How to Design a Highly Efficient, 2.5 kW, Universal Input Voltage Range, Power Factor Correction (PFC) 400 V Rectifier Using 200 V eGaN® FETs

Acknowledgement - This application note and associated hardware was developed in collaboration with **Semiconductor Power Electronics Center (SPEC)** at **University of Texas at Austin.**

Motivation

The expansion of applications such as cloud computing, wearables, machine learning, autonomous driving, and IoT drive us towards an even more data-intensive world, increasing demands on data centers and power consumption [1, 2]. The importance of efficiency, power density, and cost of the AC to DC switching power supply is driving innovative solutions that eGaN FETs can solve to yield ultra-high efficiency power factor correction (PFC) front-end rectifier solutions that are the focus of this how-to-application note.

The 4-level Flying Capacitor Multi-Level (FCML) totem-pole bridgeless PFC converter

The conventional 2-level totem-pole bridgeless PFC topology has been a popular choice to achieve high efficiency using 650 V rated GaN FETs but does not address the power density and loss limitations of the main inductor [3]-[5]. The 4-level flying capacitor multi-level (FCML) totem-pole bridgeless PFC topology is an alternative that can utilize 200 V eGaN FETs, that can operate to the maximum grid line voltage of 274 V_{ACRMS}, and make use of the volt-seconds reduction and frequency multiplication for the inductor to significantly increase the power density and yield a high efficiency solution. The power schematic of the FCML-totem-pole bridgeless PFC rectifier is shown in figure 1. An added benefit of the 4-level FCML -totem-pole bridgeless PFC rectifier topology is that due to the low inductance required it minimizes the input current harmonic distortion and can maintain switching even with the highest peak line voltage.

The 200 V rated EPC2215 for the 4-level FCML totem-pole PFC converter

One of the many benefits of using a multi-level topology is that lower voltage devices can be used. In this 4-level topology, six, cascade connected, high frequency devices (Q_1 through Q_6) are used in the high frequency leg shown in figure 1. The output DC voltage is set to 400 V so the voltage stress for each of the high frequency devices is only 133 V, plus margin, ensuring that 200 V devices are well suited for this topology. The 200 V rated **EPC2215** eGaN FET, with $R_{DS(on)}$ of 8 mΩ shown in figure 2, offers low switching loss, low driving power consumption, and zero reverse recovery compared to traditional silicon devices, enabling a high efficiency solution.

Figure 3 shows a size comparison between the EPC2215 and close match MOSFET equivalent that is 15 times larger and will consume 6.5 times more gate power. In addition, the higher output capacitance will also increase the switching losses for the MOSFET compared to the GaN FET.

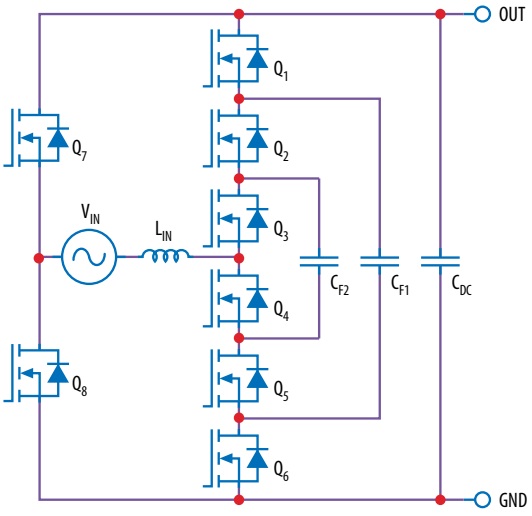

Figure 1. 4-Level flying capacitor multi-level eGaN FET totem-pole PFC rectifier schematic

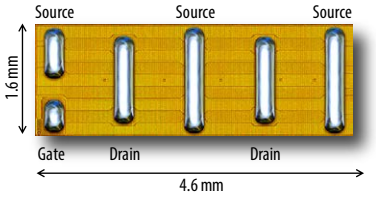

Figure 2. Photo of the bump side of 200 V rated, 8 mΩ, EPC2215

IPT111N20NFD
$R_{DS(on)}$ = 11.1 mΩ
Q_{OSS} = 162 nC
Q_G (at V_G =10 V) = 65 nC
V_{Gmin} = 7 V

EPC2215
$R_{DS(on)}$ = 8 mΩ
Q_{OSS} = 69 nC
Q_G (at V_G =5 V) = 13.6 nC
V_{Gnom} = 5 V

Figure 3. Device size comparison between the EPC2215 and closest match MOSFET counterpart, both are rated at 200 V

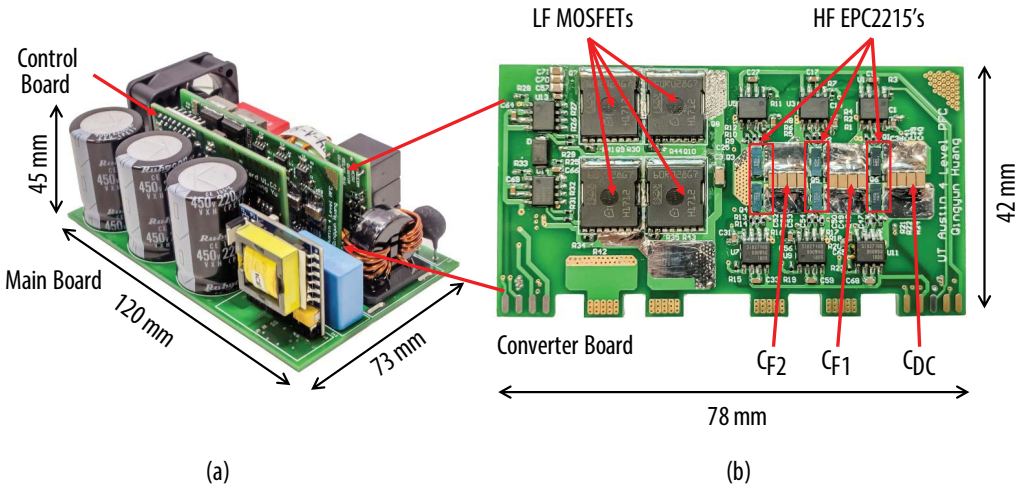

Figure 4. Photo of the (a) complete PFC rectifier and (b) the FCML bridgeless totem pole converter card

Experimental validation

A 2.5 kW, 4-level flying capacitor multilevel (FCML) GaN FET totem-pole PFC converter was built and is shown in figure 4 [7]. The experimental unit comprises multiple cards; 1) a mother board with EMI filter, housekeeping power supply and bulk output capacitance, 2) a controller card and, 3) the GaN FET flying capacitor multi-level converter card.

Figure 5 shows the measured input AC voltage, the well-controlled inductor current and the multi-level switch-node waveforms when the converter is operating with 240 V_{ACRMS} input voltage and delivering 2.5 kW into a 400 V_{DC} load.

The overall power efficiency of the 4-level FCML totem-pole GaN FET PFC is shown in figure 6 up to 2.5 kW with a peak efficiency of 99.25% at 1.4 kW and remains above 99% from 900 W and up.

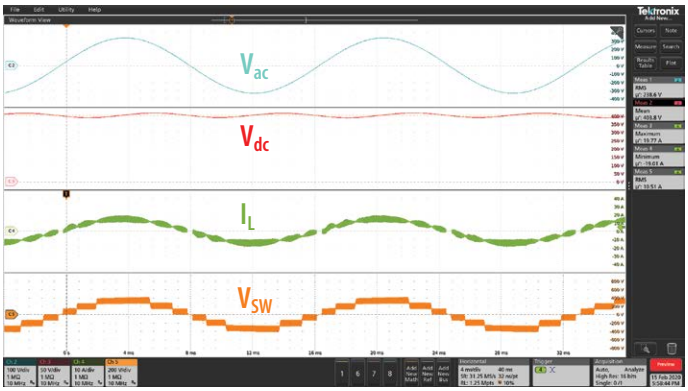

Figure 5. Measured waveforms of the inductor current (I_L), AC input voltage (V_{AC}), and switch-node voltage (V_{SW}) when delivering 2400 W into the 400 V_{DC} load

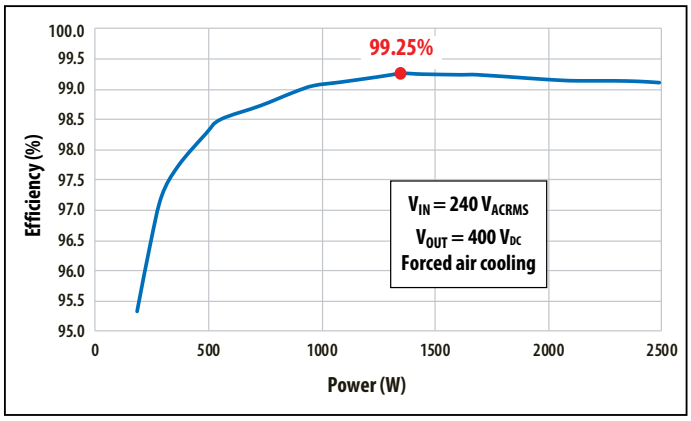

Figure 6. Power efficiency of 4-level FCML totem-pole GaN FET PFC converter

Conclusion

A high efficiency, high power density, 2.5 kW capable eGaN FET-based 4-level flying capacitor multi-level bridgeless totem-pole rectifier that is suitable for data center applications was presented. The 200 V rated, 8 mΩ, EPC2215 was used in the high frequency leg that resulted in a converter that exceeded 99% efficiency from 900 W through 2.5 kW with a peak of 99.25% at 1.4 kW. The complete converter solution has a power density of 125 W/in^3 and includes the EMI filter, bulk output capacitors, controller card, and housekeeping power supply. The advantageous characteristics of eGaN FETs [6] allowed this converter to achieve high power density, ultra-high efficiency, and low harmonic distortion.

References

[1] A. Marashi, "Power Hungry: The Growing Energy Demands of Data Centers," VXchange, June 28th, 2019, [On-line available, accessed Oct. 24, 2019] https://www.vxchnges.com/blog/power-hungry-the-growing-energy-demands-of-data-centers

[2] F. C. Lee, Q. Li, Z. Liu, Y. Yang, C. Fei and M. Mu, "Application of GaN devices for 1 kW server power supply with integrated magnetics," in CPSS Transactions on Power Electronics and Applications, vol. 1, no. 1, pp. 3-12, Dec. 2016.

[3] Z. Liu, F. C. Lee, Q. Li and Y. Yang, "Design of GaN-Based MHz Totem-pole PFC Rectifier," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 4, no. 3, pp. 799-807, Sept. 2016.

[4] L. Zhou, Y. Wu, J. Honea and Z. Wang, "High-efficiency True Bridgeless Totem Pole PFC based on GaN HEMT: Design Challenges and Cost-effective Solution," Proceedings of PCIM Europe 2015; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management, Nuremberg, Germany, 2015, pp. 1-8.

[5] Z. Liu, Z. Huang, F. C. Lee and Q. Li, "Digital-Based Interleaving Control for GaN-Based MHz CRM Totem-pole PFC," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 4, no. 3, pp. 808-814, Sept. 2016.

[6] A. Lidow, M. de Rooij, J. Strydom, D. Reusch, J. Glaser, "GaN Transistors for Efficient Power Conversion," 3rd Edition, J. Wiley 2020, ISBN 978-1-119-59414-7. Available from https://epc-co.com/epc/products/publications/gan-transistors-for-efficient-power-conversion

[7] Q. Huang, Q. Ma, P. Liu, A.Q. Huang, and M. Rooij, "3kW Four-Level Flying Capacitor Totem-Pole Bridgeless PFC Rectifier with 200V GaN Devices," in ECCE 2019.