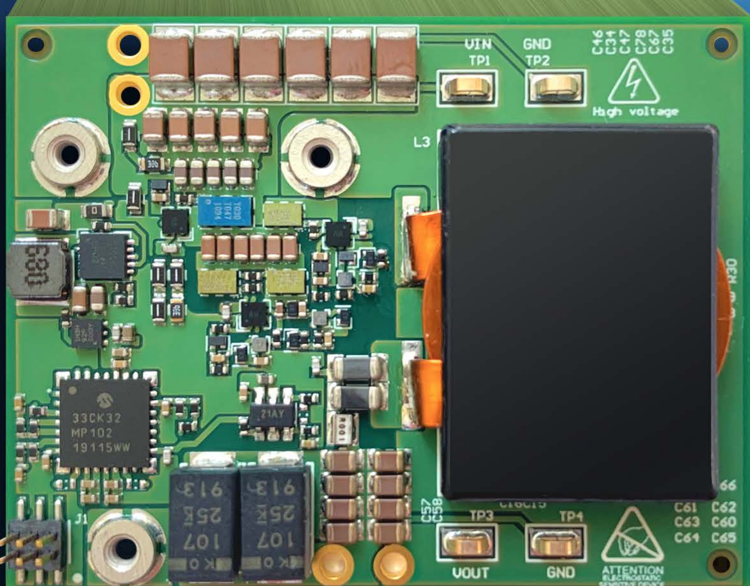
EFFICIENT POWER CONVERSION

GaN for DC-DC Conversion

Multilevel Converters



EPC9148

GaN for DC-DC Conversion

Multilevel Converters

By Michael de Rooij, Alex Q. Huang, Qingyun Huang, Penkun Liu, Qingxuan Ma, Amir Negahdari, Andreas Reiter, Jianjing Wang, Zhihong Yu, and Yuanzhe Zhang

Preface

In virtually every application of electricity in this millennium, there is a DC-DC converter in the path of electrons. In many applications, the demands for extremely high power density, light weight, thin form factors, low cost, and high reliability have caused the bounds of power transistors to be pushed beyond the capability of the aging silicon power MOSFET.

This eBook discusses multilevel converters, a topology that enables higher power density by multiplying the frequency seen by the inductors compared with the GaN transistors. This multiplication factor shrinks the size of the inductors while keeping transistor switching losses low. An additional benefit of multilevel converters is their ability to use lower voltage FETs, which have proportionately superior figures of merit. Two multilevel design examples will be discussed in this eBook: 1) 250 W, 60 V_{IN}–20 V_{OUT}, 97.8% efficient that optimizes form factor and 2) 4-Level, flying capacitor, multilevel, GaN Totem-Pole PFC at 400 V–48 V, 99% efficient at 3 kW that minimizes conduction loss of the diode bridge.

Three additional eBooks regarding different topologies for DC-DC Converter solutions using EPC GaN-based solutions address:

1. ***GaN for DC-DC Conversion – Buck Converters:*** Buck converters exploring the bounds of efficiency and size using state-of-the-art GaN transistors. Digital control is also compared with analog control showing the pros and cons of each technology.
2. ***GaN for DC-DC Conversion – Bi-Directional Converters:*** Bi-directional converters using both discrete GaN transistors and monolithic GaN power stage integrated circuits, which are being designed into computers and mild-hybrid vehicles to power 48 V power distribution buses, as well as legacy 12 V components.
3. ***GaN for DC-DC Conversion – LLC Converters:*** LLC converters that are quickly becoming the preferred topology for high density applications from 60–30 V_{IN} where power levels exceed about 300 W.

In every case, the state-of-the-art performance in terms of efficiency or power density is achieved using GaN devices.

A comprehensive analysis of GaN-based solutions, reliability, and applications are available in EPC's latest text book, ***GaN Power Devices and Applications***, released in October, 2021. The book is available for purchase on **EPC's web site**.

1.0 Example 1: Bi-Directional Buck Converter – 250 W, 60 V_{IN} – 20 V_{OUT}, 97.8% Efficient

In this example, thickness is the key design parameter considered reviewing a multilevel converter with digital control achieving an impressive peak efficiency of 97.8% and measuring only 3.5 mm maximum component thickness!

1.1 Design of a GaN FET-based, Three-Level Converter

The simplified schematic of a GaN FET-based three-level flying capacitor buck converter with cascading synchronous bootstrap gate driver power supply is shown in Figure 1.1. The circuit has three operating modes at a duty cycle lower than 0.5:

1) Input voltage charges up the flying capacitor and load inductor through Q_1 and Q_3;
2) Flying capacitor discharges while the load inductor charges through Q_2 and Q_4; and,
3) Inductor current discharges through Q_3 and Q_4 (either via the equivalent body diode of one and the channel of the other during dead time, or via the channel of both FETs).

The steady-state operation follows the cycle of 1→3→2→3. The effective frequency seen at the output inductor is thus double the switching frequency for the FETs. In combination with the reduced volt-seconds and high inductor frequency, allows the a significantly lower inductance value than required in a conventional synchronous buck converter.

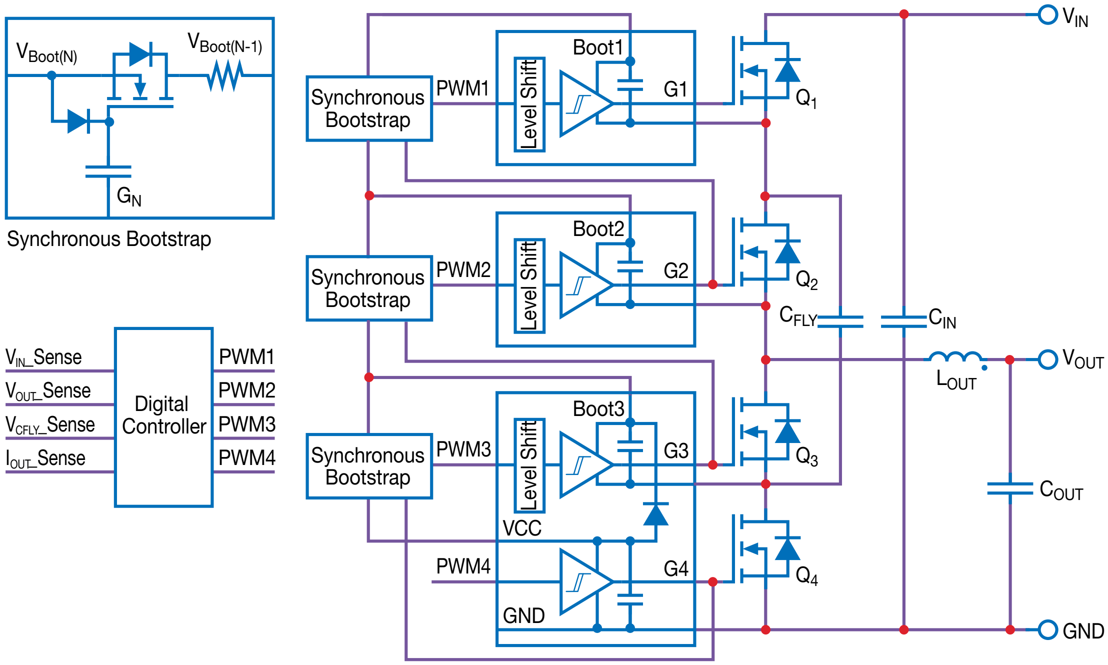


Figure 1.1 Simplified schematic of the GaN transistor-based three-level converter

The switching frequency of the converter is optimized at 400 kHz so that the effective frequency seen at the inductor is 800 kHz, high enough to allow the use of a 3.5 mm thick, 2.4 µH inductor, while maintaining low switching loss, and thus high overall efficiency and good thermal performance. The cascaded synchronous bootstrap circuit that ensures adequate gate voltage (> 4.5 V) for the upper FETs is adopted.

Three control loops are implemented using a digital controller to regulate the output voltage, output current, and flying capacitor voltage, respectively. Flying capacitor voltage should be kept at half of the input voltage at all times to avoid over stressing any of the FETs and ensure correct circuit operation.

1.2 High Performance GaN FETs for the Three-Level Buck Converter

In Figure 1.1, Q_1 blocks the 60 V input voltage before the flying capacitor voltage is established. As Q_2-Q_4 only need to block half of the input voltage at any given operating mode, they only need to be rated for 24 V. Therefore, the 100 V rated EPC2053 with $R_{DS(on)}$ of 3.8 mΩ, and the 40 V rated EPC2055 with $R_{DS(on)}$ of 3.5 mΩ shown in Figure 1.2 are selected for Q_1 and Q_2–Q_4 respectively. Both GaN FETs are of tiny size, and can operate at up to 150°C junction temperature.

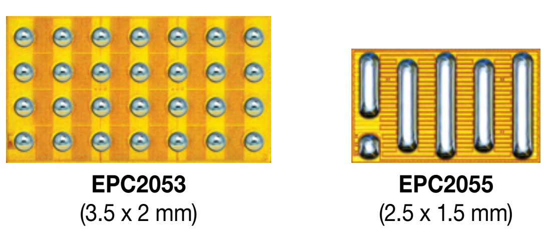


Figure 1.2 Photo of the bump side of EPC2053 (left) and EPC2055 (right)

1.3 Results

The three-level buck converter in Figure 1.3, EPC9148 [2], was built to verify the design. The overall thickness of the circuit, including the circuit board, is only 5 mm. The circuit was tested with no forced air up to 12.5 A output current with a temperature rise of 47°C. The switch-node voltage V_{SW} waveform at 8 A output current is shown in Figure 1.4. The capacitor voltage is well-balanced during charge and discharge phases.

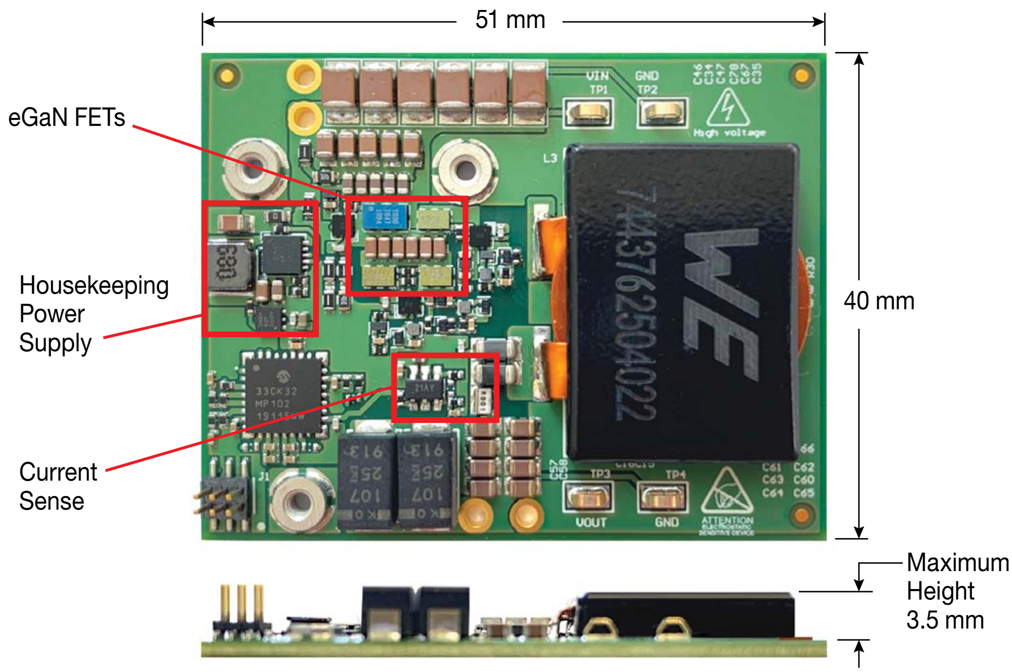


Figure 1.3 Photo of the 60 V to 20 V three-level buck converter (EPC9148)

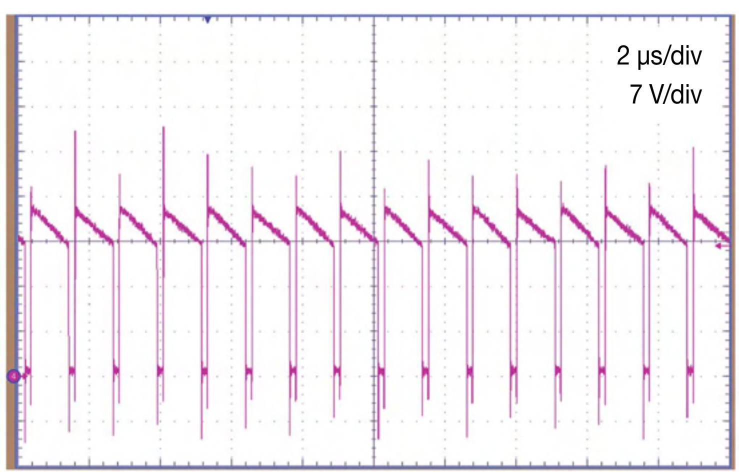


Figure 1.4 Switch-node voltage V_{SW} waveform at 8 A output current

The overall power efficiency of the three-level converter operating at 20 V output and with 800 LFM forced air is shown in Figure 1.5, with a peak efficiency of 97.8%. It maintains efficiency above 97% above 4 A load current. The overall power efficiency at 12 V output and with 800 LFM forced air is shown in Figure 1.6 with a peak efficiency of 97%. This is all achieved within the 5 mm height limit including PCB.

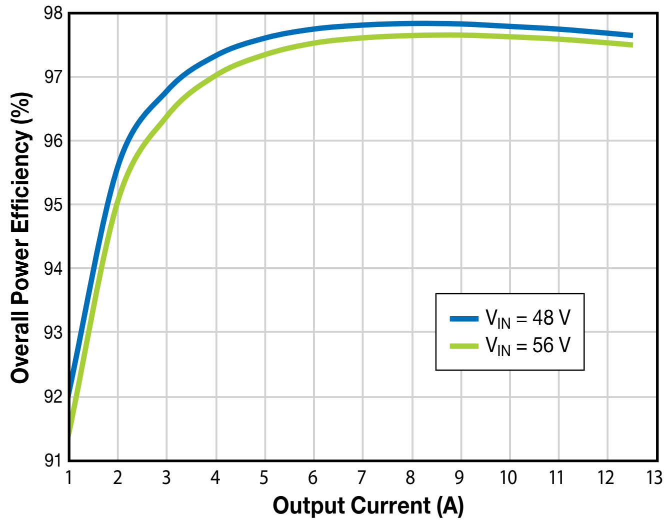


Figure 1.5 Total system efficiency including the housekeeping power consumption at 20 V output

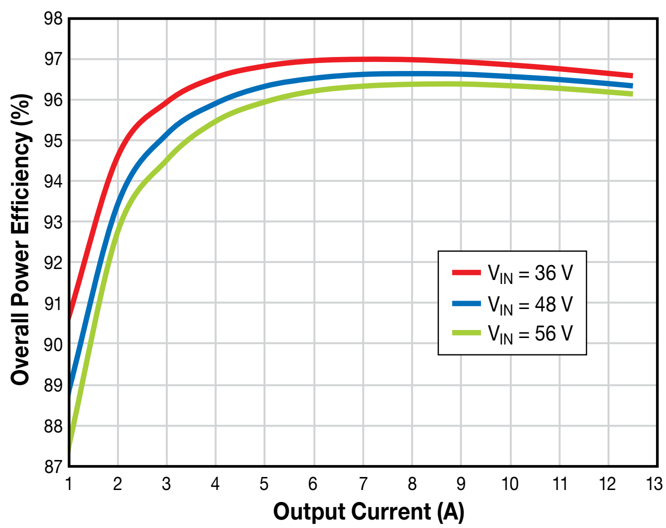


Figure 1.6 Total system efficiency including the housekeeping power consumption at 12 V output

The thermal image of the converter operating at 48 V to 20 V, 12.5 A output current with 800 LFM forced air cooling is shown in Figure 1.7. The FETs are capable of carrying much more current with forced air.

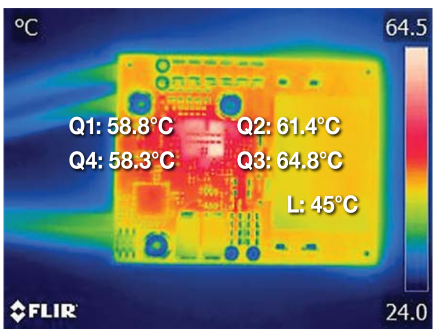


Figure 1.7 Thermal image of the three-level buck converter at 12.5 A output current and thermal steady state with 800 LFM forced air

1.4 Summary for the Multilevel Converter with Digital Control

The GaN-FET-based multilevel buck topology can be used for designing an ultra-thin and highly efficient DC-DC converter. A 60 V to 20 V, 250 W three-level buck converter built using GaN transistors achieved a peak efficiency of 98% and a maximum component thickness of only 3.5 mm.

The GaN transistors not only reduce the area occupied with their tiny footprints but improve the overall power efficiency with their fast-switching capability.

Finally, Figure 1.8 shows the power density improvement and size reduction that multilevel converters produce, when compared to a standard two-level buck converter, operating from the same input and output specifications.

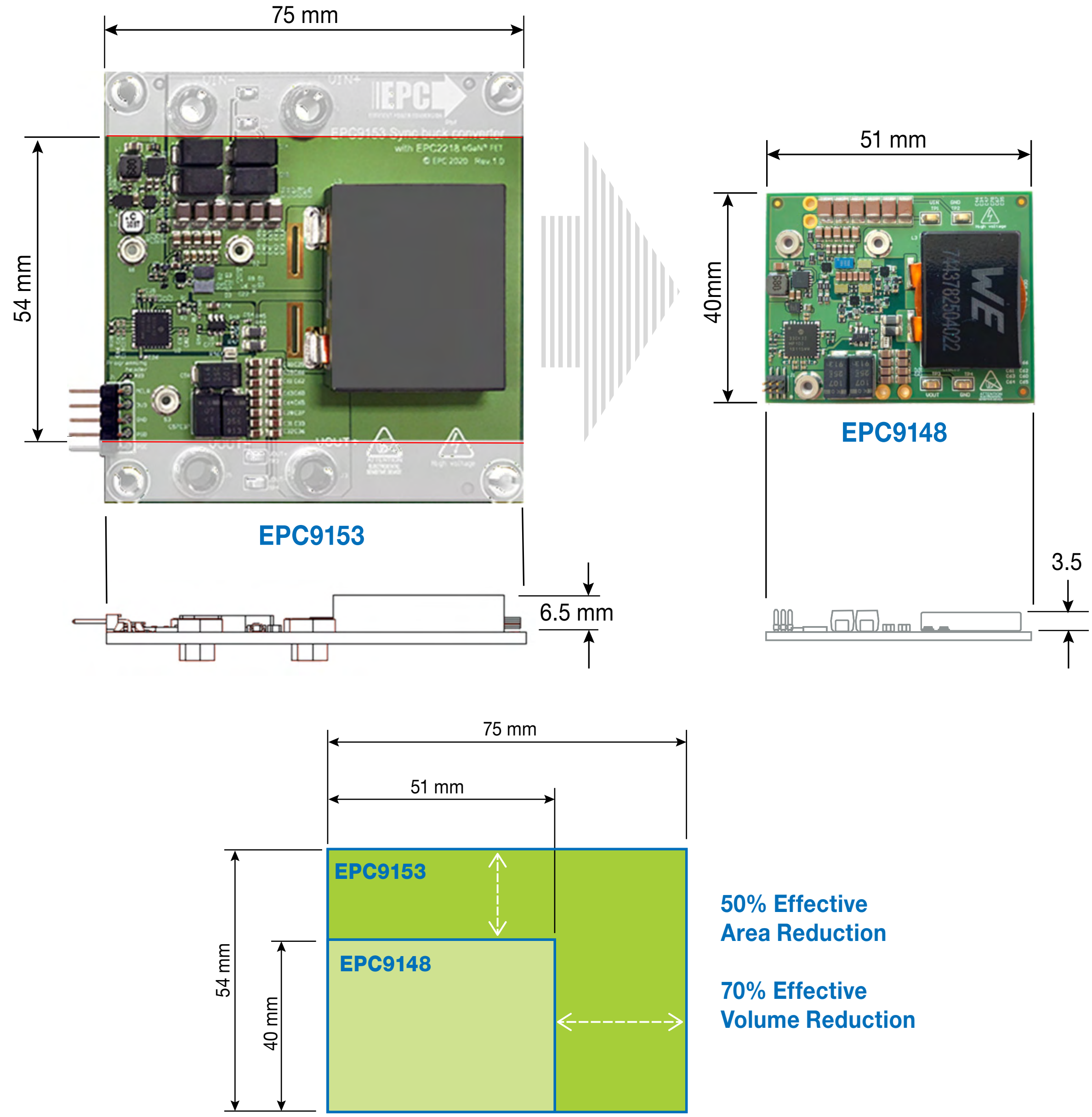


Figure 1.8 Size comparison between a two-level buck converter EPC9153 and three-level multiphase buck converter, EPC9148, that have the same input and output voltage and power specifications.

In the next section, a multilevel topology is used in a 400 V_{IN}, 48 V_{OUT}, 3 kW converter for power factor correction (PFC).

2.0 Example 2: 4-Level, Flying Capacitor, Multilevel, GaN Totem-Pole PFC: 400 V–48 V, 99% Efficient at 3 kW

2.1 Introduction

As data center energy demands grow, the efficiency and the power density of the AC/DC switching power supplies are becoming more important [3]. In the typical two-stage power supply solution, there is a power factor correction (PFC) rectifier that creates a 400 V DC bus, and an isolated DC-DC stage to convert the 400 V DC to 48 V. Bridgeless PFC topologies are getting more interest due to their reduction of the diode-bridge conduction loss [1] with an example shown in Figure 2.1.

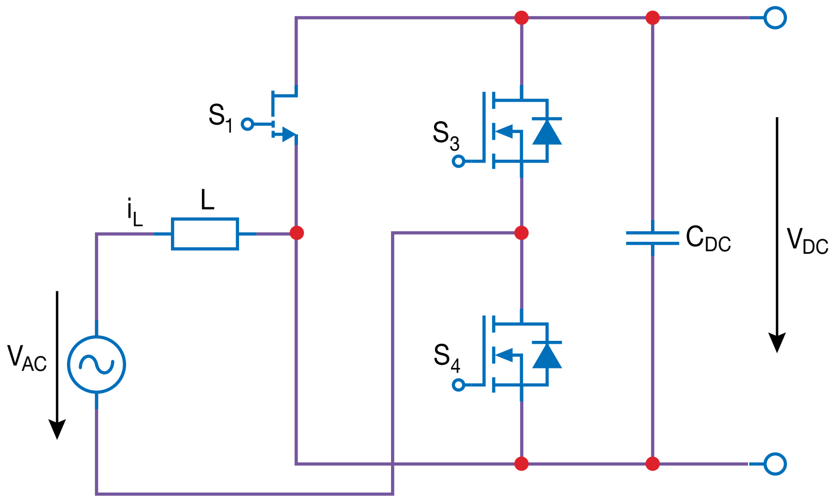


Figure 2.1 Topology of 2-level, GaN totem-pole PFC

2.2 GaN-Based Totem-Pole Bridgeless PFC

The dual-boost bridgeless PFC removes two line-frequency diodes, but it still has two low frequency diodes in the circuit. The two boost converters work alternatively, making the utilization of the inductors and the devices in the dual-boost PFC low [4, 5]. A GaN-based totem-pole bridgeless PFC has been considered as a solution recently, since the 650 V GaN FETs have no reverse recovery [6-8]. In this implementation, the GaN totem-pole PFC has two high frequency 650 V GaN FETs, two line-frequency 650 V Si MOSFETs and one inductor, as shown in Figure 2.1. This topology eliminates the diode-bridge conduction loss and highly utilizes the devices and the inductor. This GaN totem-pole PFC has been demonstrated with 99% efficiency for kW-level applications with hard-switching continuous conduction mode (CCM) operations.

The switching frequency of the CCM, FCML GaN totem-pole PFC is normally under 100 kHz to reduce the switching loss. Compared with the traditional hard-switching boost PFC, the main inductor size of the GaN totem-pole PFC is not reduced, due to their similar frequency range. The soft-switching, triangular-current mode, 2-level, GaN totem-pole PFC [9, 10] reduces the inductor size, due to the much higher switching frequency which is from several hundred kHz to several MHz. An efficiency of 99% can be achieved due to ZVS operation.

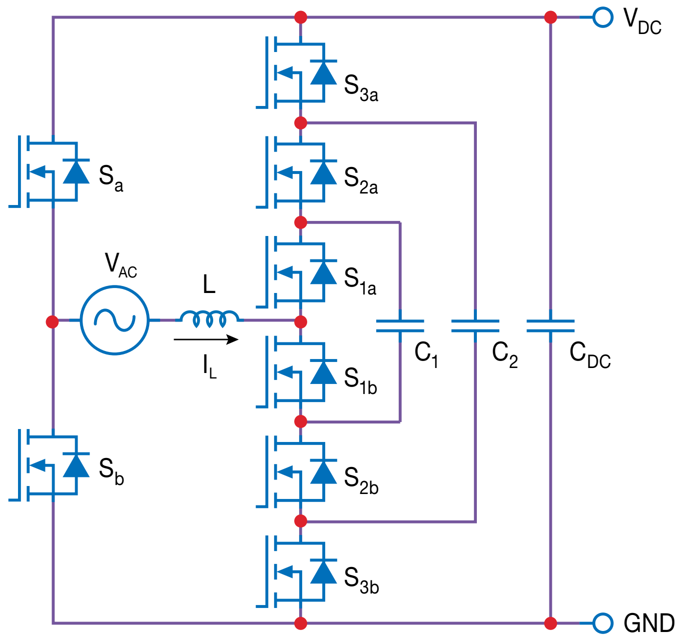


Figure 2.2 Topology of 4-level, FCML, GaN totem-pole PFC

Compared with the hard-switching CCM totem-pole PFC, the complexity of the sensing and control for the TCM totem-pole PFC is much higher due to the requirements of the high-speed current sensing and the variable frequency operation. The challenge is to achieve a reliable cycle-by-cycle ZVS at the higher frequencies.

2.3 Flying Capacitor Multilevel (FCML) Converters

The flying capacitor multilevel (FCML) converters can achieve much higher current ripple frequency with reduced switching voltage and switching loss. The current ripple frequency of an N-level FCML converter is (N–1) times of the switching frequency. This feature leads to a reduced inductor size.

FCML converters are traditionally used for medium voltage power electronics [8-10]. Recently, they have also been demonstrated with high efficiency and high density for low voltage grid connected applications [11]. A 1.5 kW bridgeless, 7-level FCML boost PFC is reported in [12]. With twelve 100 V GaN devices switching at 150 kHz, the peak efficiency is 99.07%. However, in this topology there are four line-frequency Si MOSFETs while the totem-pole PFC has only two of them. Additionally, the loss is not evenly distributed between the high-side devices and low-side devices since the boost PFC is not a symmetrical topology.

2.4 FCML Totem-Pole Bridgeless PFC Topology

The FCML totem-pole bridgeless PFC topology combines the FCML boost converter and the totem-pole PFC. It addresses the above issues of the FCML Boost bridgeless PFC. A 200 W, 4-level, FCML, totem-pole PFC rectifier with 200 V Si MOSFETs is reported in [13] and a simplified circuit diagram is shown in Figure 2.2. However, due to the high switching loss and reverse recovery loss of 200 V Si MOSFETs, the efficiency is only around 98% at 150 kHz switching frequency.

A 3 kW, 3-level, FCML, totem-pole PFC with two 150 V Si MOSFETs in series is implemented with 99% efficiency in [11] since the performance of 150 V Si MOSFETs is significantly improved compared with 200 V Si MOSFETs. However, due to its low switching frequency of 70 kHz and the 3-level operation, the main inductor size is still large [14], and not significantly improved compared with the 2-level, GaN totem-pole PFC. The voltage balance between the two series connected MOSFETs can be a major reliability issue.

To reduce the main inductor size while achieving 99% efficiency, a 3 kW, CCM, 4-level, FCML, GaN totem-pole PFC rectifier is discussed in this section. The 4-level operation reduces the device voltage stress to only one third of the DC bus voltage, and the inductor current ripple frequency is three times the transistor switching frequency.

In the system design, 200 V GaN devices are used, and the switching frequency is designed to 120 kHz while the current ripple frequency is 360 kHz. Compared with the conventional low-frequency CCM 2-level, GaN totem-pole PFC, this 4-level, FCML, GaN totem-pole PFC has much higher inductor current ripple frequency. Thus, the inductor size is significantly reduced and the switching loss is very low due to the much reduced switching voltage. Compared with the Si-based FCML totem-pole PFC, this 4-level, GaN totem-pole PFC can switch at much higher switching frequency due to the much lower switching loss and zero reverse recovery loss. Thus, the density of the 4-level, FCML, GaN totem-pole PFC is also higher than the density of the FCML Si totem-pole PFC.

2.5 Advantage of a 4-Level GaN PFC Over a 2-Level GaN PFC

The inductance required for the 4-level, FCML, GaN PFC is much lower than that for the low frequency CCM, 2-level PFC. However, a high-current, high frequency and high-density inductor design for this 4-level GaN PFC is a still a challenge since the conventional PFC inductors based on toroid powder cores and the ferrite cores are not suitable in this 4-level PFC. To design a high-density and low loss inductor for this 4-level, GaN totem-pole PFC, a low-profile matrix inductor design method is used using the commercial inductors based on powdered iron cores. Based on this design and analysis, a high-density 3 kW, 4-level, FCML, GaN totem-pole PFC prototype with 120 kHz switching frequency (360 kHz current ripple frequency) is developed and tested. The operations and performance are verified by the experimental results and the prototype achieves 99.25% peak efficiency, 99.1% full load efficiency, and 104 W/in^3 power density without heat sink and with forced air cooling. The 4-level, FCML, GaN totem-pole PFC stand-alone power stage card achieves the density of 1150 W/in^3 without heat sink and with forced air cooling.

2.6 Efficiency Compared With 2-Level GaN Totem-Pole PFC

To evaluate the efficiency advantage of the 4-level totem-pole PFC, a detailed device loss comparison between the 2-level, GaN totem-pole PFC and the 4-level, GaN totem-pole PFC with the same ripple frequency is discussed in this section. In this comparison, the grid voltage is 240 V_{AC}/60 Hz, the DC bus voltage is 400 V and the full power is 3 kW. The 4-level totem-pole PFC works at 120 kHz switching frequency, and the ripple frequency is 360 kHz.

To reduce the inductor size of the 2-level totem-pole PFC, the switching frequency of the 2-level PFC is increased to 360 kHz, and the ripple frequency is increased to 360 kHz as well. Two 650 V GaN devices for the 2-level PFC (360 kHz) and one 200 V GaN device for the 4-level PFC (120 kHz) are selected in this comparison.

The key parameters of the devices are listed in Table 2.1. The GaN device loss includes the switching turn on loss, switching turn off loss, charging and discharging C_{OSS} loss, and conduction loss. Since the GaN devices do not have reverse recovery, there is zero reverse recovery loss. The switching turn on/off losses are the switching transition losses caused by the device current and voltage overlapping.

Table 2.1 Comparison of GaN devices

Part number	Voltage rating	$R_{DS(on)}$	Q_{Gtotal}	C_{OSS}
GS66516T	650 V	24 mΩ	14.2 nC	335 pF
GS66508T	650 V	50 mΩ	6.1 nC	160 pF
EPC2215	200 V	8 mΩ	13.6 nC	556 pF

Device loss comparison between 2-level totem-pole PFC and 4-level totem-pole PFC with the same ripple frequency is given in Figure 2.3.

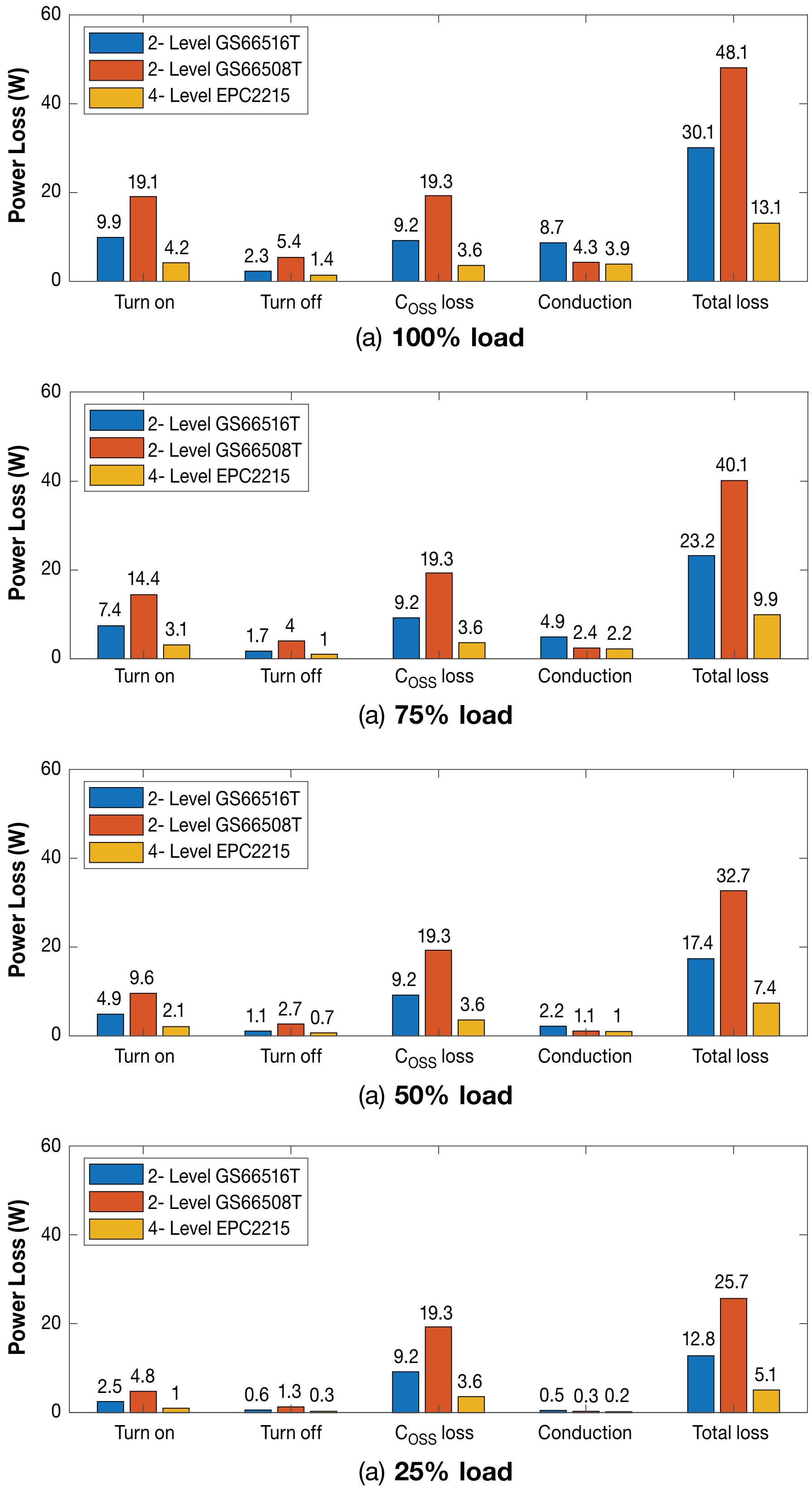


Figure 2.3 Device loss comparison between 2-level totem-pole PFC and 4-level totem-pole PFC with the same ripple frequency

The comparison between 2-level totem-pole PFC and 4-level totem-pole PFC with the same ripple frequency, shown in Figure 2.3 can be summarized as follows.

1) For the conduction loss, the 650 V, 25 mΩ GaN device GS66508T has similar conduction loss compared with the 4-level GaN solution, and the 650 V, 50 mΩ GaN device GS66516T has higher conduction loss.
2) The switching loss dominates the total loss. As shown in Figure 2.3, the 650 V, 25 mΩ GaN device GS66508T for the 2-level PFC has much higher switching loss due to the larger gate charge and the larger output capacitance compared with the 4-level GaN solution. The 650 V, 50 mΩ GaN device GS66516T reduces the switching loss compared with the 25 mΩ one, however, it still has much higher switching loss compared with the 4-level GaN solution.
3) The switching turn-on loss and the charging and discharging C_{OSS} loss are much higher than the turn-off loss. The switching turn-on loss can be reduced by further reducing the gate resistance. However, the charging and discharging C_{OSS} loss is not dependent on switching speed, and it dominates the switching loss especially under half and light load conditions. The 4-level GaN solution has only 3.6 W charging and discharging C_{OSS} loss which is much less than those of the 2-level GaN solutions.
4) The 4-level GaN solution with EPC2215 achieves more than 55% reduction of the total device loss compared with the 2-level GaN solution with GS66516T, and achieves more than 70% reduction of the total device loss compared with the 2-level GaN solution with GS66508T. The 4-level GaN solution achieves very low device loss while keeping the ripple frequency to 360 kHz and reducing the voltage swing on the inductor.

2.7 Control Strategy and Feed-Forward Modulation for 4-Level Totem-Pole PFC

The control strategy of this 4-level totem-pole PFC is shown in Figure 2.4. This control strategy is based on the dual-loop control including the outer DC voltage loop and the inner AC current loop. The duty cycle, d, is for the high-side devices. The duty cycle, d, has a step change during the AC zero crossing as shown in Figure 2.4. This step change is a challenge for the dynamic response of the AC current control loop.

To solve this issue, a feed-forward signal, d_{ff}, is added to the output of the AC current controller. The calculation of d_{ff} is expressed as $d_{ff} = V_{AC}/V_{DC}$ if $V_{AC} > 0$, and $1 + V_{AC}/V_{DC}$ if $V_{AC} < 0$. Since the feed-forward signal d_{ff} is the big signal of the duty cycle, the step change of the duty cycle is generated by this feed-forward signal. The feed-forward signal also compensates the variation of the input and output voltages.

Therefore, the output of the AC current controller, G_{cv}, can be a small number, around zero, and it does not include the step change signal. With this feed-forward signal, the dynamic response of the AC current control loop is improved. The PWM signals are generated by the duty cycle, d, and PSPWM. The voltage balancing is naturally achieved by PSPWM. The gating signals for line frequency switches S_a and S_b are determined by the AC voltage polarity detection.

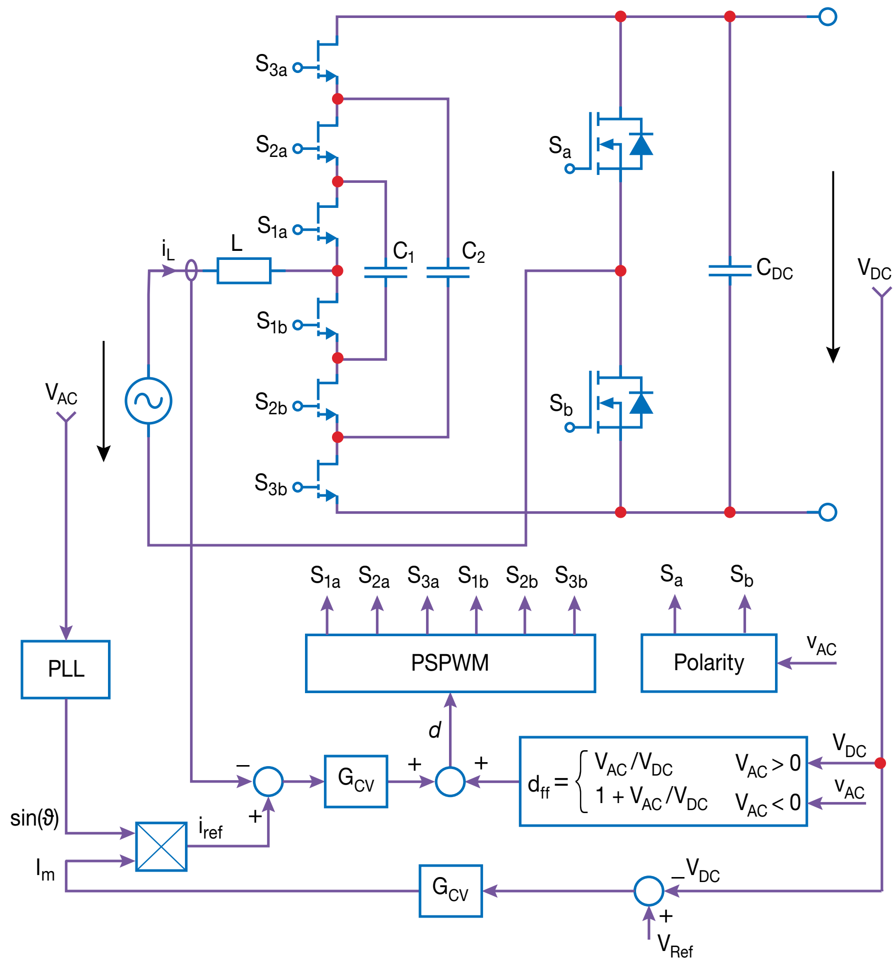


Figure 2.4 Control strategy for 4-level totem-pole PFC

2.8 Hardware Demonstration and Experimental Verification of a 4-Level, FCML, GaN FET Totem-Pole PFC

In this section, a 3 kW, 4-level, FCML, GaN totem-pole PFC is designed and tested. For the evaluation unit, the operation conditions are as follows: the grid voltage is 240 V_{AC}/60 Hz, the DC bus voltage is 400 V, and the switching frequency is 120 kHz.

The list of the key components is shown in Table 2.2. The 3 kW, 4-level, FCML, GaN totem-pole PFC power stage card is shown in Figure 2.5 and Figure 2.6. The size of the PFC card is 7.8 × 4.2 × 1.1 cm. The power density of this power stage card is 1150 W/in^3 without heat sink and with forced air cooling. This GaN PFC card is a power stage module. Figure 2.5 shows the top-side view of the GaN PFC card. The GaN and Si switches, the drivers, the driver power supplies, and the high frequency decoupling capacitors are highlighted.

Table 2.2 Components for the 2.5 kW, FCML, 4-level, GaN totem-pole PFC

Component	Part number	Parameters
GaN devices	EPC2215	200 V, 8 mΩ
Si devices	IPT60R028G7XTMA1	650 V, 28 mΩ
Isolated gate driver	Si 8271	1.8 A/4A
Flying capacitor	C5750X6S2W225K259KA	450 V, 2.2 μF, 4 in parallel
Inductor	IHLP-5050FD-01	3.3 μF, 4 in series
DSP controller	TMS320F28379	200 MHz

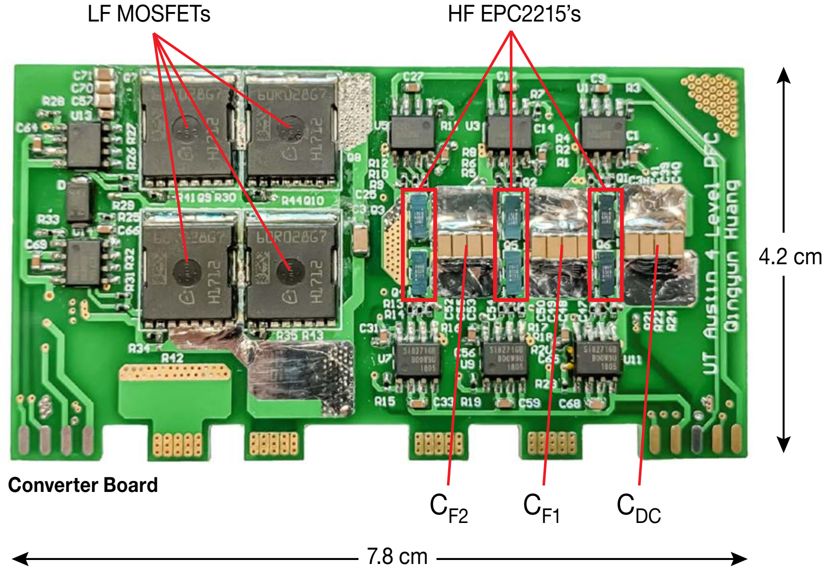


Figure 2.5 Top-side view of the 3 kW, 4-level, FCML, GaN totem-pole PFC card

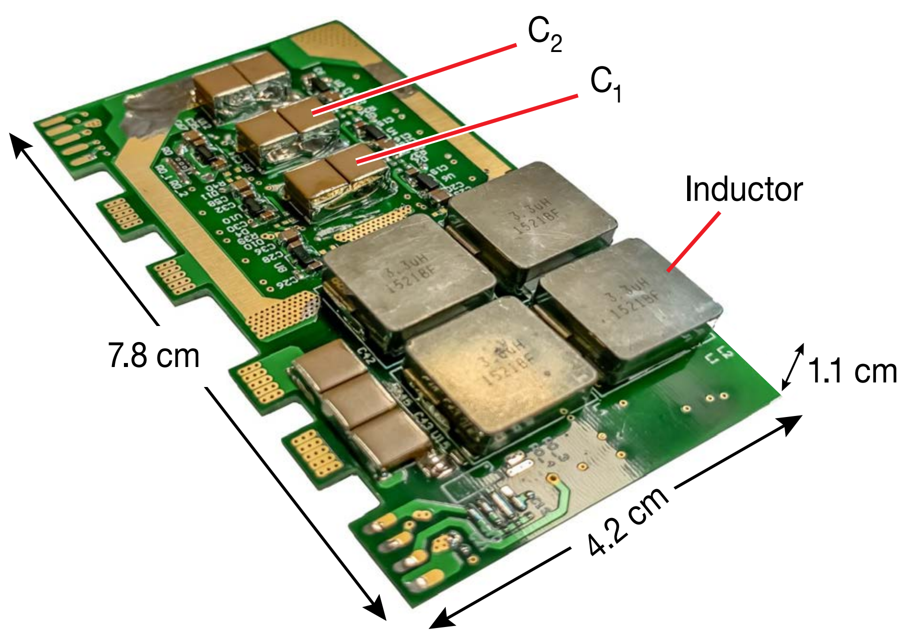


Figure 2.6 Bottom-side view of the 3 kW, 4-level, FCML, GaN totem-pole PFC card

Figure 2.6 shows the bottom-side view of the GaN PFC card. The flying capacitors and the main inductor are highlighted. This GaN PFC card, which is very compact and low profile, can be used as a PFC module in the PFC system. It is easy to build a higher power PFC system with multiple GaN PFC cards.

The driver power supply solution uses the cascaded bootstrap method [15]. This solution provides multiple driver power supplies for the FCML converter without any transformers and with low cost and small footprint area. The whole 3 kW PFC system, including the GaN PFC card, the controller card, the DC bulky capacitors, EMI filter, and relay, is shown in Figure 2.7. The size of this whole PFC prototype is 12.1 × 7.3 × 4.5 cm, and the density is 104 W/in^3 without heat sink and with forced air cooling.

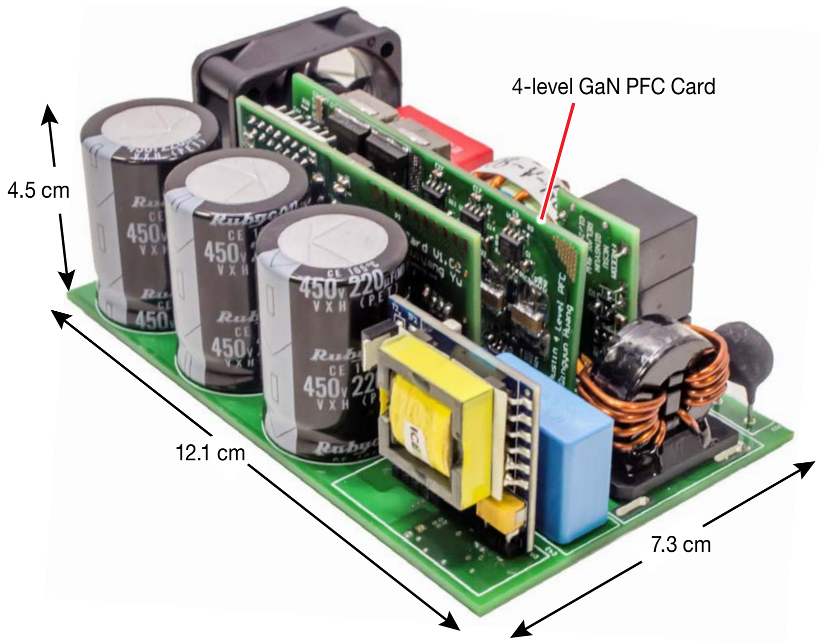


Figure 2.7 3 kW, 4-level, FCML, GaN totem-pole PFC system

Figures 2.8 through 2.10 show the experimental waveforms under the following conditions: V_{AC} = 240 V_{AC}/60 Hz and V_{DC} = 400 V. Figure 2.8 shows the start-up waveforms for 2.5 kW high power condition. The grid current, DC voltage and multilevel waveforms are controlled very well during the start-up. Figures 2.9 and 2.10 show the steady-state waveforms for 1.5 kW and 2.5 kW respectively.

The well-controlled current, DC voltage and the multilevel waveforms verify the operations and the control strategy of this 4-level, FCML, totem-pole PFC. Figure 2.11 shows the measured efficiency for the converter. The measured peak efficiency is 99.25% under half load condition. The measured full power efficiency is 99.1% and remains above 99% from 1 kW to 3 kW. The efficiency does not include the gate driver and the controller power consumption.

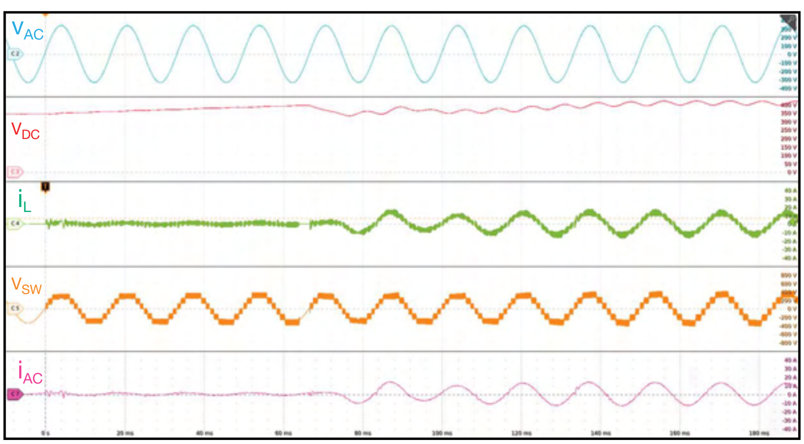


Figure 2.8 Start-up waveform for high power 2500 W condition

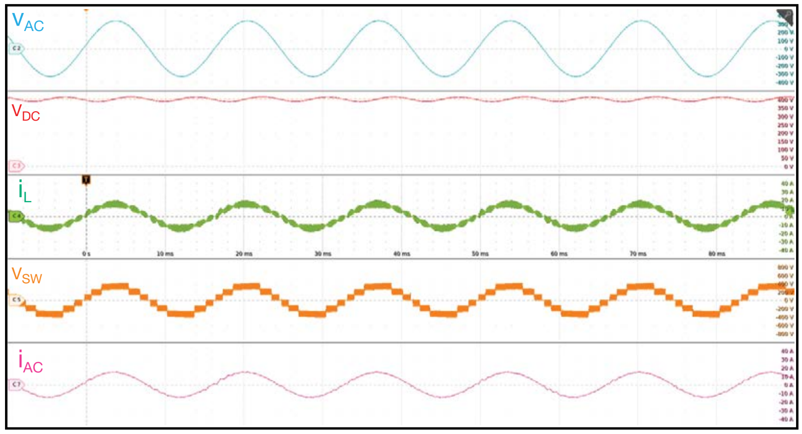


Figure 2.9 Steady-state waveform for high load 2500 W condition

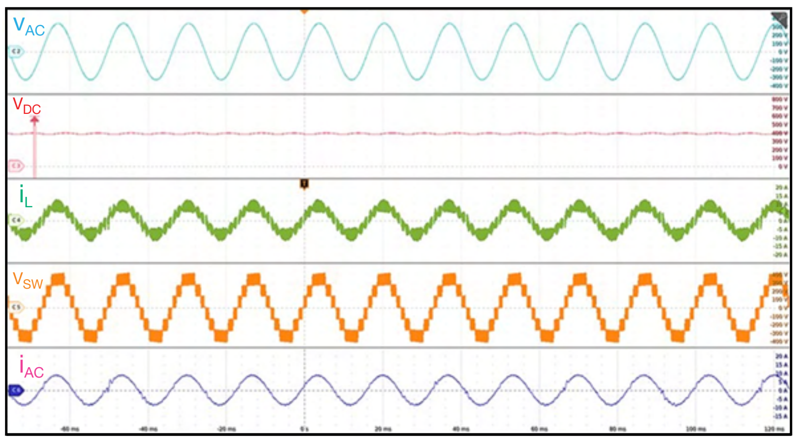


Figure 2.10 Steady-state waveform for half load 1500 W condition

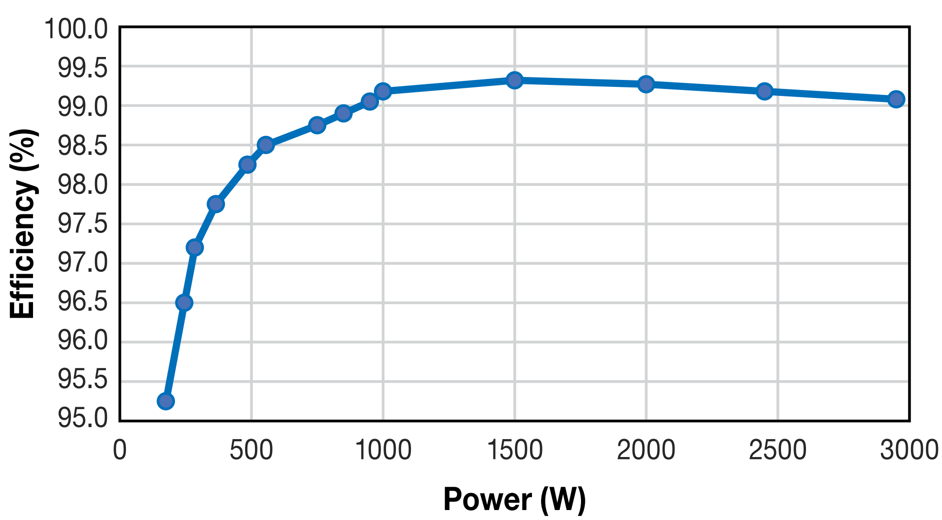


Figure 2.11 Measured efficiency for 4-level, FCML, totem-pole PFC shown in Figure 2.7

2.9 Summary for the 4-Level, FCML, CCM GaN Totem-Pole PFC

In this section, a 99% efficient, 3 kW, 4-level, FCML, CCM GaN totem-pole PFC with 200 V rated EPC2215 GaN devices was investigated, designed and tested. Compared with the conventional 2-level, CCM, GaN totem-pole PFC, this 4-level, FCML, GaN totem-pole PFC has the following benefits: utilization of the low voltage GaN devices, reduced switching voltage, reduced voltage swing on the inductor and increased equivalent ripple frequency of the inductor.

This 3 kW, 4-level, GaN PFC is designed with a 120 kHz switching frequency and has a 360 kHz current ripple frequency. The device loss between the proposed 4-level, totem-pole GaN PFC with 200 V GaN devices and the conventional 2-level, GaN totem-pole PFC with 650 V GaN devices, under the same ripple frequency 360 kHz condition were compared.

The 4-level, GaN PFC solution with EPC2215 (200 V, 10 mΩ) shows the full load device loss of only 13.1 W and achieves more than 55% reduction of the total device loss compared with the 2-level GaN solution with GS66516T (650 V, 50 mΩ), and achieves more than 70% reduction of the total device loss compared with the 2-level GaN solution with GS66508T (650 V, 25 mΩ). In addition, even if increasing the switching frequency of the 2-level GaN PFC to 360 kHz, the current ripple of the 2-level PFC is still much higher than that of the 4-level PFC, since the 4-level PFC has much less voltage swing on the inductor. The inductor is only 13.2 µH for this 3 kW 4-level PFC.

A 3 kW, 4-level, FCML, GaN totem-pole PFC prototype under 120 kHz switching frequency (360 kHz ripple frequency) is developed and tested. The start-up and steady state waveforms verify the efficient and stable operation and control of this 4-level PFC. This prototype achieves a power density of 104 W/in^3 without heat sink and with forced air cooling. The peak efficiency is 99.25% at half load, and the full power efficiency is 99.1%.

The last section discusses LLC converters which are most popular in high-density DC-DC converters with V_{IN} in the range of 60–30 V.

3.0 Summary

EPC's latest textbook , ***GaN Power Devices and Applications***, explores GaN power conversion solutions for four DC output topologies: buck, multi-level, LLC and bi-directional, discussed in this eBook.

GaN devices were examined in terms of their ability to meet the ever-increasing demands placed on power conversion systems from emerging applications requiring extremely high-power density, light weight, thin form factors, low cost, and high reliability. These constantly increasing requirements have caused the bounds of power transistors to be pushed beyond the capability of the aging silicon power MOSFET.

In all power conversion topologies reviewed, best-in-class performance in terms of efficiency or power density, is achieved with GaN devices.

ASK AN EXPERT GaN **For design assistance submit a request to Ask a GaN Expert**

References

1 Efficient Power Conversion Corporation (2021, Revision 3.0), *EPC9528 – dsPIC33CK Controller Module*, [Online]. Available: https://epc-co.com/epc/Portals/0/epc/documents/guides/epc9528_qsg.pdf

2 Efficient Power Conversion Corporation (2021, Revision 1.0), EPC9148 – Development Board, *EPC9148 – 28 V Three-level Synchronous Buck Converter*, [Online]. Available: https://epc-co.com/epc/Portals/0/epc/documents/guides/epc9148_qsg.pdf

3 Lee, F. C., Li, Q., Liu, Z., Yang, Y., Fei, C., and Mu, M., "Application of gan devices for 1 kw server power supply with integrated magnetics," *CPSS Transactions on Power Electronics and Applications*, vol. 1, no. 1, pp. 3–12, 2016.

4 Huber, L., Jang, Y., and Jovanovic, M. M., "*Performance evaluation of bridgeless pfc boost rectifiers*," IEEE Transactions on Power Electronics, vol. 23, no. 3, pp. 1381–1390, 2008.

5 Jang, Y. and Jovanovic, M. M., "*A bridgeless pfc boost rectifier with optimized magnetic utilization*," IEEE Transactions on Power Electronics, vol. 24, no. 1, pp. 85–93, 2009.

6 Liu, Z., Lee, F. C., Li, Q., and Yang, Y., "*Design of gan-based mhz totempole pfc rectifier*," IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 4, no. 3, pp. 799–807, 2016.

7 Zhou, L., Wu, Y., Honea, J., and Wang, Z., "*High-efficiency true bridgeless totem pole pfc based on gan hemt: Design challenges and cost-effective solution*," in Proceedings of PCIM Europe 2015; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management, 2015, pp. 1–8.

8 Liu, Z. Huang, Z., Lee, F. C., and Li, Q., "*Digital-based interleaving control for gan- based mhz crm totem-pole pfc*," IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 4, no. 3, pp. 808–814, 2016.

9 Marxgut, C., Krismer, F., Bortis, D., Kolar, J. W., "*Ultraflat Interleaved Triangular Current Mode (TCM) Single-Phase PFC Rectifier*," IEEE Transactions on Power Electronics, Vol. 29, No. 2, pp. 873-882, February 2014.

10 Haryani, Nidhi, "*Zero Voltage Switching (ZVS) Turn-on Triangular Current Mode (TCM) Control for AC/DC and DC/AC Converters*" Dissertation submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Electrical Engineering, November 6, 2019

11 Lei, Y., Barth, C., Qin, S., Liu, W., Moon, I., Stillwell, A., Chou, D., Foulkes, T., Ye, Z., Liao, Z, and Pilawa-Podgurski, R. C. N., "*A 2-kw single-phase seven-level flying capacitor multilevel inverter with an active energy buffer*," IEEE Transactions on Power Electronics, vol. 32, no. 11, pp. 8570–8581, 2017.

12 Qin, S., Lei, Y., Ye, Z., Chou, D., and Pilawa-Podgurski, R. C. N., "*A highpower-density power factor correction front end based on seven-level flying capacitor multilevel converter*," IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 7,no. 3, pp. 1883–1898, 2019.

13 Vu, T. T. and Young, G., "*Implementation of multi-level bridgeless pfc rectifiers for mid-power single phase applications*," IEEE Applied Power Electronics Conference and Exposition (APEC), Long Beach, CA. (March 2016)., pp. 1835– 1841.

14 Vu, T. T., and Mickus, E., "*99% efficiency 3-level bridgeless totem-pole pfc implementation with low-voltage silicon at low cost*," IEEE Applied Power Electronics Conference and Exposition (APEC), Anaheim, CA. (March 2019). pp. 2077–2083.

15 Ye, Z., Lei, Y., Liao, Z., and Pilawa-Podgurski, R. C. N., "*Investigation of capacitor voltage balancing in practical implementations of flying capacitor multilevel converters*," IEEE 18th Workshop on Control and Modeling for Power Electronics (COMPEL), 2017, pp. 1–7.