Next generation Electric Drive Units with multi-level GaN inverter for highest HV EV performance and efficiency

- Comparison of 2-level and 3-level inverter topologies -

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ABSTRACT: This paper discusses the importance of multi-level inverters in electrical drive applications, particularly for the automotive industry. Multi-level inverters offer benefits such as higher voltages, reduced harmonic losses, and improved NVH characteristics and EMC behavior. Gallium-Nitride-based (GaN) components are gaining traction over traditional silicon components due to their superior performance. hofer powertrain has developed a new 3-L GaN inverter, which has shown to improve e-motor efficiency by reducing losses in the WLTP drive cycle by 25%. This improvement translates into less cooling demand, increased performance, and an extended driving range. Additionally, the inverter reduces "Lautheit" by 25% and exhibits similar improvements in EMC behavior, which can be used to meet higher electric drive requirements or to reduce efforts in EMC filtering and NVH damping.

KEY WORDS: electric vehicle, power electronics, efficiency, powertrain, gan, inverter, wltp, voltages

1. INTRODUCTION

The advent of high power and high voltage applications in modern electrical drives has led to the increased demand for efficient inverter architectures and new technologies, also in the automotive industry. It becomes crucial for cost-effective and high-performance solutions. This chapter delves into the use of 3-L Gallium Nitride (GaN) inverters for automotive applications, emphasizing their ability to deliver superior power quality and efficiency compared to silicon-based technologies and 2-level inverter topology. The growing electrification of the automotive sector will further drive the demand for advanced power components, with GaN-based inverters set to play a pivotal role in enhancing the performance and sustainability of electric cars in the coming decades (1) (2).

2. MULTI-LEVEL INVERTER

2.1. The growing importance of multi-level inverters

Multi-level inverter is state-of-the-art today´s in electrical drive applications with high power and high voltages (e.g., electric power plants) or in applications which require a good quality of sinusoidal currents (e.g., photovoltaics inverter). With the trend of higher voltages and power demand in automotive electric drivetrains, these advantages become valuable for automotive main traction drives, too. The generated significant demand for power components, which comes with electrification of the automotive industry will continue its growth for the next decades. In parallel, the efficiency of battery energy usage is critical for the cost and performance of electric cars. Gallium-Nitride-based components, which are superior to competing technologies, are undermining the long reign of silicon in the power world.
Speaking of multi-level inverter, more sinusoidal currents (lower total harmonic distortion – THD) reduce harmonic losses in the e-motor, support the NVH characteristics of the electric drivetrain, improve the EMC behavior and therefore also reduce the stimulation of bearing currents. This reduced THD is generated by the additional voltage level of +/- UDC/2 in the output voltage to e-motor compared to 2-level type inverter.

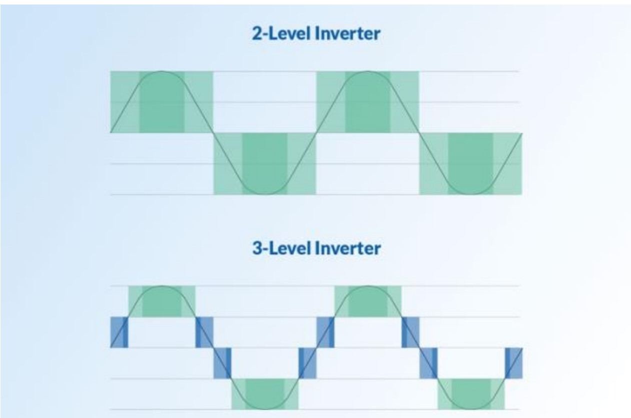

Fig. 1: Comparison of output voltage to the e-motor

All these effects are well known from the textbook. In the recent years hofer powertrain developed an IGBT based NPC 3-L inverter as part of a 3-in-1 system with an induction motor and a gearbox. Based on this electric drive system the different effects were investigated in great detail.

2.2. Improvement of the e-motor efficiency

Especially, the improvement of the e-motor efficiency is of high interest for the automotive industry, since this results in less cooling demand and increased performance as well as driving range. The investigations for a 170 kW induction motor carried out by hofer powertrain show that e-motor losses in WLTP drive cycle can be reduced by 25%. Such an outstanding improvement cannot be achieved by any other measure for efficiency improvement.

When looking at NVH characteristic, measurements on e-motor side showed that “Lautheit” can also be reduced by about 25%. In the same magnitude improvements of EMC behavior were observed. These “side effects” can either be used to reach a higher level of requirements for the electric drive or can be considered as a degree of freedom to reduce efforts within EMC filter of the inverter, NVH damping of the electric drivetrain or countermeasures on bearing currents.
Of course, this improvement comes at the cost of additional effort in the inverter. Due to the multi-level topology additional switches become necessary. hofer powertrain chose for the 3-level inverter the Neutral Point Clamping (NPC) topology to reduce the requirement of breakdown voltage for the power switches from 1200 V down to 650 V at a battery voltage of up to 950 V. Other additional effort needs to be considered for the DC link capacitor and the gate drive board.

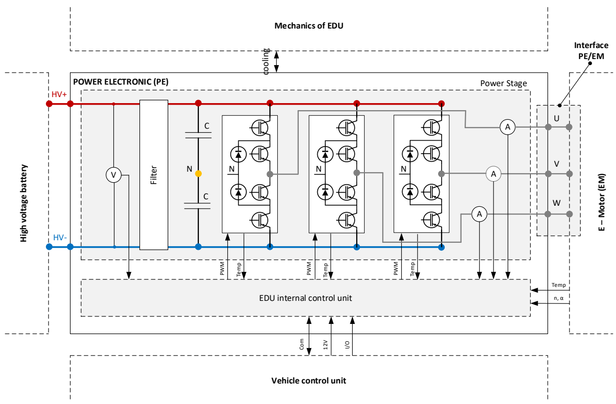

Fig. 2: Block diagram of NPC inverter

3. POWER MODULES

3.1. In-depth analysis of different power switches

Overall, this results in a minimal increase of inverter volume and more power switches in the power path. This demands a careful selection of these power switches. Today's automotive IGBT power modules with breakdown voltage of 650 V provide a good power to cost ratio but show a rather poor efficiency from automotive point of view, especially when combined in a 3-L inverter. In the end a reduction of the efficiency improvement gained by the e-motor on electric drive system level can be observed.

Another opportunity is a Silicon Carbide (SiC) based power switch or a hybrid solution out of IGBT and SiC switches and diodes. For such a configuration the efficiency of the inverter will be comparable to a state of the art 2-level type inverter based on SiC power switches for WLTP drive cycle. Main drawback for a SiC configuration is the high costs for the power switches regardless of the topology.

To find the best solution, hofer powertrain has been investigating the use of Gallium Nitrite power switches for the use in a 3-L inverter.

3.2. Benefits of Gallium Nitride (GaN) transistors

Gallium Nitride (GaN) power devices have shown great promise in providing high-efficiency power conversion. The unique structure of wide bandgap GaN semiconductors creates devices with very high transport characteristics and charge density in the channel, operating at high voltages. These characteristics allow the devices to be used at much higher frequencies and with fewer parasitics. Inherent in these unique characteristics is flexibility in device design to enable robust operation and high performance.

Not all Gallium Nitride transistors are the same. There are two implementations of lateral GaN power devices: a normally on or depletion mode (D-mode) device and a normally off or enhancement (E-mode) device, and each device has its advantages and disadvantages. The gate region is quite different for these two implementations and plays a critical role in the potential reliability. Understanding these trade-offs is necessary to make a proper choice for an application.

3.3. The right GaN technology is key

VisIC Technologies' D^{3}GaN technology (Direct Drive D-Mode) was developed for the high-reliability standards of the automotive industry and offers the lowest losses per RDS (on). It also simplifies the system and enables highly efficient and affordable powertrain platform solutions. This solution reduces the cooling system requirements and the size of the electronic car's inverter; thus, EV Cars can save 50% on inverter power losses over the electric car's driving cycle, reduce battery cost and increase driving range. The ability to support vehicles with an 800V and 400V battery is a significant step forward in GaN worldwide adoption by the automotive electrical driveline.

For inverter applications, the ability to parallel GaN devices is paramount, and the D^{3}GaN topology was a-priori designed to support device paralleling. With the direct access to the GaN gates and positive temperature coefficients, along with the already highest current rating per die (i.e., 200Amp), this solution paves the way to the simplest GaN system implementation that meets the high-power demand of the automotive market.

An exciting system development, aimed for 800 V application, is utilizing the proven 650 V rated devices in a 3-L Inverter. This design highlights GaN devices' capabilities to improve 800V Electric Motor systems by lowering the phase current ripple and improving drive cycle efficiency. With lower total losses versus the standard 2-L approach, the D^{3}GaN power switches offer the best utilization performance and Total Cost of Ownership (TCO).

hofer powertrain and VisIC technologies announced in 2022 the news regarding a traction inverter with D^{3}GaN technology that ran successfully in lab tests. Here hofer powertrain realized a first lab sample of a 3-L NPC inverter based on GaN discrete power modules with a current rating of 100 Arms. This lab sample supported the subsequent development of an A-sample in the beginning of 2023 which proved to reach state of the art current ratings for automotive electric main drives and show the full potential of combining 3-L inverter topology with GaN on electric drive system level.

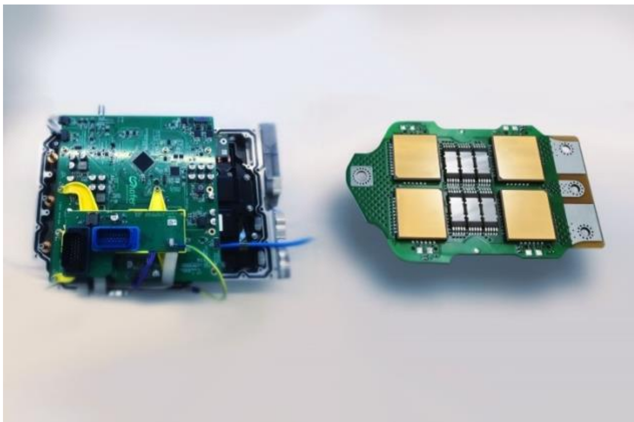

Fig. 3: First lab sample of a 3-L NPC inverter based on GaN discrete power modules

4. CURRENT DEVELOPMENTS

At present, hofer powertrain is diligently working on the development of their GaN technology-optimized 3-L POW automotive module, with an ambitious current rating target of 600A. This significant step is essential in elevating the technology to a higher level of maturity, making it ripe for mass-market automotive introduction soon. The cutting-edge module will also be incorporated into the new generation of hofer powertrain traction inverters, demonstrating a clear commitment to innovation and increased efficiency in the automotive industry. As the market demonstrates readiness and eagerness to embrace this groundbreaking technology, numerous customer projects within the automotive space are contributing valuable insights into the benefits of GaN technology for real-life applications. Interest in this technology is surging rapidly, as industry players recognize the transformative potential of GaN in revolutionizing the automotive landscape. By optimizing performance, improving energy efficiency, and reducing overall system costs, hofer powertrain's 3-L POW automotive module will undoubtedly play a critical role in shaping the future of sustainable mobility and the broader automotive market.

Especially in Commercial Vehicles, Motorsport vehicles, Hypercars and eVTOLs the use of Multilevel Inverter technology is beneficial already today. Within these applications high power demand and reduced sensitivity for inverter BOM costs result already today in an improvement of the electric drive system on vehicle level compared to the 2-L type. With the introduction of GaN power switches more applications will follow.

REFERENCES

(1) hofer powertrain (2021-23). Efficiency Optimization in Powertrain Systems with Multi-Level inverters and D3GaN Technology. Internal rapid development, in-depth analysis, and testing in cooperation with VisIC power electronics.

(2) hofer powertrain (2019-21). Efficiency Optimization in Powertrain Systems with Multi-Level inverters various semiconductor technologies. Internal research, development, in-depth analysis, and testing.