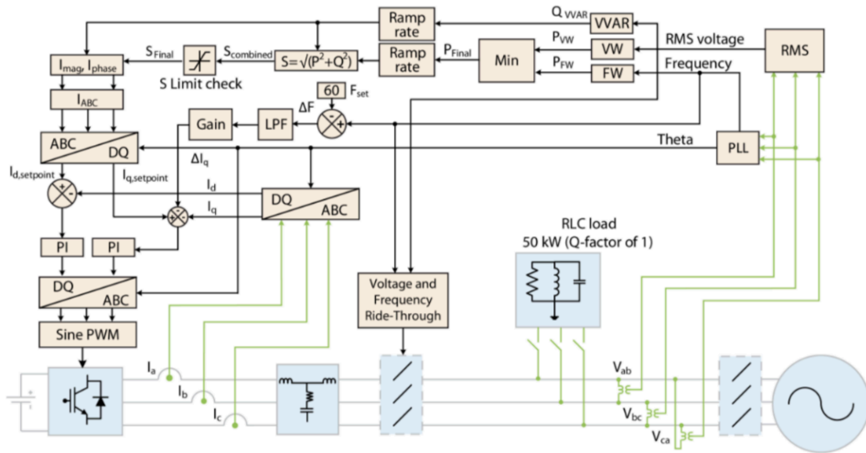


Figure 10 Diagram of Inverter Control [73]

Besides GaN and SiC-based inverters, a number of papers have thoroughly analyzed the implementation of FPGA and its impact on Si IGBT-based inverters [74-76]. The paper [74] presents a control structure for voltage and frequency regulation of VSI using the ADALINE-FLL -Adaptive Linear Neuron (ADALINE) with Frequency Locked Loop (FLL). The objective was to ensure stable operation and efficient power control for both standalone and grid-connected systems. The FPGA implementation was chosen due to its ability to handle high-speed computations and real-time signal processing. The FPGA's flexibility and reprogrammability were crucial for integrating the ADALINE-FLL structure, allowing accurate harmonic decomposition and synchronization, significantly improving the VSI's performance under various operating conditions.

Moreover, another paper [75] analyzed a full control system for a grid-connected current-controlled VSI on an FPGA (Figure 11). The main focus was phase tracking (phase-locked loop (PLL)), inverter logic control, and managing active and reactive power flows. The control system utilized a compactRIO module with VHDL-generated code from LabView G-code, enabling high-speed burst logging and fault detection. The practical viability was demonstrated in a 30-kW experimental setup connected to the local grid, where the system maintained unity power factor and handled step responses in active power flow effectively. The FPGA's capabilities were utilized to achieve precise control and stability, demonstrating its superiority over traditional microprocessor-based systems in terms of speed and flexibility.

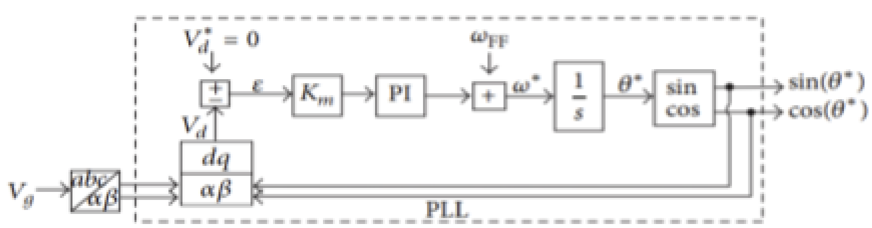


Figure 11 Block diagram of PLL for grid-phase tracking [75]

CONCLUSION

This literature review underscores the significant advancements and potential of FPGA-controlled GaN-based inverters in modern power electronics. GaN technology offers substantial improvements in efficiency, high-frequency operation, and thermal management, making it a preferred choice for high-performance applications. The use of FPGAs as controllers enhances these benefits by providing precise, high-speed switching and flexible, reconfigurable control, essential for optimizing the performance of GaN-based inverters. Despite the challenges associated with thermal conductivity, cost, and implementation complexity, the combination of GaN and FPGA technologies represents a major step forward in power electronics. These advancements are particularly impactful in renewable energy systems, electric vehicles, and industrial motor drives, where efficiency, reliability, and performance are paramount.

Integrating FPGA technology with GaN-based inverters has been proven to significantly improve control precision, system efficiency, and adaptability. Studies have demonstrated that FPGA-based controllers can handle the high switching frequencies required by GaN devices, leading to reduced switching losses and improved overall performance. This review highlights the importance of continuing research in this field to address the remaining challenges, such as optimizing thermal management and reducing costs. The future of power electronics is promising with the ongoing development and implementation of FPGA-controlled GaN-based inverters, which hold the potential to revolutionize various high-demand applications through enhanced efficiency and reliability.

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