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On the impact of current generation commercial gallium nitride power transistors on power converter loss

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The enormous potential benefits of gallium nitride based power switching devices, only commercially available very recently, in terms of power switching device loss are highlighted. This is first demonstrated through a simulated prediction of loss in multilevel converters, followed by experimental validation. While the simulations focus on losses in multilevel converters, the observations made are relevant in a broad range of applications.

Introduction: Currently, power switching devices are predominantly silicon (Si) based, with the notable exception of silicon carbide based power switching devices which already find somewhat widespread use, especially in high-voltage switching applications. Gallium nitride (GaN) based high electron mobility transistors for power applications are a new technology, with few commercial suppliers and little market penetration, but are under continuing development. This research focusses on a new generation of devices recently released by Efficient Power Conversion (EPC), specifically their sixth generation eGaN technology [1]. While other manufacturers are producing GaN power transistors (e.g. Texas Instruments and ON Semiconductor etc.), none appear to have made more progress in lower voltage, higher current devices, which are of interest to the authors' ongoing research.

Simulated results: As part of ongoing research, a system was created for predicting switching device losses in cascaded H-bridge multilevel converters of increasing order, specifically for bidirectional grid–battery electrical energy storage. This type of converter for this application is an active area of research but not currently implemented commercially [2, 3]. A simplified schematic of a converter consisting of three cascaded H-bridges is shown in Fig. 1, giving a seven-level multilevel converter.

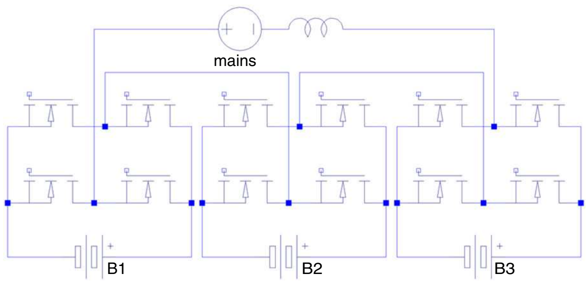

Fig. 1 *Simplified schematic of seven-level multilevel converter for bidirectional grid–battery interface consisting of three cascaded H-bridges*

As the number of cascaded H-bridges increases, there are more switching devices required, but they can have a lower voltage rating. In an effort to investigate the optimum number of cascaded levels, total switching device associated power loss was calculated from a range of sources: on-state resistance, transient gate dissipation, $V_{DS}I_D$ transient product during switching and gate driver losses [4].

The total losses are calculated for all members of a database collated from a range of power MOSFETs (Si and GaN), discounting devices that are not suitably rated. In each case, the device with the lowest total loss was selected as optimum, and its total loss was plotted along with a breakdown of the sources of loss. This plot can be seen in Fig. 2*a*, estimated for a reference 6 kW converter, with a nominal 500 V DC link and connected to a single-phase 230 V supply.

Fig. 2*b* shows that the results include the GaN devices produced by EPC, whereas Fig. 2*a* omits them and only considers Si devices. Above the threshold of five cascaded bridges, the results are in stark contrast. This threshold is the point at which the required drain–source voltage rating is low enough that EPC's eGaN devices are usable (160 V), with a derating of 20%. This shows that use of these devices can result in a much lower total converter switching associated power loss.

Upon inspection of the subdivision of losses, on-state conductance losses dominate, showing that turn-on gate energy is very low.

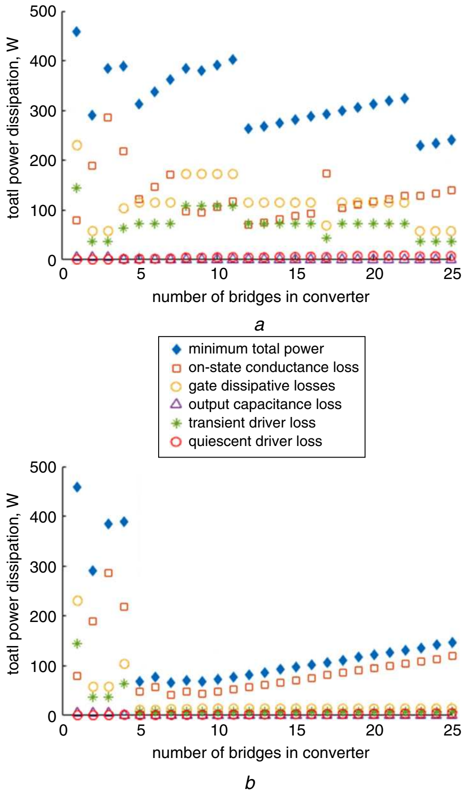

Fig. 2 *Plots showing subdivided total switching loss of optimal device at switching frequency of 100 kHz with respect to increasing multilevel converter order*

a Results when omitting GaN devices
b Results when including GaN devices

The predictions made in Fig. 2 consider the performance at a fixed switching frequency, which while informative, does not give a full picture. With the apparent gate dissipation being so low, it suggests that the benefits will become greater still at higher switching frequencies. This is in line with the suggestions made by EPC's marketing material [5].

An analysis was therefore performed which predicted switching loss not only over a range of total converter levels, but also over a range of frequencies. The frequencies considered range from 4 kHz to 1 MHz. While both the GaN devices and some Si devices are capable of frequencies higher than this (EPC's marketing material suggests switching frequencies of 5 MHz are easily attainable), simulations performed beyond 1 MHz yielded no additional insight.

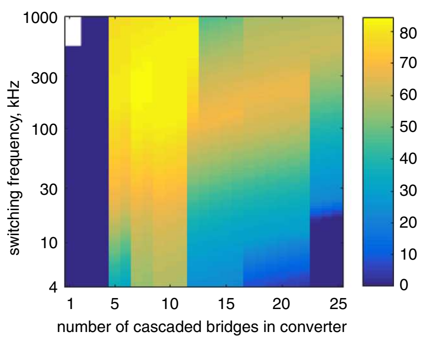

Fig. 3 *Heat map of percentage reduction in switching associated power loss enabled by GaN power devices*

The product of this analysis is shown in Fig. 3. Rather than showing the total losses in the two cases, it shows that percentage reduction in switching loss enabled by the GaN devices. Darker colours show regions of little or no improvement, while lighter colour regions show the greatest benefit. The exception being the white region to the top left, which denotes a region of there being no suitable devices, with there being no 300 V+ rated MOSFETs capable of switching at more than ∼500 kHz. Not immediately apparent in Fig. 3 is that 80 V GaN devices (the lowest voltage rating available) can significantly outperform even 30 V rated Si devices at higher switching frequencies (see top right of Fig. 3).

The results in Fig. 3 show that total switching device loss can be reduced by as much as 84%. The greatest benefits are found at medium voltage (150–60 V) and higher switching frequencies. At higher voltages, there are no suitable devices, whereas at lower voltages low voltage (40–30 V) Si devices become very competitive.

The gains at higher switching frequency are mostly due to the reduction in gate turn-on energy. A strong contributor to this is the low threshold voltage, in the order of 1 V. In fact, the maximum rating of the GaN devices only permit a gate driver peak voltage of 5 V. In order to validate these predictions, experimental data was gathered.

Experimental data: As the gains shown in simulation stem predominantly from very low turn-on gate energy, this was to be experimentally investigated. A range of Si devices were selected to be compared against some of EPC's eGaN devices. Specifically, the Si devices chosen were: the Infineon BZS0904NSI (30 V), the Fairchild FDMC86340 (80 V), the Fairchild FDMS86103 (100 V) and the Infineon BSB165N15NZ3 (150 V). These devices were compared with the GaN devices EPC2029 (80 V) and the EPC2034 (160 V). All are rated to ∼40–50 A.

Fig. 4 shows the drain–source voltage and the gate–source voltage through a turn-on event for the 80 V rated Si and GaN devices. It is switching the same inductive load across 75 V. The Si device has a peak gate driver voltage of 10 V, whereas the GaN device has a peak gate driver voltage of 5 V. The control signals occurred simultaneously.

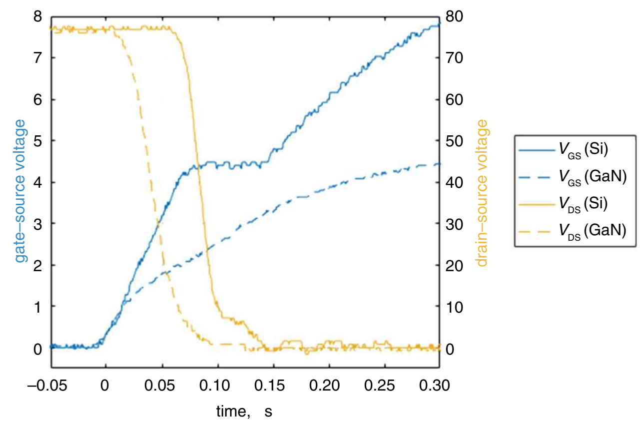

Fig. 4 *Turn-on characteristics of 80 V rated Si and GaN power devices switching an inductive load across a 75 V supply with same 50 Ω gate resistor*

From these voltage curves (gate driver output was also instrumented), the gate charge–voltage curves can be derived. The instantaneous gate current can be calculated from the voltage across the gate resistor (a known resistance) which is simply the difference between the gate driver output voltage and the drain–source voltage.

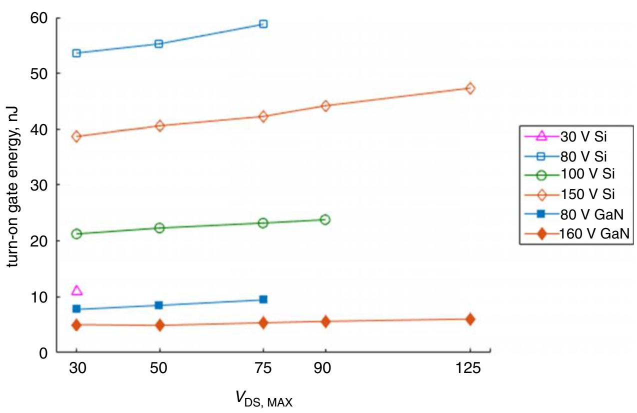

Fig. 5 *Turn-on gate energy for a range of devices over a range of maximum drain–source voltages*

Fig. 5 shows the gate turn-on energy (the gate charge–voltage integral between gate driver output turn-on and gate-source voltage falling to zero), for the aforementioned range of devices at a selection of maximum drain–source voltages.

The results in Fig. 5 show that the turn-on gate energy is very low for the GaN devices, as much as eight times less than equivalent Si devices. Also, while there is no strong correlation between drain–source voltage rating and gate energy, even the lowest voltage rated Si device, which also happens to have a very low turn-on energy for a Si device, cannot match a GaN device of much higher rating.

While not a complete validation of simulation the drastically lower turn-on gate energy predicted in simulation strongly holds true under experimental investigation.

Conclusions: The EPC sixth generation eGaN technology shows that there are very significant benefits, at least in terms of efficiency, that can be found through the use of these cutting-edge power switching devices. This is even when not considering the benefits that the access to higher switching frequencies might enable.

There are noteworthy disadvantages however. The cost of these devices can be as much as ten times that of an approximate Si equivalent. Furthermore, concern for parasitics in design of drive systems for these devices is greater than ever, with potential oscillatory behaviour being a significant, documented challenge [6]. The authors also experienced repeatable and immediate device failure near voltage limits with a larger gate resistance, apparently due to an excess $V_{DS}I_D$ product during the slower turn-on. Perhaps not unreasonable, but something not experienced by any Si device even when pushed further in this respect.

Overall, these devices appear to enable a striking jump in potential converter efficiency under certain conditions, but not without a burden in terms of cost and ease of implementation.

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One or more of the Figures in this Letter are available in colour online.

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