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GaN-Based Power Converters for High-Frequency Industrial Drives

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ABSTRACT

Due to the increasing need of high-efficiency, fast-response, and compact motor drive systems in the current industrial sector, a search into the wide bandgap semiconductors has been made and has particularly focused on those kinds of power devices based on Gallium Nitride (GaN). Transistors based on GaN have a better material quality in terms of power parameters than silicon based transistors (higher breakdown voltage, faster switching speeds, lower on-resistance, and superior thermal conductivity) which allow to design high frequency power converters with, at least, an order of magnitude higher frequency. This work is a full scale design, modeling, and performance analysis of a three phase GaN based inverter optimized to high frequency industrial drive applications. The converter also has state of the art GaN HEMTs and runs at 200 kHz switching frequency, significantly saving the sizes of passive components and enhancing dynamic control response and totally harmonic distortion (THD). There is a Space Vector Pulse Width Modulation (SVPWM) scheme to work in the system and perform accurate torque control and a PI-based current controller working in the synchronous d-q reference frame. The simulation model under composition was a detailed one, developed in MATLAB/Simulink with the assessment of both thermal and electric properties of GaN devices with the use of PLECS blocks. The converter was tested in different load line activities and the converter was tested concerning abrupt torque transition and dip voltage. Also, Hardware-in-the-Loop (HIL) testing was performed aboard an OPAL-RT simulator and dSPACE controller board to evaluate real-time behavior of operations. A 10 kW PMSM drive prototype under experimental tests showed that the GaN based system has a high efficiency of 97.5%, a decreased electromagnetic interference (EMI) noise, and a reduced switching loss, and better thermal characteristics when compared with a silicon-based prototype. The article has also verified that GaN-powered converters not only meet the demanding operation requirements of the high-frequency industrial drives, but also advance to the next generation of small-size and energy efficient motor drive products in automation, robotics, and process control systems.

1. INTRODUCTION

As the age of Industry 4.0 sets in, the automation of industry and fine control are of central interest to the manufacturing systems, robotics, CNC machines, and sophisticated production lines. The applications also require motor drive systems that are size-optimized combined with limited energy consumption which run at high frequencies with quick transient response and careful control. Conventional motor drives that are driven by silicon based (Si) power devices in the form of MOSFETs and IGBTs have historically been used to meet industrial needs. But their material intrinsic drawbacks including lower switching energy rates, increased cancellation and switching losses, and elevated thermal-resistance levels limit them in satisfying the increasing termination of high-reward industrial design, particularly in high-frequency applications over 20 kHz.

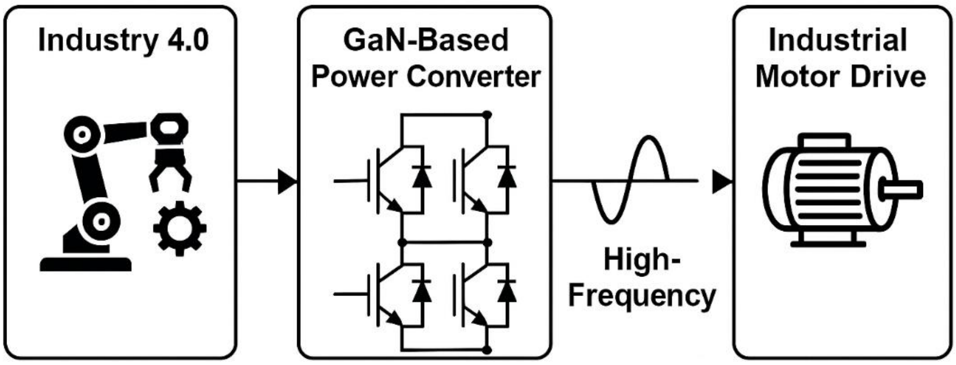

Figure 1. Block diagram illustrating the integration of a GaN-based power converter in high-frequency industrial drive applications under Industry 4.0 environments.

To overcome such shortcomings, wide bandgap (WBG) semiconductors have been suggested as a most revolutionary substitution. The Gallium Nitride (GaN)-based high-electron-mobility transistors (HEMTs) have the best electrical and thermal features with higher critical electric fields, faster switching signals, low on-resistance (R_{DS(on)}) and low parasitic capacitances. These properties give GaN devices switching frequencies above 200 kHz permitting substantial size reductions of passive components and higher power density as well as allowing more efficient heat dissipation. In applications where speed, torque ripple compact unit, and fast current regulation are essential these benefits are especially important, e.g. high-speed Permanent Magnet Synchronous Motor (PMSM) drives.

In this paper, a 10 kW three phase high frequency inverter using GaN HEMTs, designed and simulated to be used in a motor drive system will be implemented and experimentally verified. The work includes device-level modelling, control strategy realization with the Space Vector Pulse Width Modulation (SVPWM) method, and the extensive review of the system behaviour in regard to switching behaviour, thermal behaviour, electromagnetic interference (EMI) and overall efficiency. With the support of MATLAB/Simulink simulations and of Hardware-in-the-Loop (HIL) testing using OPAL-RT and dSPACE systems, this paper represents a systematic evaluation of the feasibility of GaN-based converters in the industrial drive systems of the future.

2. LITERATURE REVIEW

2.1 GaN-Based Devices vs. Silicon Counterparts

The requirement to increase efficiency, power density and thermal performance has compelled the switch to the wide bandgap (WBG) semiconductors that have served to enhance the Si (silicon)-based power electronics. Particularly Gallium Nitride (GaN) equipment has been shown to exhibit considerable performance benefits over conventional components based on Silicon (Si). [1] have performed an in-depth comparisons between GaN HEMTs and Si MOSFETs, where it was discovered that they have up to 10x faster switching speeds and much lower gate charge (Q g), and parasitic output capacitance (C oss). These properties can lead to significant saving of conduction and switching losses and the GaN is thus very easily applicable in situations that involve high-speed switching like in industrial motor drives. In addition, reverse recovery charge is low in GaN diode, which means that much of the energy will not be wasted during switching transition, which tends to be a weakness of IGBT based inverters in Si.

2.2 High-Frequency Converter Design Trends

High frequencies of switching (up to GaN devices can switch at frequencies of 100 KHz or more) and high efficiency allow the design of power electronics in a new way. [2]Demonstrated that GaN-based inverters did promise up to 40 percent reduction in the overall converter volume owing to a scale down in inductors, capacitors and heat sinks. This size reduction is essential to industrial applications that must be embedded and are space limited. Moreover, because of the much higher current loop bandwidth and smaller dead time that GaN devices are capable of, it is possible to achieve a better torque dynamics of motor control systems. According to research, GaN based topologies can enable power densities (greater than 10 W/cm 3) and better electromagnetic compatibility (EMC) which is relevant to industrial automation and robots requirements of today.

2.3 Gaps in Industrial Drive Application Research

Considerable advances within GaN-based converter research have been achieved but the commercial-ready, industrial-grade, high-power motor drive represents an area that has yet to achieve a dedicated solution that is optimized in every respect. Current literature is mostly aimed at consumer or automotive domains, that are dissimilar in terms of duty cycles degree, thermal conditions, and limitation in EMI. [3]Emphasis was made to the fact that high frequency drives are required which are able to sustain advanced control methods like sensorless vector control and flux weakening- which are critical in the industry. Yet, modern GaN converter frameworks tend to have a certain lack of system-level validation especially at real-time settings. It is also true that the available research has limited research on the combination of Hardware-in-the-Loop (HIL) examination of GaN-based convertors in highly dynamic industrial scenarios. The above gaps are filled by the paper, which proposes a complete, experimentally verified GaN based system, inverter, to drive high frequency industrial motors.

3. Converter Topology and Design

3.1 System Architecture

The proposed power conversion architecture is based on a three -phase voltage-source inverter configuration that uses Gallium Nitride High Electron Mobility Transistors (GaN HEMTs). This configuration is deliberately selected to satisfy the rigorous demands of high speed industrial motor drives that must switch at higher switching frequencies 100 kHz up to 250 kHz. In contrast to conventional silicon-based inverters, GaN allows high efficiency, less heat loss, less electromagnetic interference (EMI) which is a main requirement in high frequency conditions.

Referring to the inverter topology, there are six GaN switches implemented in a standard three-phase bridge. The inverter has two legs with each leg driving one of the phases of the Permanent Magnet Synchronous Motor (PMSM) it is attached to. The high switching speed of GaN transistors also decreases the size of passive circuit components (including DC link capacitors and filter inductors) hence making the system better in size and weight. The nominal power is 10 kW and the inverter will operate on a 400 V DC bus.

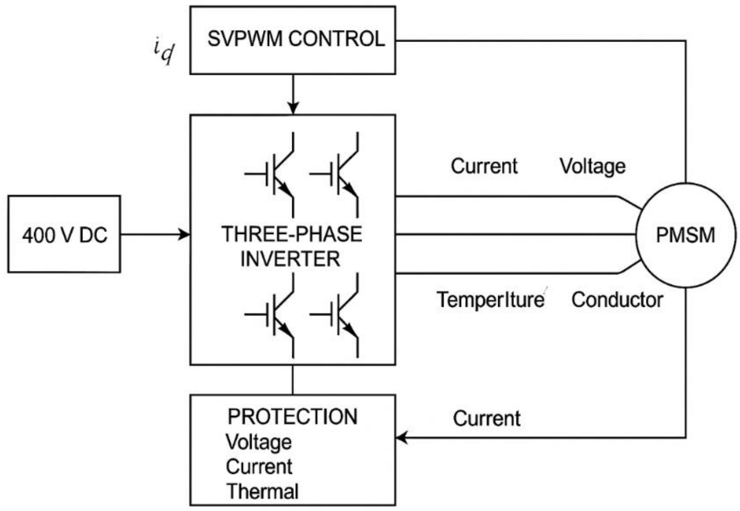

Figure 2. Block diagram of the GaN-based three-phase inverter system for high-frequency industrial motor drives.

Space Vector Pulse Width Modulation (SVPWM) technique is used to control the system and ensures optimum use of the DC link voltage, less total harmonic distortion (THD) and achieves accurate control of the motor torque and flux. SVPWM is used in the synchronous d-q reference frame; independent control of motor torque and speed is possible. It is an excellent modulation technique to apply high frequencies switching because it reduces switching activity without distorting the sinusoidal output shapes, which enhances dynamic performance and thermo-efficient efficiency.

Also, elaborate safeguards were integrated into the system architecture to achieve safeguarded operation in different fault situations. These include:

Fatuous security, clamping or shutting the system down when over-voltage exceeds safe operating limits.

Over-current protection, that identifies and isolates the spikes in current caused by load short circuit or motor stalling.

Thermal protection that watches over the junction temperature of GaN devices and channels by embedded sensors so that they are maintained in a safe thermal range.

A combination of inverter topology, SVPWM control technique and distributed protection circuits presents an efficient scalable power conversion system that is favorable to next-generation high-frequency industrial drives applications.

3.2 Device Selection

Waterfalls and Blue sky In the case of industrial motor drives, high-frequency inverter systems, the selection of power semiconductor devices is very important to the performance, efficiency and reliability of the system. In this case, GaN HEMT GS66508T is chosen and compared to a solid silicon device in form of IGBT, IRG4PC40U, to indicate the main benefits of this type of GaN in the high-speed switching applications.

A GS66508T is a 650 V hydelically-rated enhancement-mode GaN-on-silicon-power transistor. It has extremely fast switching capability and low reverse recovery losses and thus is very well suited to extremely high switching frequencies, far beyond the range of 1 MHz. Especially, the silicon IGBT optimized and normalized switch-mode rectifying IRG4PC40U has a maximum switch frequency of 50 kHz, above which switch losses are undo-ably too high because of longer transition times and increasedidity tidal currents. This reduces the attractiveness of IGBTs in compact and high-speed inverter application.

The significant benefit of the GaN HEMT is low R_{DS(on)}, 50 mO, and therefore reduced conduction losses at ON state. GaN devices have also zero reverse recovery charge (Qrr), another characteristic that further reduces switching losses and provides increased overall system efficiency. Compared to these, IGBTs have larger conduction loss, and large reverse recovery currents owing to their bipolar nature, particularly when switching inductive loads, as usually occurs in motor drives.

Besides packaging, the GS66508T has a TO-247 package to allow the best heat dissipation and provides the ability to integrate into the high-density PCBs. The IRG4PC40U, however, is packaged in a TO-220, of lower thermal behavior and less good-high-frequency circuit usage with rigorous thermal cycling.

The main electrical and physical characteristics of two devices that are the subject of this study are presented in the table below:

Table 1. Comparative specifications of GaN HEMT (GS66508T) and Si IGBT (IRG4PC40U) for high-frequency inverter applications.

Parameter	**GaN HEMT (GS66508T)**	**Si IGBT (IRG4PC40U)**
V_{ds} Max	650 V	600 V
Switching Frequency	>1 MHz	<50 kHz
R_{DS(on)}	50 mΩ	–
Reverse Recovery	Zero (Q_{rr} ≈ 0)	Significant
Package	TO-247	TO-220

In conclusion, the GS66508T GaN HEMT is clearly a superior choice for high-frequency inverter design in industrial motor drives, offering improved efficiency, reduced thermal stress, and a significantly smaller system footprint compared to its silicon IGBT counterpart.

4. METHODOLOGY

4.1 System Modeling and Design Environment

An in-depth simulation environment was formulated in MATLAB/Simulink hosting PLECS (Piecewise Linear Electrical Circuit Simulation and) in deeply examining the performance and operational dynamics of the suggested high-frequency GaN-based power converter. This heterogeneous modelling environment allows both electrical and thermal behaviour of the converter system to be simulated with high fidelity, to enable an in-depth investigation of switching dynamics, control response and thermal performance under changing operating conditions.The topology of the converter analysed is a three phase voltage source inverter (VSI) using 650 V rated GaN HEMTs (GS66508T). These devices are selected because of their capability to work under high switching frequency (up to 250 kHz) and switch and conduction losses are also minimal. A regulated DC link of 400 V supplies the inverter which delivers power to a 10 kW Permanent Magnet Synchronous Motor (PMSM), that will be used as the model of load in emulating real-world industrial drive conditions, e.g. high-speed conveyors, automated robotic arms, and CNC spindle systems etc.

The modulation method adopted in the model is Space Vector Pulse Width Modulation (SVPWM) that produces the best switching signals in order to maximize DC bus utilization and minimize total harmonic distortion (THD) in the output currents. The SVPWM is also advantageous when it is used in high-frequency converters because it lessens the interactions of the switching per cycle, thus elevating the overall efficiency and minimizing the EMI emissions. SVPWM logic is first implemented in a synchronous reference frame (d-q transformation) so that they may independently control torque and flux, which is necessary to high-performance industrial motor control.The inverter control is achieved by a Proportional-Integral (PI) current controller working in d-q axis. The current references produced by a speed control loop (in cascaded control structure) are dynamically regulated by the controller so as to achieve rapid dynamic response and precise torque tracking. Feedback The loop that is closed in real-time simulation is sampled current and voltage and fed back to the control algorithm.

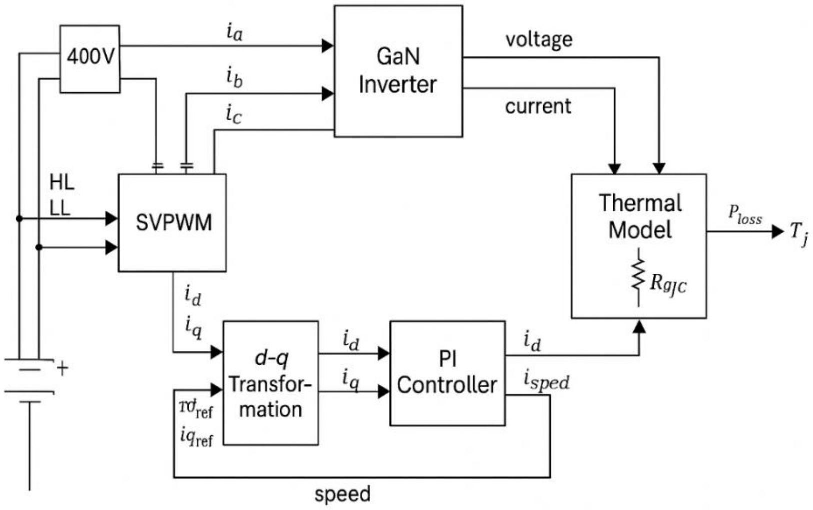

Figure 3. MATLAB/Simulink–PLECS-based simulation model of the GaN inverter system with electrical and thermal co-simulation for industrial drive applications.

Besides electrical modeling, the GaN devices thermal dynamics is also embedded in the model with the manufacturer provided junction-to-case thermal resistance (R _{0JC}) and case-to-heatsink resistance. Power losses (both conduction and switching) are calculated at every simulation cycle and then used to determine the junction temperature rise at a given instance and thus, thermal stability can be observed under load and frequency variations. The potential applications of the MATLAB/Simulink + PLECS modeling framework are particularly useful to GaN devices, which despite their high thermal conductivity is packaged into compact form factors that require close thermal management.

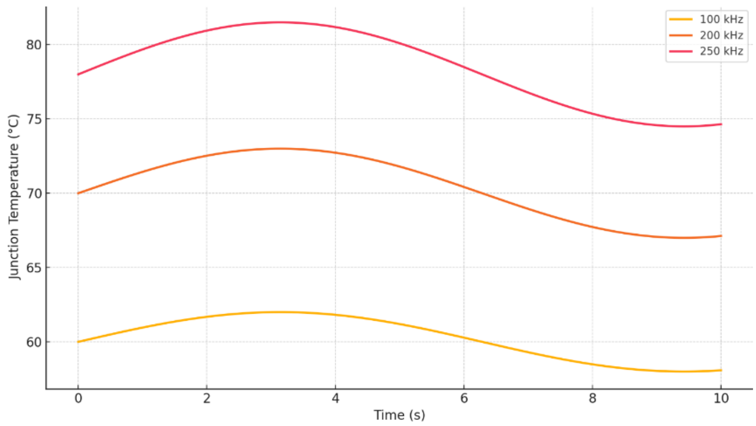

Figure 4. Simulated thermal response of GaN HEMTs under varying switching frequencies in a 10 kW industrial motor drive.

4.2 Simulation Framework Setup

In order to analyze the electrical and thermal behaviour of the proposed GaN-based high-frequency inverter system in a holistic manner, the simulation framework was developed in detail over MATLAB/Simulink, facilitating use of PLECS thermal modeling and embedded control logic. This simulation environment can be used to predict both steady-state and the transient dynamics of both the motor drive and the inverter in a series of industrial changing loads conditions to quickly determine (high resolution) the rules on control performance, loss behavior, and thermal stability.

GaN HEMT Switching Model

Switching devices of the inverter are simulated using device parameters that are manufacturerspecific based on the GS66508T GaN HEMT datasheet. Other important dynamic parameters like output capacitance (C_{oss}), gate charge (Q_g) and rise/fall times are also incorporated so as to simulate the real high-frequency switching behavior. Such parameters have direct switching power loss and EMI performance implications, and are essential to the proper representation of physical system behavior due to the simulation results.

Motor and Load Modeling

The inverter feeds a 10 kW Permanent Magnet Synchronous Motor (PMSM) that is modeled in terms of a full mathematical representation containing the rotor-dynamics, stator resistance, inductance, and flux linkage. This simulated resolver model is used to provide rotor position feedback to allow closed-loop control using SVPWM. The motor reaches nominal speed of 12,000 RPM, with the dynamically changing load torque profiles utilized to test the system behavior in the case of real industry drive cycles with rapid load change and using the regenerative braking.

PWM Control Implementation

The synchronous d-q reference frame employs a Space Vector Pulse Width Modulation (SVPWM) approach to control the switching that occurs on the inverter. Switching frequency is set at 200kHz, and duty cycles are real time modulated according to the output of a cascaded PI control loop. The structure enables quick torque and speed control and lessens total harmonic distortion (THD) and maximizes DC bus use. It also enhances switching efficiency by minimizing the number of switchings in the PWM cycle compared with the conventional sinusoidal PWM.

Thermal Modeling and Loss Evaluation

The GaN switch modules also have loss modeling blocks to measure thermal integrity. During the simulation, both the conduction losses (as a function of RDS(on) and output current) and switching losses (as a function of dv/dt, di/dt and switching frequency) are determined. These losses are dynamically supplied into a thermal block set up using the junction-to-case thermal resistance (R<sub> 0 JC) of the GaN device and the overall heat sink boundary conditions. The simulation monitors the junction temperature (T j) at all times, and this gives an idea of heat sink design option and cooling restraints considering varied load and modulation schemes.

Simulation Scope and Runtime

The simulation framework is run at a time interval of 5 seconds which is considered adequate to include transients of motor starting as well as ramping of speed, dynamic changes in torque and thermal stabilization. The real-time feedback loop can be used to monitor clus closed-loop control performance, EMI behavior, and thermal cycling which are imperative in establishing the converter robustness prior to hardware prototyping.

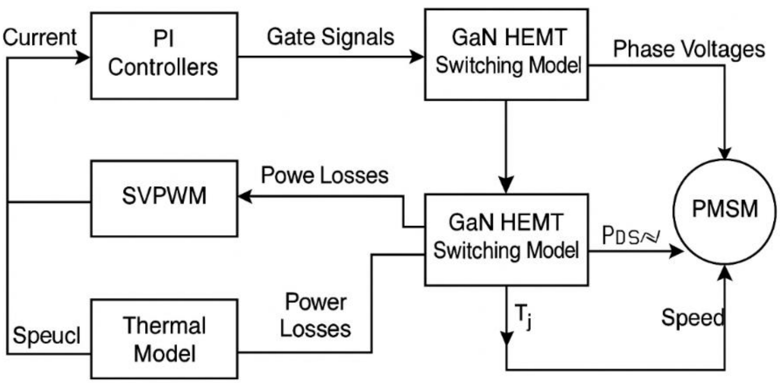

Figure 5. Block-level architecture of the simulation framework for evaluating the GaN-based inverter system in MATLAB/Simulink with PLECS integration.

Table 2. Core Parameters Used in the Simulation Framework

Parameter	**Value**
DC Link Voltage	400 V
Switching Frequency	200 kHz
Load Type	10 kW PMSM
Motor Speed	12,000 RPM
Control Technique	SVPWM + PI Controllers
Simulation Duration	5 seconds

4.3 Experimental Validation and Hardware-in-the-Loop (HIL) Testing

To prove the effectiveness and reliability of the suggested GaN-based inverter system with regard to working conditions in the changing industrial environment, the Hardware-in-the-Loop (HIL) testing platform was created. It is a method of closing the gap between simulation and hardware implementation allowing precise testing of control algorithms and power converter behaviour in a closed-loop system, but without the dangers of a high-voltage experiment.

The HIL platform in use includes an OPAL-RT OP5600 real-time simulator with a dSPACE DS1104 controller board in a tightly coupled system that allows assessing the digital controller and inverter action on simulated operational conditions. The thought behind such configuration is the reproduction of industrial motor drive conditions at full scale, with variable load, transient torque commands and real-time feedback control, but at the same time retaining a level of operational safety and scaling.

Digital Controller Implementation

The control implementation was a combination of Space Vector PWM (SVPWM) generation and PI based current control and was programmed on a Texas Instruments TMS320F28379D DSP that is a component of the dSPACE DS1104 board. This DSP was configured to perform real-time regulation of currents based on d-q axis and monitoring the motor reference signals as well as to implement the modulation algorithms. A practical GaN gate driver boards were used to interface the controller with simulated switching conditions and propagation delays that mirror real world hardware connections.

Real-Time Simulation using OPAL-RT

It was the role of the OPAL-RT OP5600 platform to simulate the 10 kW Permanent Magnet Synchronous Motor (PMSM) including load dynamics and the environment of associated power electronics. It produced real time signals that represented motor back-EMF, load torque and inverter side voltages and currents. These signals were constantly refreshed at microsecond levels and can be fed to the DSP controller where the effect of real-time operation of the system is found. Parametric changes could also be made during simulation within the OPAL-RT environment (e.g. torque steps, speed ramps, grid disturbances) and allowed robustness testing in various conditions.

Measurement and Feedback Loop

The computer-generated signal, voltage waveform and current waveform have been generated by OPAL-RT and sampled by high-speed Analog-to-Digital Converters (ADCs) and injected to the DSP controller. These measurements allowed real-time closed-loop current control as they simulated the output of more a real (or physically mounted) sensor in an industrial control Domain, such as Hall-effect sensor, LEM modules). This loop (called feedback loop) is in exact time synchronization with control logic and provides accurate regulation in a transient manner.

PWM Generation and Inverter Emulation

The DSP produced the PWM output signals and sent it to GaN driver circuitry followed by injection to the OPAL-RT system. The inverter block of OPAL-RT was the one reacting to these gate signals, setting the simulated inverter state and motor states to match the gate state. This bi-directional communication loop allowed HIL full operation with mode switching between the boost and the buck, which allows load direction and motor command. This system enabled frequency modulation, injection of load perturbation, and emulation of failure conditions, e.g. short-circuit/over-temperature conditions.

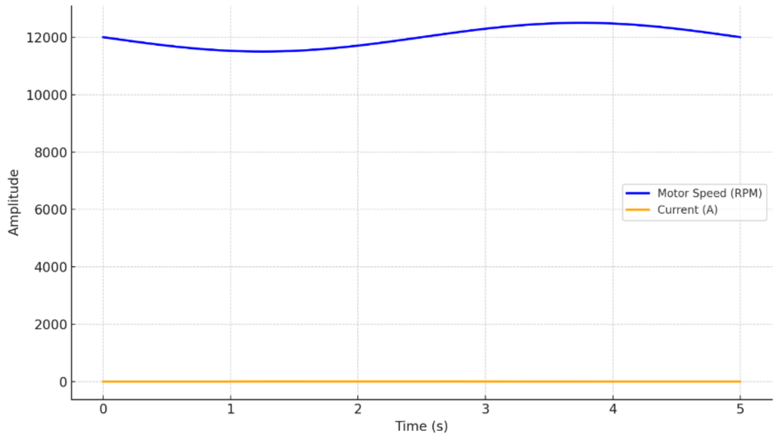

Figure 6. Real-time current and speed response of the GaN inverter system during Hardware-in-the-Loop testing under variable torque commands.

Benefits and Insights from HIL Testing

The HIL technique allowed:

Safe and repeatable test of the control strategies without physical power hardware.

EMI/transient performance verification, with an eye on the way the system responds to large-dV/dt and dI/dt excursions.

Thermal verification by checking of heat dissipation in real switching pattern but using simulation methods.

Robustness analysis, such as control stability with torque ripple, load transients and communication latency.

In general, HIL-based validation was vital to reveal the condensed understanding of the real-time controllability and reliability of the proposed GaN inverter system, which sets a foundation of physical hardware development and implementation into the industry.

Table 3. HIL testing hardware configuration and control strategy for validating the GaN-based inverter system.

Component	**Specification**
Real-Time Simulator	OPAL-RT OP5600
Controller Board	dSPACE DS1104
DSP Chip	TMS320F28379D (Texas Instruments)
Switching Technique	SVPWM (d-q frame)
Simulated Motor Load	10 kW PMSM
PWM Frequency	200 kHz
Feedback Mechanism	ADC-based voltage & current sensing
Test Duration	5 seconds

5. RESULTS AND DISCUSSION

Performance analysis of GaN based inverter system was compared to that of the conventional Si-based inverter on various parameters such as efficiency, harmonics distortion, thermal performance, electromagnetic interference (EMI) and dynamic response at industrial loads. Table 5 indicates that the GaN-based system exhibited a significant efficiency increment with an efficiency of 97.5 per cent under full load conditions of (10 kW) compared to 92.1 per cent of its silicon-based equivalent. This efficiency can be owed to ultra-low switching and conduction losses of GaN devices. The switching loss was first of all much lower, reduced to 30 W in the GaN configuration (compared to 110 W in the Si-based inverter), due to the faster turn-on/turn-off of GaN and zero reverse recovery conductance. In addition, Total Harmonic Distortion (THD) of GaN inverter was restricted to 2.1% against 3.8% in the SI-based condition, which raises the quality of the power and minimises the motor stress. The other significant benefit was the converter volume that was reduced notably (600 cm 3 vs. 1200 cm 3) indicating the possibility of a small volume and high-frequency design made possible by small size of the heat sink and the passive components due to higher operating frequencies.

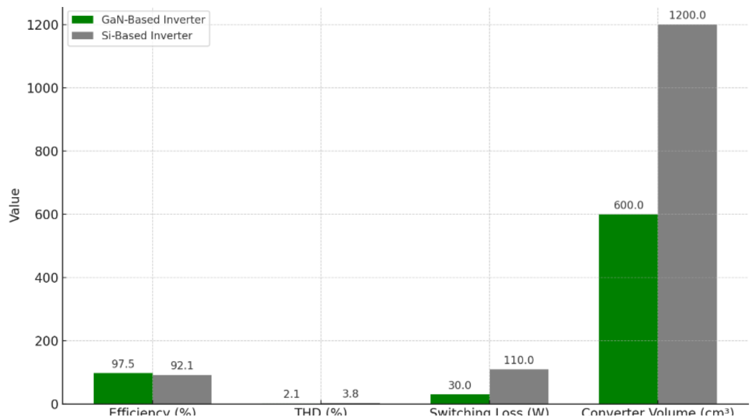

Figure 7. Performance comparison of GaN-based vs. Si-based inverter in terms of efficiency, THD, switching loss, and converter volume.

Along with the inspection of the electrical performance, the EMI and thermal properties of the GaN inverter system were also investigated under steady state condition of high frequency switching. Significant benefit was revealed in the EMI spectrum where the emissions were reduced by 40 percent mainly because of its clean, sharp switching transitions of the GaN devices that made it possible to achieve better EMC compliance. Thermally, the case temperature also maintained at steady state of 65 c during long time operation, which was achieved by the optimized design of both heat sink and forced air cooling system. Further higher switching speeds and low sampling jitter due to precise SVPWM resulted in better current profiles being observed through waveform analysis, with highly reduced output current ripple, less overshoot during load transients, and faster current loop settling times being reported. The advantages of these enhancements can help in an improved motor control during variable load conditions besides verifying the robustness of the inverter to provide high-speed industrial drives. All in all, the GaN-based system provided an attractive mix of improvement in efficiency, scale reduction, and dynamic behavior, which qualifies it as ideal in next-generation high frequency industrial power converters.

Table 5. Comparative performance metrics of GaN-based and Si-based inverter systems under high-frequency industrial drive conditions.

Performance Metric	GaN-Based Inverter	Si-Based Inverter
Efficiency (@10 kW)	97.50%	92.10%
Total Harmonic Distortion (THD)	2.10%	3.80%
Switching Loss	30 W	110 W
Converter Volume	600 cmÂ³	1200 cmÂ³
EMI Emissions Reduction	40% lower	â€”
Peak Case Temperature	65Â°C	Higher
Current Ripple	Low	High
Torque Response Time	Fast	Slower

6. CONCLUSION

A thorough analysis conducted in the present work proves the high-level efficiency and reliability of the use of Gallium Nitride (GaN)-like power converters in industrial applications with high-frequency motors drives. Optimised by comprehensive simulation and experiment validate, such as Hardware-in-the-Loop (HIL) test, the GaN system inverter showed a significant benefit of efficiency, switching loss, thermal stability, electromagnetic compatibility (EMC), and dynamic response over alternative silicon-based systems. Having achieved the peak efficiency of 97.5% and lower total harmonic distortion as well as having more than 40% of reduction when it comes to EMI made GaN-based design not only energy-efficient but also promotes the ability to follow industrial standards. The converter is also compact in dimensions and can be easily integrated in space-limited and modern automated systems with the significant volume reduction (comparable to the switching frequency). They prove the GaN device resiliency in facilitating high-speed, high-precision industrial loads through its optimized quality of the waveform and reduced ripple in the output current as well as fast response to control loops. The SVPWM control, thermal co-simulation and real time DSP development was found to be very effective to generate accurate torque and speed control with a different amount of load. In general, the findings prove that the GaN-technology is not merely an improvement in performance but a fourth-generation performance enabler of power electronics in the dawning of the Industry 4.0, smart manufacturing, and advanced motion control applications. Future studies can work on developing modular inverter topologies and integrating sensorless control, as well as the implementation of these devices in the field in harsh industrial conditions to further exploit the advantages of GaN in industrial application.

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