EVS30 Symposium
Stuttgart, Germany, October 9 – 11, 2017

Highly Dynamic Gallium-Nitride DC-DC Converter for 48 V Systems

Deru Song[1], Christian Korte[2], Christian Stark[2],
Till H. Lütje[2], Malte Jaensch[2], and Stefan M. Goetz[2]

[1] *Porsche Engineering Shanghai, Shanghai, P. R. China*
[2] *Porsche Engineering Group, Weissach, Germany*

Summary

The 48 V system is currently established as a low-voltage supply for high-power loads and auxiliaries that do not justify the cost and safety issues associated with high voltage systems, such as small electric drives in mild hybrids, active chassis systems, and electric turbo chargers. The high dynamics of such loads present high challenges for the supply as they often involve highly dynamic transients and fluctuations. In electrical active chassis systems that are currently under development, for example, road irregularities and critical drive situations are reflected in the power demand as well as sudden direction changes. We will present a fast bidirectional multiphase Gallium-Nitride (GaN) DC–DC converter between the 12 V supply and the 48 V island system for high-power auxiliaries, which reduces or eliminates the present need for an additional 48 V energy storage, can follow the fast dynamics of typical loads, cope with rapid changes of the power flow direction, and compensate the 12-V voltage fluctuations originating from the 12-V generator as well as sudden load changes of other units. We will present a fast combination of feed-back and feed-forward control that keeps the voltage of the active suspension within an interval of +/– 2 V.

Keywords: DC-DC, converter, on-board, component, car.

---

1 Introduction

In conventional vehicles, the dominant portion of power was in the mechanical domain, including the drive train and potential hydraulic systems, whereas the electrical system consisted mostly of mechanical and resistive loads supplied through an alternator and a battery [1, 2]. Due to the limited power requirements with relatively slow dynamics, early cars used low voltages around 6 V to supply electrical and electronic components. Later, the voltage was lifted to 12 V – 14 V, which is currently the industry standard for passenger vehicles. Although earlier approaches to increase the voltage to 24 V – 28 V as used in commercial vehicles or 42 V could not gain traction, the latest trend to install 48 V faces substantially different conditions [3-8].

Most importantly, the power requirements and load dynamics of latest electrical loads in vehicles have increased rapidly, rendering a supply by 12 V impossible or risking interference with safety-critical units, such

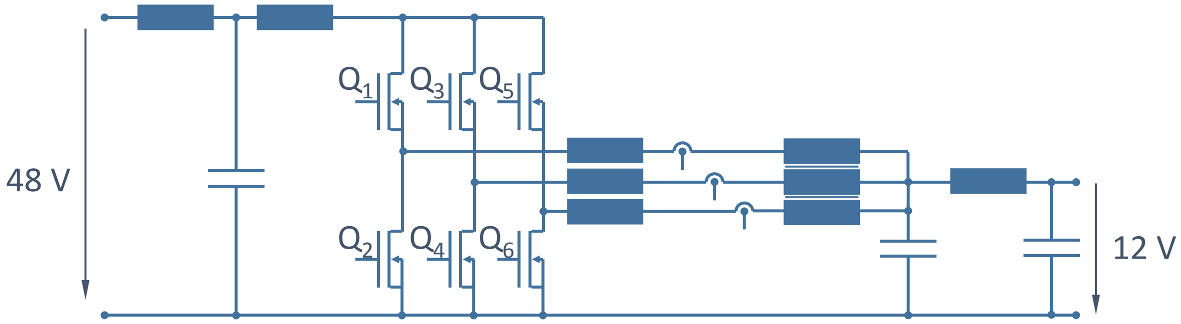

Figure 1. Topology of the 12 V/48 V multiphase inverter.

as power steering, the anti-lock braking system (ABS), or the electronic stability program (ESP). Furthermore, the 48 V supply is at present not considered to entirely replace the 12 V supply, but to coexist so that loads can be assigned to either voltage level according to the specific needs [8, 9].

The coexistence of at least two supply voltages, i.e., 12 V and 48 V, complicates power generation and the balance of both [10, 11]. Instead of a parallel island operation of both supplies with dedicated batteries and generators, power exchange between both through electronic DC–DC converters is considered more efficient, reliable, and economic. Such DC–DC converters can pass energy from one to the other if only one of both systems comprises a generator or balance load differences between both in case of independent supply [12]. However, latest 48 V loads, such as starter-generators, chassis control as well as active suspension systems, electric turbo chargers, and replacement of formerly hydraulic systems, differ in their requirements from most conventional 12 V auxiliaries and substantially exceed those with respect to required power, rapid power fluctuation, and bidirectionality of power as they can sink and source power dependent on the drive situation.

Electrical active chassis control, as available in the latest Porsche Panamera, can serve as an exemplary application. Such systems typically incorporate a fast-spinning electric motor with high power density and a high gear ratio to adjust the chassis to road conditions and cornering as well as roll the vehicle, while compensating road irregularities [13-16]. However, high-frequency excitation from such road irregularities and the bidirectional power flow lead to rapidly changing electric load with frequency components exceeding 1 kHz, while standards limit the voltage range on the 48 V supply system [17]. Furthermore, the 12 V system is far from stable, with dips and spikes ranging from 6 V to 18 V, caused by highly dynamic 12 V loads and particularly strong ripple of the 12 V generator, which may in some cases not be transferred to the 48 V supply [18]. The resulting high power fluctuations have to be compensated to comply with the voltage limits of the 48 V system [17]. In consequence, latest vehicles typically rely on an additional battery or double-layer-capacitor storage on 48 V, which is slowly recharged from the 12 V vehicle supply. The 12 V system, on the other hand, is energized by a conventional lead-acid battery and an alternator.

In this paper, we will present a novel 12 V-to-48 V bidirectional DC–DC converter that can follow rapid load changes and alternating power flow direction as caused by latest 48 V auxiliaries. We achieve this performance gain over conventional production 12-V-to-48-V DC–DC converters with fast-switching wide-bandgap Gallium-Nitride (GaN) normally-off transistors, which in our application allow more than four times higher switching speed at exceptional efficiency [19, 20]. A multiphase circuit topology triples the possible control dynamics. We further eliminate the impact of the 12 V ripple through a highly dynamic model-based feed-forward term in our control.

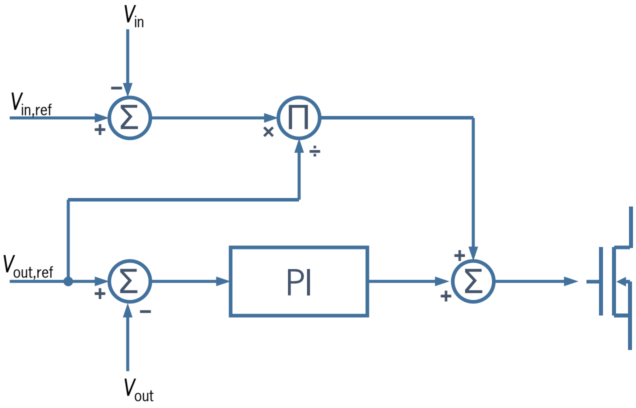

Figure 2. Control topology with combined feed-back and fast feed-forward loops.

2 Design of the GaN DC–DC Converter

2.1 Powertrain

Key design target of the DC–DC converter is a high dynamic range to follow the high-frequency components and rapidly changing current flow direction caused by latest 48 V loads such as active chassis systems. Our design achieves the necessary fast response through a rapid control loop and a high switching speed. The switching-performance requirements exceed the reasonable operation range of standard silicon devices. Whereas hard-switching topologies typically limit these devices to less than 100 kHz for reasonable loss, resonant soft-switching topologies are unfit for the rapidly changing current flow direction of the active suspension, which would require active de-excitation of the resonators [21, 22]. The design necessarily incorporates wide-bandgap GaN transistors. The higher cost of the latter is overcompensated by the elimination of a costly 48 V energy storage in addition to the standard 12 V battery. A further increase of the dynamic is achieved by the implementation of multiple phases that can be interleaved in operation so that the control loop can operate at a multiple of the individual switching speed (Fig. 1). We selected a multiphase design with three interleaved boost stages with 120-degree shift between phases. For an average 48-V-side current of 25 A and a 1 s peak load of 75 A, the multiphase design furthermore splits the total current into moderate portions for the ferrite-core inductors. Each phase is designed for a switching speed of at least 300 kHz. The boost phases are designed completely without silicon diodes to avoid reverse recovery. Instead, complementary body-diode-free high-side GaN transistors serve as synchronized rectifiers.

2.2 Control

A mixed feed-forward/feed-back controller is responsible for the high dynamic range of the bidirectional interleaved multiphase converter stage (Fig. 2). The controller is required to keep the 48 V side stable despite the large and rapid load fluctuation, current reversals, and 12-V-side voltage ripple. The feed-back loop implements PI voltage control of the measured output voltage to the reference, which is further transformed by x^{-1} to compensate the nonlinearity of boost converters. In principle, the feed-back loop alone would be able to compensate the influence of fluctuations on the input side on the output. However, the rapidity and the magnitude, which may range from 6 V to 18 V, easily exceeds the control dynamics and results in over-and/or under-voltage [18]. Instead, a fast model-based feed-forward loop measures the voltage at the input side, transforms it through the transfer equation of the converter into the duty-cycle space and adds it to the duty-cycle output of the feed-back loop.

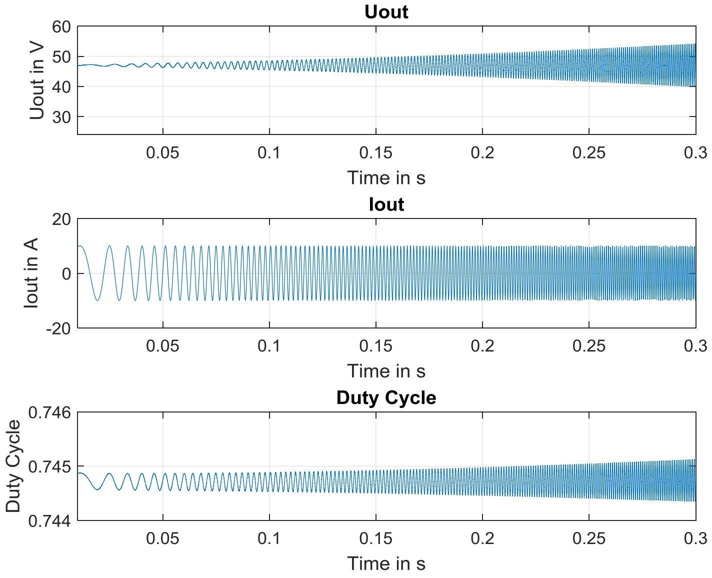

Figure 3. Control behavior in a Fourier sweep of the load.

In accordance with standards and regulations for automotive 48 V supplies, the output voltage must not exceed 52 V or fall below 36 V in any operating point, despite the rapid load variation [17, 18]. Thus, the reference voltage is typically set below 48 V to increase the head room to the absolute limit of 52 V. The controller operates at a multiple of the individual switching rate so that the duty cycle is updated at least with each interleaved phase starting a new cycle. As expected, the multiphase design approximately tripled response dynamics and reduced the ripple by more than 70%.

3 Model and Control Performance

In the DC–DC converter, the feed-back loop has to compensate the load fluctuations caused by high-frequency excitation from road irregularities and keep the output voltage stable. Design and simulation of the

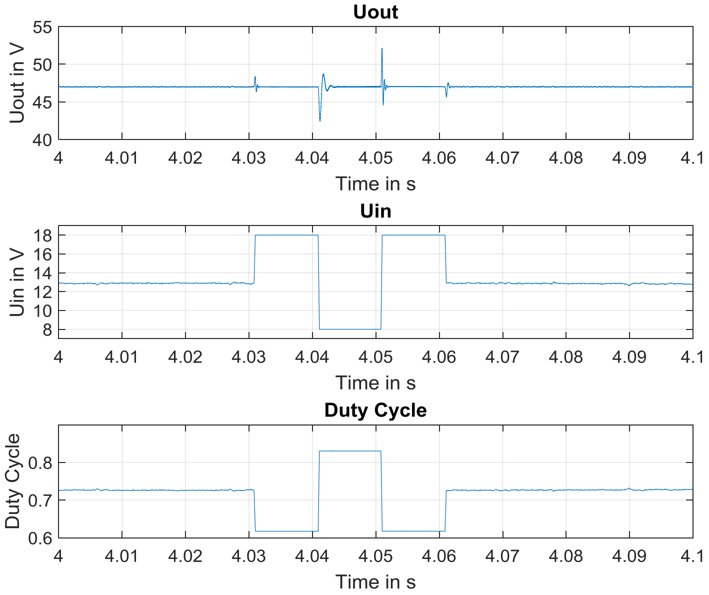

Figure 4. Response of the feed-forward/feed-back controller to rapid voltage steps of the 12 V side.

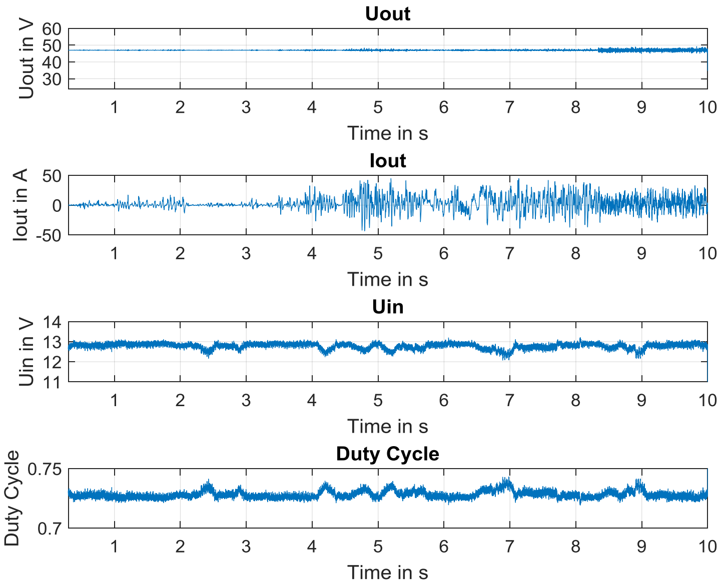

Figure 5. Behavior of the controller tested with recordings of 48 V load profiles and 12 V voltage fluctuations from an actual vehicle.

controller was performed in Matlab/Simulink (The Mathworks, Natick, MA, USA). The presented controller design underwent a Fourier load test with a current at a linearly increasing frequency and amplitude increments from 0 A to 30 A in 5 A steps. Figure 3 shows the output voltage for sinusoidal load current. The duty cycle (lowest panel) follows the sinusoidal excitation. The output voltage stays within the specified limits into the high kilohertz range. Similarly, the feed-back loop compensates load steps.

In addition to the load fluctuations, which depend on the road conditions, the 12 V system presents a widely fluctuating voltage due to rapid load changes of large appliances, such as power steering units, ABS, and ESP, likewise reaching into the high kilohertz range. The given examples often coincide with the occurrence of pot holes. Additionally, conventional Lundell-type claw-pole alternators—though highly cost effective—cause substantial ripple on the 12 V supply [23-25]. The feed-forward loop implements a model of the boost phases. As shown in Fig. 4, the feed-forward loop compensates voltage steps of the input between 8 V and 18 V in less than 100 µs.

We applied 48 V load measurements from the actual load on a comfort test track with high road irregularities and single-sided pot holes. Measurements were performed in a Panamera vehicle with electric Porsche Dynamic Chassis Control and stabilization of the 48 V through a double-layer capacitor and incorporated all currents flowing in and out of the load, including those provided by the double-layer capacitors. Furthermore, we applied recordings reflecting the voltage fluctuation on the 12 V supply. The recordings were replayed in Matlab/Simulink to challenge the controller design (Fig. 5). The rapid feed-forward loop is obvious in the duty cycle (lowest panel) and leads to a stable output voltage. Despite the rapid load and supply fluctuations, the feed-back loop successfully stabilizes the output voltage in the range of 45 V to 50 V, which is well within the normative limits of VDA 320 [17].

4 Hardware Performance Test

A laboratory test setup incorporating the three-phase DC–DC boost converter was used to validate the control approach for the use with above-described 48 V chassis actuator. We implemented the boost-stage with commercially available GaN transistors (GS61008, GaN Systems, Montreal, QC, Canada), inductors (Coilcraft, Cary, IL, USA and Vishay, Malvern, PA, USA). The controller was implemented on a DSP-FPGA combination (Kintex 7-325T, Xilinx, San Jose, CA, USA). The feed-back/feed-forward controller model was designed and tested in Matlab-Simulink and completed with peripheral IO as well as the test periphery in LabVIEW (National Instruments, Austin, TX, USA), from where it was synthesized as well as programmed to the

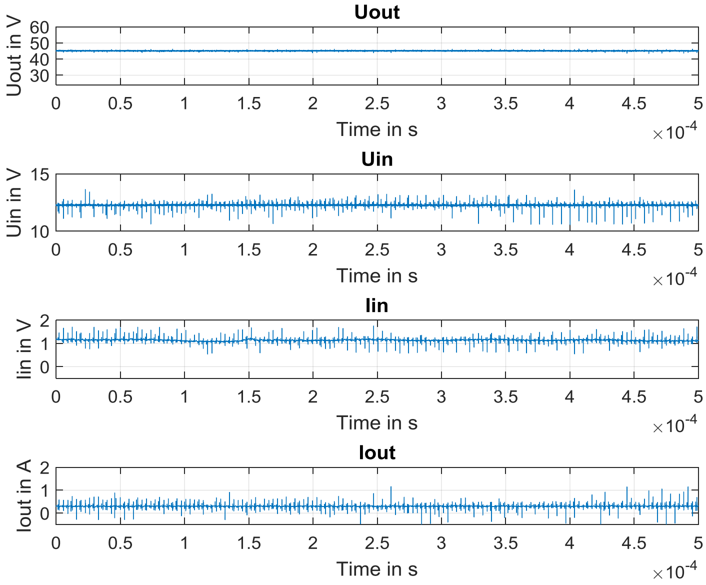

Figure 6. Measurement of the prototype reflecting a widely constant output voltage.

hardware platform. All tests of this paper were performed through programmable loads (EA-EL9080-170B, EA, Viersen, Germany) and sources (EA-PS8160-170 High-speed, EA, Viersen, Germany) controlled through LabVIEW.

Figure 6 shows the steady-state performance of this physical power-stage circuit in a representative 500 µs window. In this measurement, the individual phases are operated at 300 kHz with a third period offset and individual pulse-width modulators for the required high dynamic performance.

Figure 6 displays measurements of input and output parameters under fluctuating load generated through controllable load and sink systems based on vehicle-recorded load data. To center the output within the allowed band of VDA 320, which defines overvoltage starting at 52 V for the 48 V system, we set the output reference to 44 V. The output voltage fluctuates by less than 9 V. As it stays well between 39.0 V and 47.8 V with an actual average of 45.0 V, the converter complies with VDA 320.

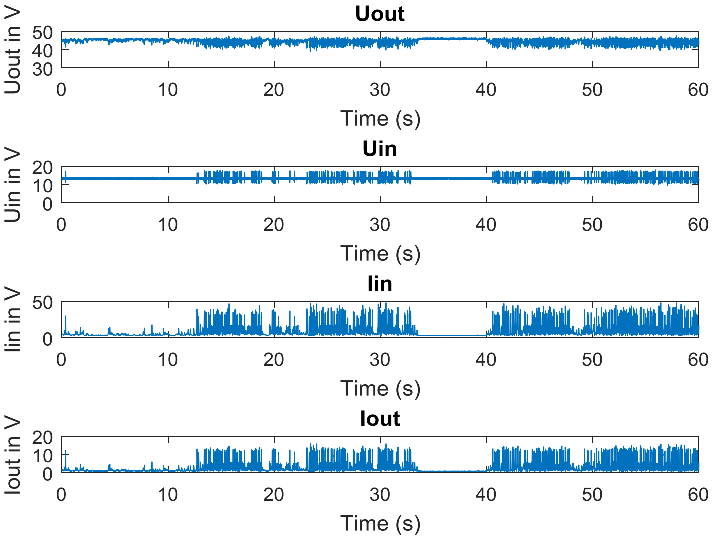

Figure 7. Measurement of the prototype for an entire drive cycle on a comfort test track.

5 Conclusions

We presented a bidirectional high-bandwidth automotive 12 V-to-48 V DC–DC converter that is able to manage rapidly changing voltage and power profiles of the latest vehicle appliances. In our specific situation, it is able to supply a highly dynamic 48 V active suspension system as well as to sink the power sourcing from street excitation. As our converter is fast enough to establish a stiff supply to reduce or eliminate a heavy and costly 48 V energy storage, the still substantially higher cost of the GaN semiconductors is overcompensated to enable the automotive application. To avoid independent energy storages, the present popularity gain of 48 V drives, e.g., in mild hybrids, is expected to create additional need for similarly fast DC–DC converters.

In this paper, we further described the control strategy that achieves the required fast response to the output and tolerance to rapid voltage fluctuations on the input side through a combined feed-back/feed-forward design and a rapid control loop that operates at the effective switching rate of the multiphase system. We tested its performance using real-world load profiles and showed their corresponding measurements of the power-stage electronics, which will be notably expanded upon completing the next sample stage.

References

[1] J. M. Miller and P. R. Nicastri, "The next generation automotive electrical power system architecture: issues and challenges," *17th DASC. AIAA/IEEE/SAE. Digital Avionics Systems Conference. Proceedings (Cat. No.98CH36267),* vol. 2, pp. 1-8, 1998.

[2] J. G. Kassakian, "Automotive electrical systems-the power electronics market of the future," in *APEC 2000. Fifteenth Annual IEEE Applied Power Electronics Conference and Exposition (Cat. No.00CH37058),* 2000, pp. 3-9 vol.1.

[3] H. Huang, J. M. Miller, and P. R. Nicastri, "Automotive Electrical System in the New Millennium," *SAE Technical Paper,* vol. 1999-01-3747, 1999.

[4] W. M. da Silva and P. P. de Paula, "12V/14V to 36V/42V Automotive System Supply Voltage Change and the New Technologies," *SAE Technical Paper,* vol. 2002-01-3557, 2002.

[5] L. C. Marcoccia, "42V Power Supply Systems Impact for Emerging Market Projects," *SAE Technical Paper,* vol. 2005-01-4115, 2005.

[6] E. Ceuca, "The 42 V Power Net Architecture Standards," *Acta Universitatis Apulensis,* vol. 2, pp. 59-68, 2001.

[7] J. G. Kassakian, J. M. Miller, and N. Traub, "Automotive electronics power up," *IEEE Spectrum,* vol. 37, pp. 34-39, 2000.

[8] M. Kuypers, "Application of 48 Volt for Mild Hybrid Vehicles and High Power Loads," *SAE Technical Paper,* vol. 2014-01-1790, 2014.

[9] C. S. Kim, K. Park, H. Kim, G. Lee, K. Lee, H. J. Yang, *et al.*, "48V Power Assist Recuperation System (PARS) with a permanent magnet motor, inverter and DC-DC converter," *2013 1st International Future Energy Electronics Conference (IFEEC),* pp. 137-142, 3-6 Nov. 2013 2013.

[10] Y. Kusaka and K. Tsuji, "Novel Power Conversion System for Cost Reduction in Vehicles with 42V/14V Power Supply," *SAE Technical Paper,* vol. 2003-01-0307, 2003.

[11] J. M. Miller, "Trends in Vehicle Energy Storage Systems: Batteries and Ultracapacitors to Unite," *2008 IEEE Vehicle Power and Propulsion Conference,* pp. 1-9, 3-5 Sept. 2008 2008.

[12] C. Korte, E. Specht, and S. Goetz, "A Novel Spectral Control Method for an Automotive Gallium Nitride DC-DC Converter," in *PCIM Europe 2017; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management*, 2017, pp. 1-7.

[13] A. Sorniotti, "Electro-Mechanical Active Roll Control: A New Solution for Active Suspensions," 2006.

[14] H. Kajino, S. Buma, J.-S. Cho, and R. Kanda, "The Future Development and Analysis of an Electric Active Suspension System," 2008.

[15] J. Yin, X. Chen, L. Wu, and J. Li, "Design Aspects of a Novel Active and Energy Regenerative Suspension," 2016.

[16] D. Song, K. Schwaiger, C. Korte, C. Stark, T. Luetje, M. Jaensch, *et al.*, "Highly dynamic multiphase wide-bandgap DC-DC converter for automotive active suspension systems," in *2017 IEEE 3rd International Future Energy Electronics Conference and ECCE Asia (IFEEC 2017 - ECCE Asia),* 2017, pp. 528-533.

[17] VDA, "Electric and Electronic Components in Motor Vehicles 48 V On-Board Power Supply," VDA 320, 2014.

[18] VDA, "Electric and electronic components in vehicles up to 3.5 t," LV 124, 2010.

[19] E. A. Jones, F. Wang, and B. Ozpineci, "Application-based review of GaN HFETs," in *Wide Bandgap Power Devices and Applications (WiPDA), 2014 IEEE Workshop on*, 2014, pp. 24-29.

[20] J. Roberts, "Lateral GaN Transistors - A Replacement for IGBT devices in Automotive Applications," in *PCIM Europe 2014; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management; Proceedings of*, 2014, pp. 1-8.

[21] Y. Wu, M. Jacob-Mitos, M. L. Moore, and S. Heikman, "A 97.8% Efficient GaN HEMT Boost Converter With 300-W Output Power at 1 MHz," *IEEE Electron Device Letters*, vol. 29, pp. 824-826, 2008.

[22] O. Garcia, P. Zumel, A. d. Castro, and A. Cobos, "Automotive DC-DC bidirectional converter made with many interleaved buck stages," *IEEE Transactions on Power Electronics*, vol. 21, pp. 578-586, 2006.

[23] R. Ivankovic, J. Cros, M. T. Kakhki, C. A. Martins, and P. Viarouge, "Power Electronic Solutions to Improve the Performance of Lundell Automotive Alternators," in *Advances in Vehicular Technology and Automotive Engineering*, J. Carmo, Ed., ed: InTech, 2012.

[24] D. J. Perreault and V. Caliskan, "Automotive power generation and control," *IEEE Transactions on Power Electronics*, vol. 19, pp. 618-630, 2004.

[25] D. J. Perreault, T. A. Keim, J. H. Lang, and L. M. Lorilla, "Applications of Power Electronics in Automotive Power Generation," *Proc. Automotive Power Electronics*, pp. 1-9, 2006.