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Beyond-Nominal Operation of GaN-Based Converters for High-Power Density Applications

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Abstract

There is zero-tolerance for failure in various critical applications, including aerospace, naval ships, and electric vehicles where power converters are crucial for system operation. Uncertain scenarios, such as sudden converter unit failures may push these systems to operate beyond-nominal conditions and stress other converters on the power system. The loss of even a single converter can risk critical operation capabilities. A 1-MHz buck converter is assumed to be a fully functional component in a damaged power system, and its reliability under a high-stress, beyond-nominal operating condition is investigated to enable full power system capabilities with reduced components. The converter was designed for a maximum current rating of 6.5 A and nominal operation of 5.5 A and tested up to 30 % above the nominal current rating. Operating a converter beyond-nominal test conditions places each component at risk of degradation or failure which needs to be monitored in these conditions. For example, the change in on-resistance is an important factor to consider for beyond-nominal operating conditions in switching devices for monitoring health. Therefore, a simple and accurate method to measure the dynamic on-resistance is also provided with experimental results.

Introduction

- Power electronics have become integral for electrified transportation, such as electric vehicles, eVTOLs, and electric ships [1],[2]. Due to their critical role in these systems and impact on application safety, these applications demand a zero-tolerance for failure. Therefore, the reliability of power converters should be given priority in the design process [3]. In this context, reliability can be defined as the ability of the system to perform as expected under given conditions for a specified period [4]. Failures in converters not only compromise system integrity but also lead to substantial increases in the overall cost of these systems.

Problem Statement

- Studying converters that operate beyond their designed limits is pivotal to preparing for inevitable damaged conditions and enabling the system to continue at near full capacity.
- Operating beyond-nominal conditions puts each component at risk of degradation. For example, inductors can saturate beyond certain current values while capacitors may experience reduced lifetimes under extreme temperature, voltage, and current conditions [5].
- While degradation in power electronic converters has been well documented [6], research exploring the effects of operating converters beyond their rated capacities has not been provided. This is a vital aspects in applications such as naval and aerospace systems where the harsh operational environments may necessitate operating some converter beyond their standard ratings for some period of time.

Solution

- This paper aims to provide a clearer understanding of the consequences of pushing power converters beyond their designed capacities.
- This study concentrates on the impact of exceeding the operational limits of converters on the degradation of switching components, such as GaN High Electron Mobility Transistor (HEMT) device and SiC Schottky diode.
- An analytical method has been developed to correlate the increase in power beyond rated limits with changes in the on-state resistance of the switches.
- A schematic of a buck converter designed for testing, highlighting components that are susceptible to failure, is presented in Fig. 1.

Beyond-Nominal Characteristics

- By using the normalized curve for the R_{DSon} of this device provided by the manufacturer, R_{DSon_m}, a linear equation was formulated to calculate the normalized on-state resistance, R_{DSon_norm}, based on the T_j of the device as

$$R_{DSon\_norm} = aT_j + b \quad (1)$$

$$R_{DSon\_calc} = R_{DSon\_m} R_{DSon\_norm} \quad (2)$$

- The T_j is calculated from thermal network as shown in Fig. 2 is,

$$T_j = P_{loss} R_{jc} + T_c \quad (3)$$

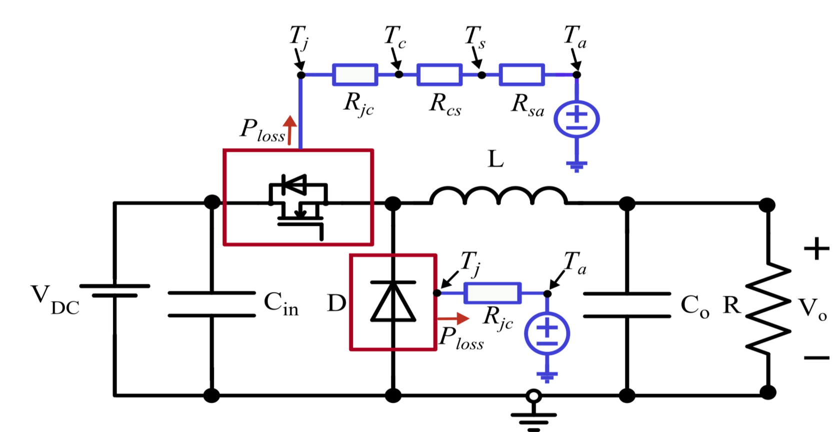

Fig. 1. MHz buck converter showing components susceptible to failure.

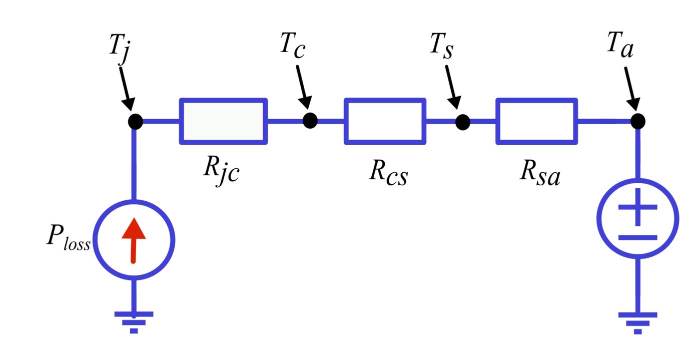

Fig. 2. Thermal network for GaN HEMT.

Results and Discussion

- Buck converter operating at 1-MHz is utilized, as depicted in Fig. 3.
- Figure 4 presents GaN HEMT R_{DSon_calc} with respect to load in per unit (PU). Overall, there is 46% increase in on-resistance under beyond-nominal load conditions compared to using the static normalized R_{DSon} provided in the datasheet.
- Figure 5 illustrates the GaN HEMT losses and the discrepancy in error, comparing on-resistance values from the datasheet against those derived using the method presented. Figure 5 (a) highlights a rise in GaN losses attributed to an increase in on-resistance when subjected to beyond-nominal load conditions. Figure 5 (b) illustrates the error percentage, with losses differing by 7% at nominal load and nearing 11% at beyond-nominal load.
- Figure 6 shows that there is an observed 11% difference in T_j under conditions 30% above nominal, compared to a 6.5% difference at nominal operation.

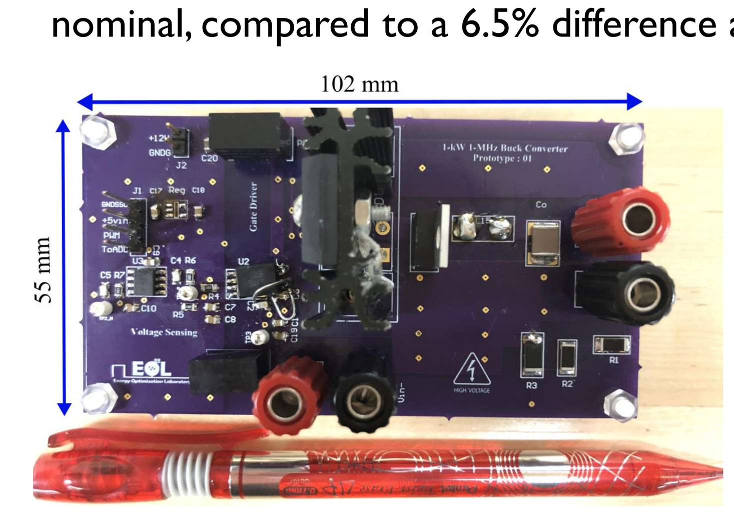

Fig. 3. 1-MHz Buck converter prototype built in laboratory.

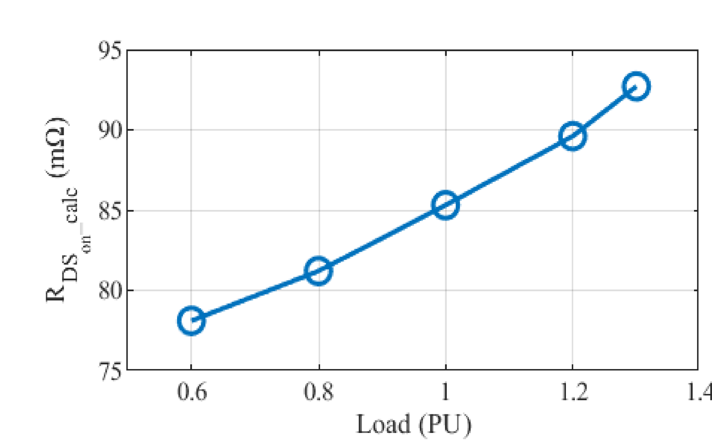

Fig. 4. GaN HEMT device R_{DSon_calc} with respect to load.

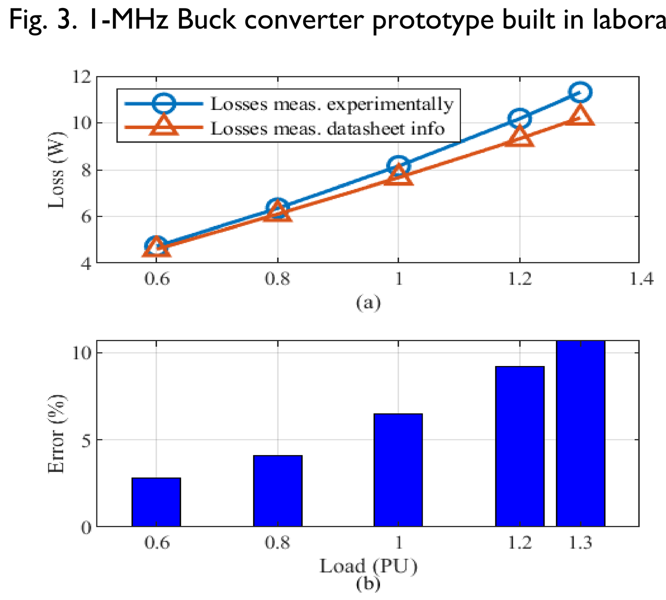

Fig. 5. Losses of GaN HEMT (a) experimentally measured losses and calculated losses with information given in the datasheet (b) % error.

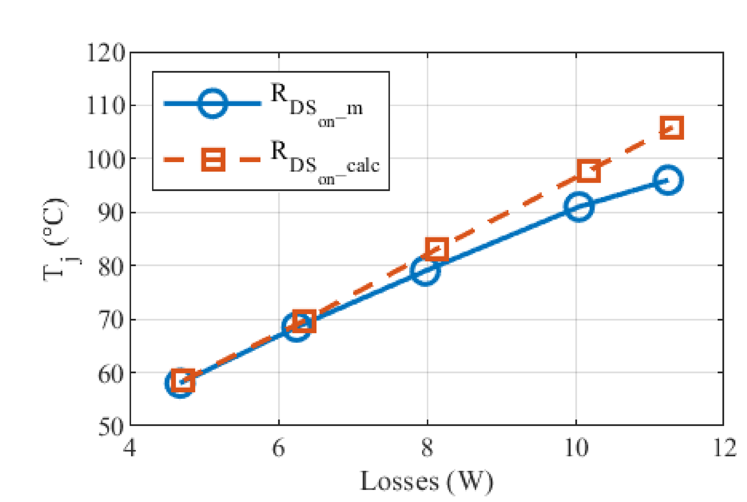

Fig. 6. Comparison of losses with T_j calculated form thermal networks for GaN HEMT with losses using $R_{DS\_on\_m}$ and $R_{DS\_on\_calc}$.

- Figure 7 highlights the experimentally measured T_j with respect to loading. The switching device, diode, and inductor reached a maximum temperatures of 106˚C, 180˚C, and 70˚C respectively at beyond-nominal loads.
- In this experiment, the diode was intentionally operated without a heatsink, causing it to exceed its maximum temperature rating under off-nominal conditions.
- The thermal images taken during the experiment, are illustrated in Fig. 8, where GaN HEMT, inductor, and the overall converter temperatures are shown.

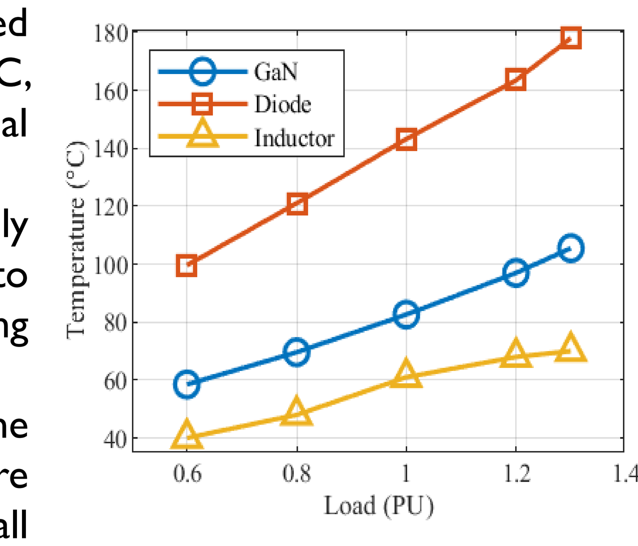

Fig. 7. GaN HEMT, SiC diode and inductor temperature profiles at various loads.

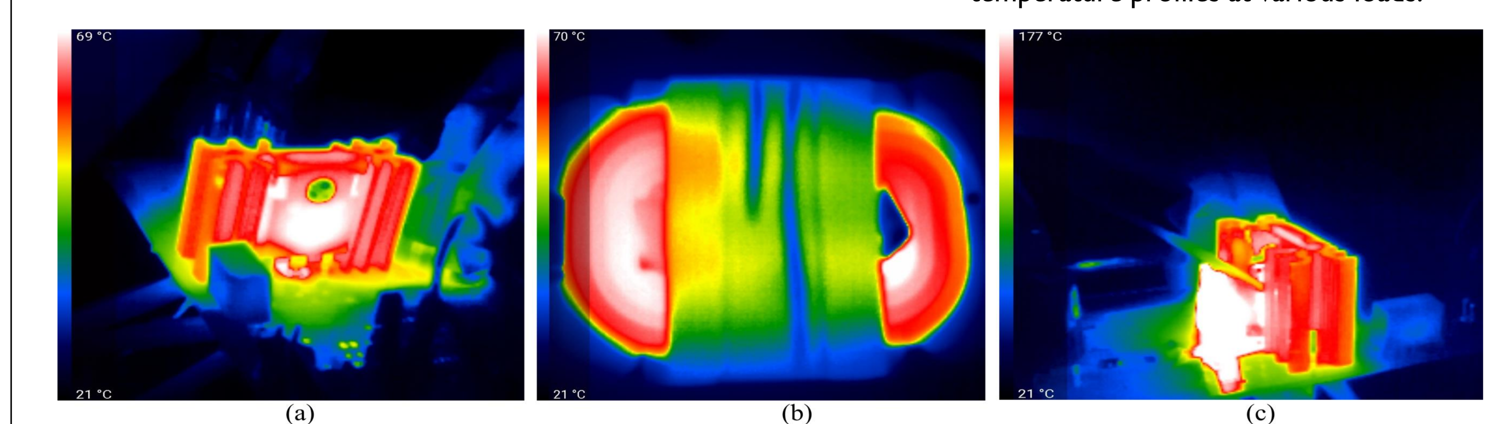

Fig. 8. Thermal images taken during beyond-nominal operating conditions (a) GaN HEMT device (b) inductor and (c) overall converter.

Conclusions

- The experimental results showed that the method used in this study provided more realistic temperature estimations than the static resistance.
- The power losses in GaN HEMT and SiC Schottky diode reveal a notable increase, accompanied by a significant increase in junction temperatures. With amplifying load, losses increase due to an increase in R_{DSon} , and T_j rises as well.
- The diode T_j, calculated from the thermal network, shows that it reached its maximum thermal rating at a 6.5 A load, eventually leading to its failure at 7 A.
- The important precursors for degradation, such as changes in R_{DSon} in the switching device and temperature stresses in other parts in converter should be considered.
- It is paramount to consider beyond-nominal operation scenarios when designing converters for high-power dense applications.

References

[1] A. Narwaria, S. Sachan, and P. Swarnkar, "A review on hybrid electric vehicle drive and its controlling using optimized control algorithm," in *2023 1st International Conference on Innovations in High-Speed Communication and Signal Processing (IHCSP)*, 2023, pp. 353–358.

[2] L. L. Petersen, "A history of silicon carbide (sic) wide bandgap (wbg) advancement through power electronic building blocks (pebb) and infrastructure for the future," in *2023 IEEE Electric Ship Technologies Symposium (ESTS)*, 2023, pp. 362–368.

[3] F. Blaabjerg, H. Wang, I. Vernica, B. Liu, and P. Davari, "Reliability of power electronic systems for ev/hev applications," *Proceedings of the IEEE*, vol. 109, no. 6, pp. 1060–1076, 2021.

[4] H. Wang and F. Blaabjerg, "Power electronics reliability: State of the art and outlook," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 9, no. 6, pp. 6476–6493, 2021.

[5] B. Yao, X. Ge, H. Wang, H. Wang, D. Zhou, and B. Gou, "Mult timescale reliability evaluation of dc-link capacitor banks in metro traction drive system," *IEEE Transactions on Transportation Electrification*, vol. 6, no. 1, pp. 213–227, 2020.

[6] Ghadrdan, S. Peyghami, H. Mokhtari, H. Wang, and F. Blaabjerg, "Dissipation Factor as Degradation Indicator for Electrolytic Capacitors," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 11, no. 1, pp. 1035–1044, 2023.