Driving of a GaN Enhancement Mode HEMT Transistor with Zener Diode Protection for High Efficiency and Low EMI

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Keywords

«Gallium Nitride (GaN)», «Power semiconductor device», «Switching losses», «Power factor correction», «EMC/EMI»

Abstract

The ultra-low gate charge characteristics and low gate voltage limitation of a GaN enhancement mode HEMT in combination with stray circuit elements poses many challenges of driving them in power electronic applications. This paper investigates the effect of changing gate resistances and including a Zener diode for overvoltage protection in the gate circuit. The goal is to achieve low switching losses and low EMC signature. Due to the very low gate capacitance of the GaN HEMT compared to the junction capacitance of the Zener diode, the addition of the Zener diode has an effect on the switching waveforms. The effects were investigated through simulation and measurements on a 1 kW PFC boost converter. The Zener diode was shown to increase time delay between the PWM signal and the switching of the GaN device. Furthermore, both fall and rise times of the drain-source voltage were influenced. Efficiency and EMC measurements highlight that the choice of gate resistor is an optimization problem, as faster switching increases efficiency but increase the EMC signature of the converter.

Introduction

Wide band gap devices promise lower conduction and switching losses compared to Si devices due to better material characteristics. The recent availability of GaN devices has led to a greater interest from industry to implement GaN devices in applications, especially within electrification of transport, distributed renewable and industrial applications [1]–[3]. However, the characteristics of the new devices necessitate that design methods are revised.

The low gate threshold voltage and low gate charge characteristics of a GaN HEMT poses many challenges for driving them in power electronic applications. This challenge is made bigger when considering the fast switching times of these devices and presence of stray elements in the gate and power loop of the converter. The need to minimize gate and power loop inductance has already been emphasized in literature, for example in [4]. However, these stray elements are never completely removed.

To protect the gate from overvoltages beyond 6 V, this paper investigated the addition of a Zener diode between gate and source of the GaN enhancement mode HEMT. Adding a Zener diode to the gate is a known solution to power electronic engineers and has been used for a long time. While they were previously used with Si switching devices, GaN devices has a much lower gate capacitance and the effect of additional components is no longer negligible. For applications that necessitate dead time control, even small effects from additional components would have to be taken into account.

Moreover, the fast switching characteristic of GaN HEMTs is an advantage for switching losses. On the other hand, it can lead to more EMI content for the converter. This EMI must be controlled for

GaN devices to be successfully implemented in applications. For devices operating in an inductive circuit, fast switching can cause overshoots of the drain voltage causing failures, as the GaN HEMTs have no avalanche capability. Therefore, it is important to optimize the switching speed so that the switching losses and overshoots are minimum.

GaN Enhancement Mode HEMT

Commercially available GaN devices are based on a HEMT structure, which is intrinsically a normally-on device. Some manufacturer offer normally-off devices that consist of HEMTs in cascode with a low voltage Si MOSFET. The enhancement mode HEMT (eHEMT) is a normally-off device and different manufacturers use different methods of making the device normally-off [5]. The eHEMTs that have insulated gate structures are voltage driven only, which enables the use of simple voltage source gate drive (VSGD) circuits. Most results in literature using eHEMTs use VSGD [4], [6], while a few papers suggest the more complex current source or resonant drivers [7], [8].

An additional challenge for GaN eHEMTs is the maximum voltage limit that is close to the recommended driving voltage. For the device used in this paper, the recommended gate driving voltage is 6 V while maximum gate voltage limits are +10 and -20 V. Thus, gate voltage ringing must be avoided as the limits are very tight and device break down could occur. The challenge with using VSGD is that the presence of stray elements could lead to oscillations on the gate voltage, in particular, if the gate and power loops have a common loop inductance. Even small values will influence operation when the switching speed is high. To address this issue, packaging of eHEMTs with kelvin connections for the gate loop are offered, effectively removing the common inductance. However, this is not in place for all devices offered on the market. Another case to consider is other type of overvoltages in abnormal operation (EMI or surge voltage events). Consequently, it might be necessary with gate protection to ensure device robustness against spur overvoltages.

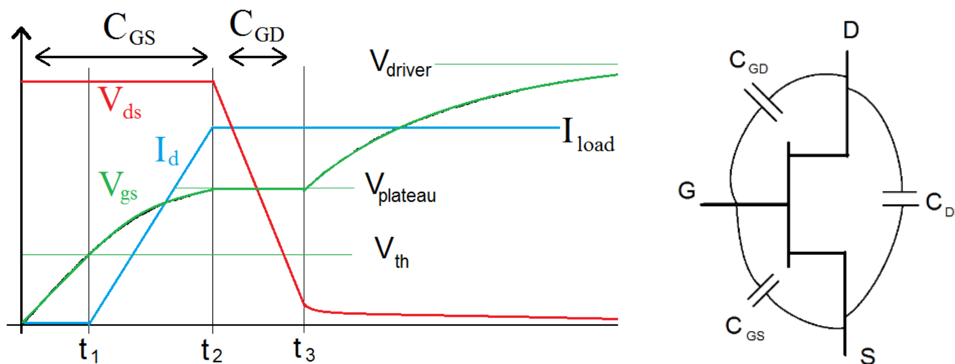

Figure 1. Left: Gate voltage waveform during turn-on. Right: MOSFET capacitance model.

The switching model of a GaN HEMT, shown in Fig.1, uses voltage dependent capacitances between each of the 3 terminals: gate, source and drain [9]. Ideal voltage and current waveforms for switching of a clamped inductive load for device turn-on are shown in the same figure. The waveform shows how the switching speed is dependent on the gate-source and gate-drain capacitance. Increasing the gate source capacitor is expected to give the following changes to the switching waveform:

1. Increased turn-on and turn-off delay between driver input and device output as it will take longer time to charge the gate voltage to the threshold value.
2. Increased turn-on and turn-off time for the device drain current, since it will take longer time to charge the gate voltage from the threshold value to the miller plateau.
3. Increased time operating with increased on-state resistance, as it takes longer time to charge the gate from the plateau voltage to the driver voltage when the device is completely enhanced

It is expected that the increased gate-source capacitance will mainly affect the delay time and have a small effect on the switching losses. The increase in switching losses will be due to a slower current

commutation. The voltage fall or rise time should be less affected, as that transition is mainly affected by the gate-drain capacitance.

Zener Diode Properties

Zener diode is a diode that is designed to operate in the reverse breakdown of its safe operating area. The breakdown mechanism of Zener diodes changes depending on voltage level [10]. For voltage lower than 4.5 V, the breakdown mechanism has been identified as the Zener effect. For breakdown voltages above 6.5 V, the effect is pure avalanche breakdown. In between there is a combination of the two. Depending on the type of breakdown mechanism, the characteristics of such a device will change notably. Of the two types, the avalanche diode has the most favorable characteristics for protection in a gate circuit.

Furthermore, the pn-junction of these devices will provide a capacitance for voltages below the breakdown voltage. Some datasheets include the device capacitance at room temperature at one given frequency. A common value seems to be in the order of a few hundred pico farads. This is in the same magnitude as GaN eHEMT input capacitances, hence the influence of the Zener diode capacitance on gate ringing and influence on switching speed should be verified.

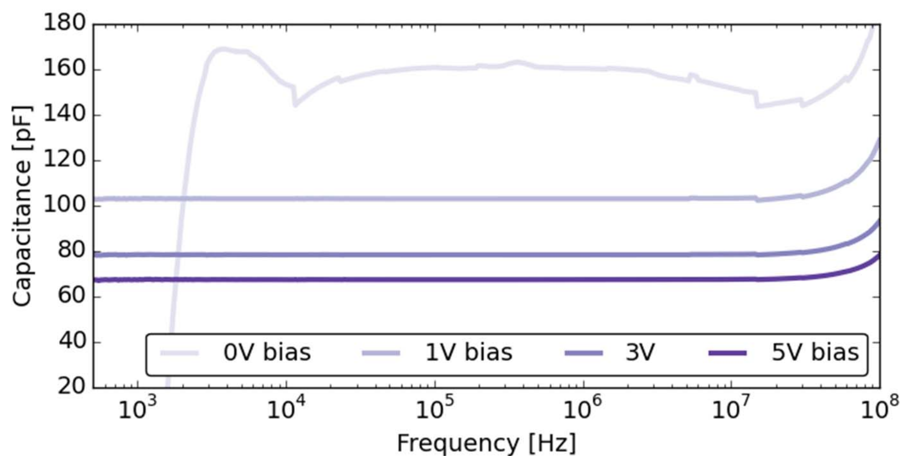

Figure 2. Frequency and voltage dependence of a 6.2 V Zener diode.

The frequency and voltage dependence of the capacitance was investigated for a 6.2 V Zener diode (BZT52C6V2). As can be seen in Fig 2, the Zener diode capacitance with 1 V bias is close to the rated value of 100 pF for a large frequency range. However, as the bias voltage increases to 3 and 5 volts, the capacitance decreases. For higher bias voltage of 5.5 V, the diode no longer exhibits any capacitance.

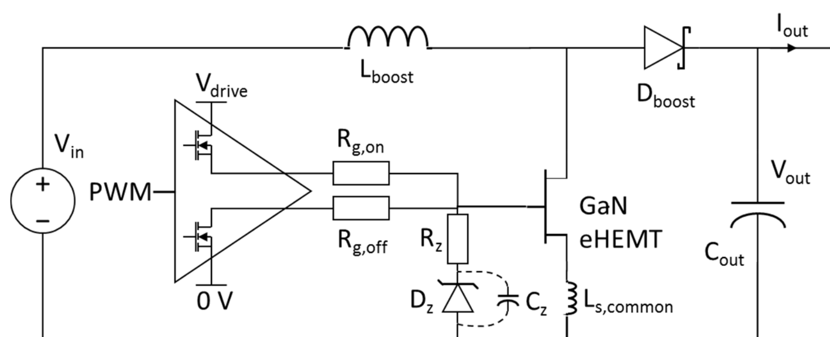

Figure 3. Schematic for the simulated boost CCM topology.

Simulations on the effects of gate circuit parameters

The goal of protecting the GaN eHEMT gate can be achieved by adding a Zener diode. However, the Zener diode capacitance will be added to the gate capacitance and thus affect the switching waveform. Simulations were done in LTSPICE in an effort to quantify the change in switching behavior. A boost topology was selected for the investigation, shown in Fig. 3. A SiC Schottky diode was selected as boost diode to minimize the reverse recovery current. To model the GaN eHEMT, the SPICE model for GS66508 available on the manufacturer website was used. The Zener diode is modelled as a capacitance, C_Z. The simulation includes a resistor, R_Z, in series with C_Z to investigate the possibility of shaping the gate signal. Stray inductances of 3 nH was added to the gate and drain connections. On-resistance of 100 Ω and off-resistance of 17 Ω were used.

Effect of Zener Diode Capacitance on Switching Waveform and Losses

Simulated drain-source voltage and drain current during both turn-on and turn-off for varying Zener capacitance are shown in Fig. 4. For these simulations, the series resistance R_Z was set to zero. An increase in the turn-on or turn-off delay is clearly visible. For the turn-on, this delay is measured to approximately 3 and 6 ns for 100 and 200 pF, respectively. As an example, rate of change for the current changes slightly from 1.4 to 1.1 and 1.0 A/ns for 1 pF, 100 pF and 200 pF respectively. The effect of the Zener diode could be decreased by adding a series resistor. With an increasing resistance value, the junction capacitance is increasingly decoupled from the gate circuit. Consequently, the time delay is reduced and simultaneously the protection function is decreased.

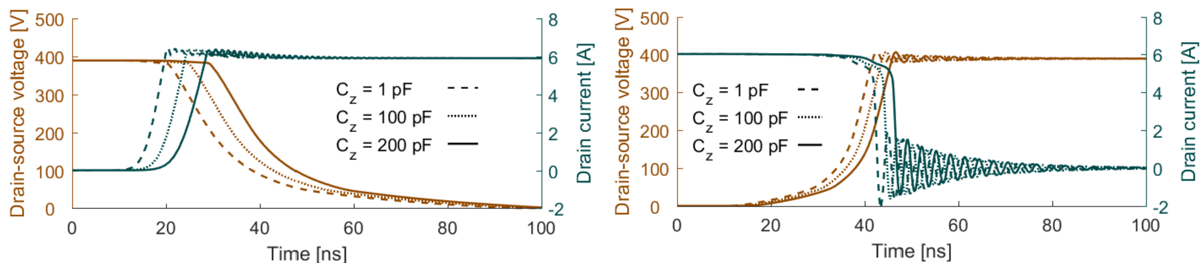

Figure 4. Effect of increasing Zener diode capacitance on drain-source voltage and drain current for turn-on (left) and turn-off (right).

EMI Spectrum of the Fast Switching Transient and Adaption by Changing Turn-off Resistance

Faster switching waveforms decrease the converter switching losses. Yet, the effect of increasing switching speed leads to increased high frequency EMI generation. The high switching speed of GaN HEMTs are favorable in terms of switching losses, but it leaves a concern regarding how the generated noise will affect converter operation and emissions. The power spectral density of the drain-source voltage from the simulated circuit is shown in Fig. 6. The graph shows how changing the gate turn-off resistor and thus changing the turn-off speed, also changes the resulting harmonic content generated by the switching transistor. The peak seen at approximately 300 MHz for 20 Ω resistor is a result of the oscillations on the drain-source voltage during turn-off. This peak in the spectral density is removed when the turn-off resistor is increased and the switching speed is decreased sufficiently to avoid oscillations on the drain-source voltage. This is in line with the investigation made in [11]. Moreover, there is a small overall increase in the conducted spectrum which will have to be managed to pass EMI testing. Nevertheless, if oscillation frequency of the switching unit can be designed to stay well above 30 MHz, the EMI filter requirements are less affected by the increased switching speed.

On one hand, increasing the gate resistance and thus increasing the switching time will remove the generation of high frequency noise. On the other hand, the switching losses will increase, as shown in Fig 5. For reference, the turn-off loss with 20 Ω gate turn-off resistance switching a current of approximately 6 A gives a loss of 16 μJ. Increasing the resistance to 80 ohms almost quadruples the

turn-off loss. Thus, from the converter system point of view, the choice of gate resistor is an optimization problem.

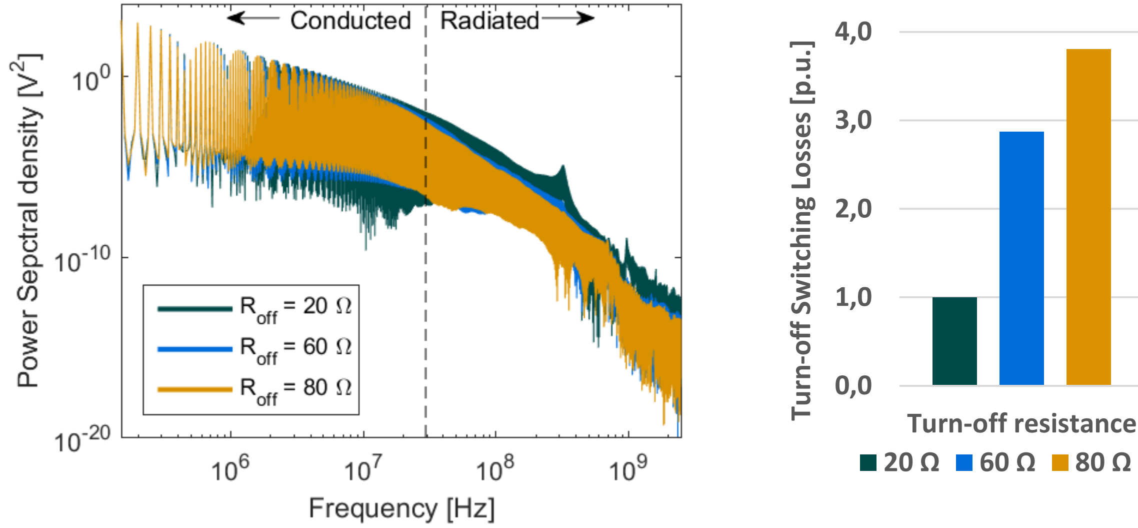

Figure 5. Effect of changing the turn-off resistance on the EMI spectrum of the drain-source voltage and the switching losses.

Experimental Setup and Results

A 1 kW PFC continuous conduction mode (CCM) boost converter was designed to investigate the presented considerations of this paper. A photo of the converter is shown in Fig. 6. The input voltage is taken from a single-phase 230 V supply. A NCP1654 PFC controller supplies the PWM signal for a target output voltage of 385 V and a switching frequency of 65 kHz. Even though the low switching frequency does not exploit the good switching characteristics of the GaN HEMT, it is sufficient for the goal of investigating the switching waveforms. A G66508T eHEMT from GaN Systems was used. Due to technical limitations of the test facilities at the time of testing, output power was limited to 800 W.

Table I: Test points according to gate component variation

Parameter	Values	
R_{ON}	100, 82, 62, 43	Ω
R_{OFF}	100, 82, 62, 43, 20	Ω
Zener diode	With and without	
Power	100, 200, …, 800	W

To obtain an overview of the change in waveforms by the Zener diode, the gate resistors were varied according to Table I to obtain performance trends. The converter efficiency was measured with a Yokogawa WT1800 Power Analyzer, while waveforms and timing values were acquired using a Tektronix DPO 5104 oscilloscope using TPP1000 probes. In addition, the control circuit power consumption and GaN HEMT transistor temperature were monitored by separate meters. The converter made for this setup has an intentional common stray inductance between the power and the gate loop.

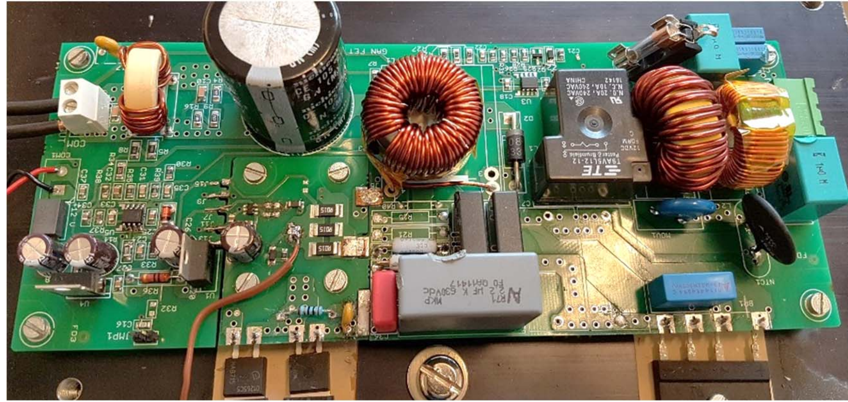
Figure 6. Photo of the 1 kW PFC CCM boost converter prototype.

The following investigations looks at the time delay introduced by the Zener diode. It is expected that the Zener diode increases the delay times between the PWM signal and the switching transient. The delay stems from the capacitance introduced by the Zener diode. However, as shown in impedance measurements, the capacitance decreases with bias voltage. Thus, the effect is largest for small gate voltages, in the same range as the GaN HEMT threshold voltage. Hence, the effect should be greater during turn-on than turn-off.

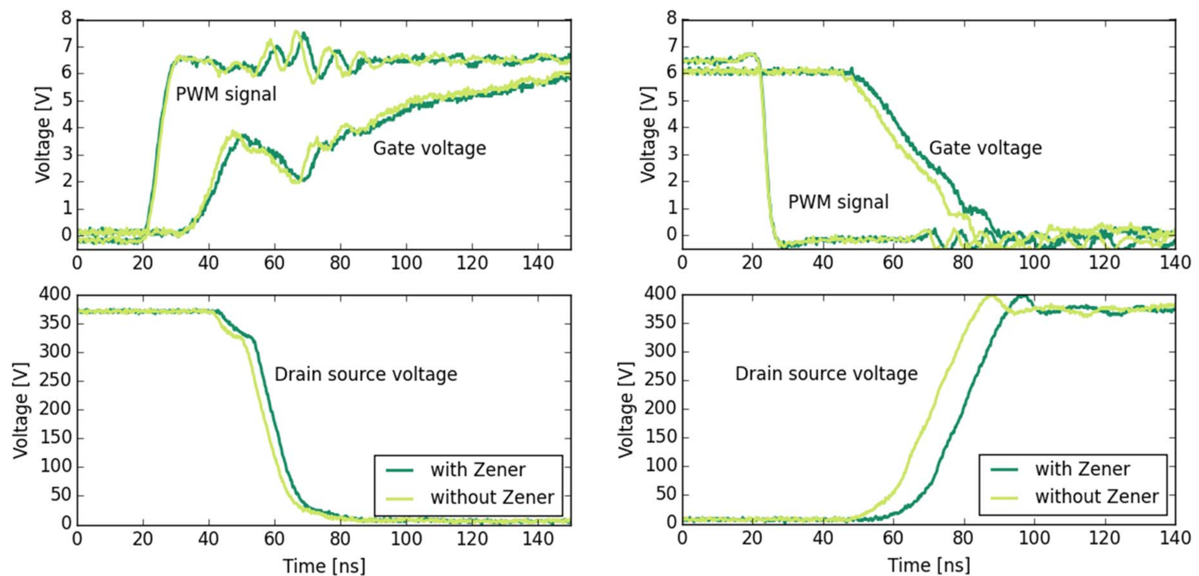

Figure 7. Switching waveforms for turn-on (left) and turn-off (right) with R_{ON}=43 and R_{OFF}=20.

Figure 7 shows switching waveforms during the peak of the PFC current at 800 W output power. The darker lines indicate the waveforms with a Zener diode on the gate. Both turn-on and turn-off transients are affected by the addition of the Zener diode.

The waveforms are useful for visualizing the effect of changing parameters. However, for timescales in the nanosecond range, factors such as signal propagation and signal jitter can affect the numerical value. The timing signals were quantified using measurement functions of the oscilloscope that were averaged over typically 100 measurements. The delay times, fall time and rise time are shown in Fig. 8 and 9.

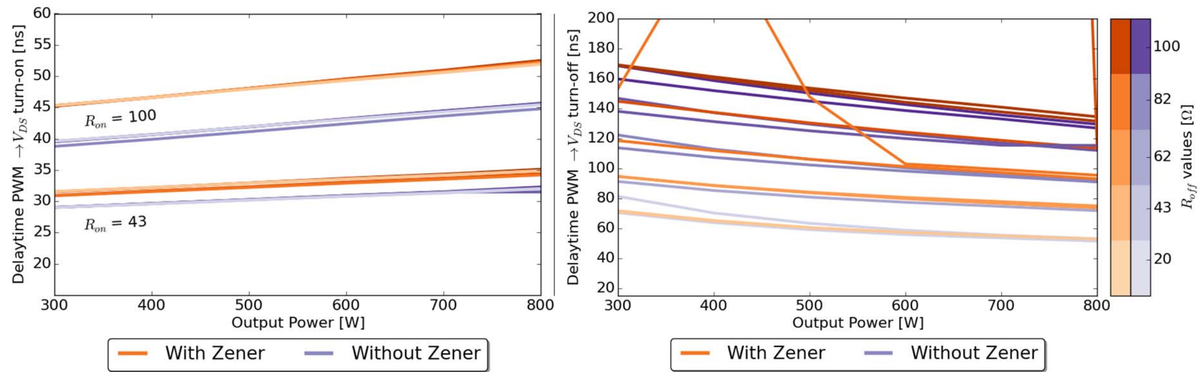

Figure 8. Influence of gate resistor and Zener diode on the time delay between the PWM signal to gate driver and 50% of drain-source voltage during turn-on and turn-off.

In Fig. 8, the delay times are shown for both turn-on and turn-off. During turn-on, the delay time changes with R_{ON} while all is unchanged with R_{OFF}, as is expected. The addition of the Zener diode increases the delay time as hypothesized. This is seen by the increased value of the lumped orange lines compared to the purple lines. The increase in delay time increases with the resistor value as the current charging the gate capacitance decreases and in turn increases the delay time. For fast switching circuits, the introduced delay will be minimal. From the figure, it can be seen that the time delay changes from approximately 6 ns to 2ns when the turn-on resistor is changed from 100 to 43 ohms.

During turn-off, the delay time changes with R_{OFF} while the delay times are essentially unchanged with R_{ON}, as is expected. The effect of the Zener diode appears to be minimal as the orange and purple lines for the same turn-on resistor (color brightness) are lumped together. The Zener diode capacitance is minimal at high voltages, and thus the gate current capability at a given gate voltage becomes more prominent. The measurements that differs greatly are disregarded as erroneous operation during measurement.

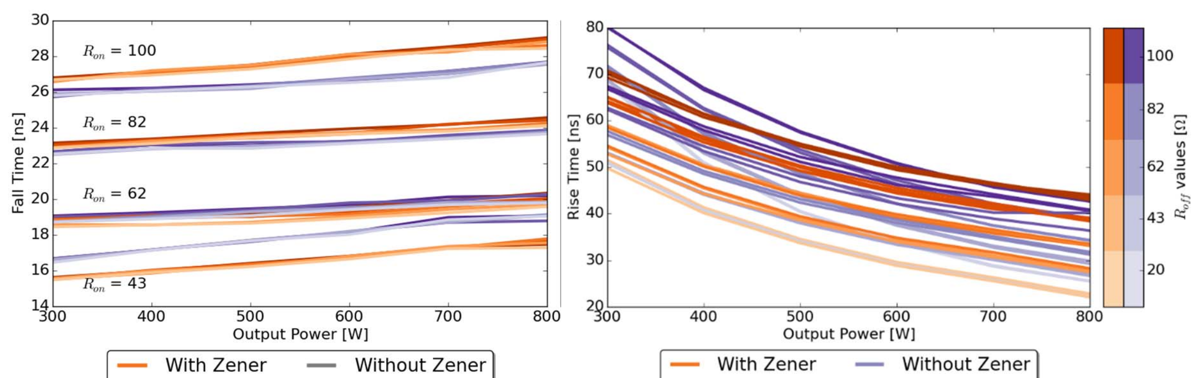

Figure 9. Influence of varying gate resistor and addition of the Zener diode on the fall time and rise time of the drain-source voltage.

The fall and rise time of the drain-source voltage are shown in Fig. 9. The fall time (turn-on) changes with R_{ON} and are unaffected by R_{OFF}, as is expected. The addition of the Zener diode is observed to have different effect according to the chosen R_{ON}. For a high turn-on resistance value, the Zener diode increases the fall time. This would be equal to the Zener diode constituting a capacitor, as the charging time would increase between the gate threshold voltage and the miller plateau. However, for lower gate resistor values, the fall time appears to decrease compared to the circuit without the Zener diode.

This effect can be recreated in simulation. It is suspected that the Zener diode improves the gate transient when dampening the high frequency oscillations during commutation. However, the increased gate capacitance increases the current rise time, resulting in slightly increased turn-on losses for the GaN transistor. This is confirmed in the experimental setup as the operating temperature with

Zener diode was higher for the GaN transistor than without. A temperature increase up to 0.5 degrees was measured at the source terminal of the eHEMT while delivering 800 W of power at the output.

The rise time (turn-off) changes with R_{OFF} while staying unchanged with varying R_{ON}, as is expected. This is seen in Fig. 9 as the brightness of the lines is consistently increasing with falling rise time, while equally bright colors are lumped together. The effect of the added Zener diode appears to decrease the rise time by a small amount for low load. For high load, on the other hand, the rise time is equal or slightly larger. This is likely because the charging of the device output capacitance by the load current is much more influential than the change in gate waveforms. Again, the change in rise time is negligible for small resistance values.

The converter efficiency is shown in Fig. 10. As expected, the efficiency increases with decreasing resistor values as switching losses decrease. Yet for high gate resistance values, a slight trend of increasing converter efficiency is observed when the Zener diode was added. The above investigation of the rise and fall time of the drain voltage showed that the transistor losses increased with the addition of a Zener diode for high gate resistance values. However, the efficiency measurement shows that the total converter efficiency increases slightly despite higher switching losses. The direct cause of this has not been investigated, as it is not within the goal of the work reported in this paper. For smaller gate resistance values, the converter efficiency is close to unchanged when adding the Zener diode.

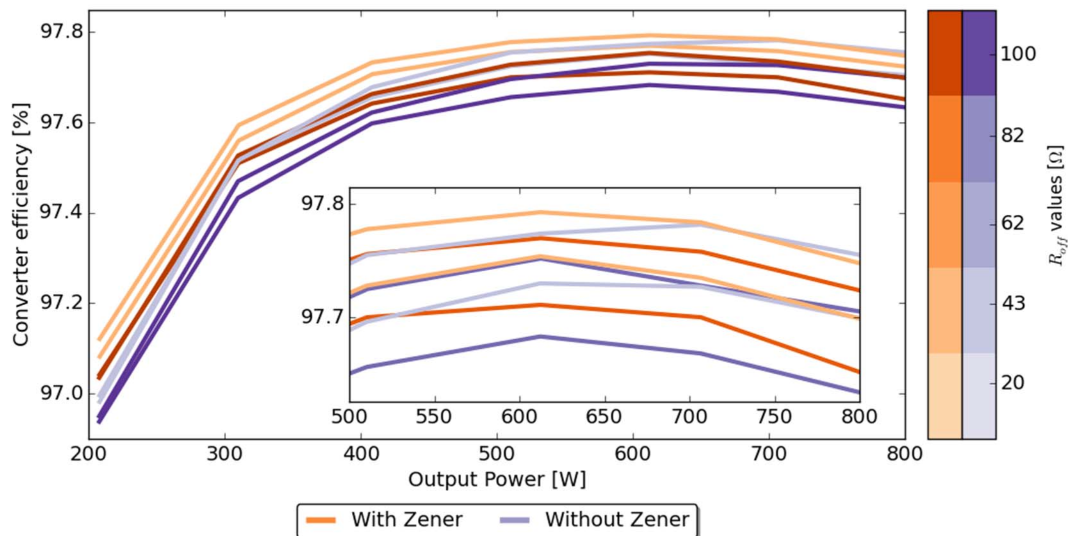

Figure 10. Efficiency of the converter for values of R_{ON}=82 and 43, and R_{OFF}=100, 43.

EMI Measurements

Figure 11 shows the EMI emissions of the PFC converter to mains measured according to CRISPR 16 standards and compared to the limits in EN 55022. The graph shows the measured peak values over 100 scans, and these values should be compared to the quasi-peak limit (QP). The change in gate resistance from 100 to 43 Ω does not change the EMC signature substantially. Yet, there is a minor increase over the whole frequency range. However, there is a visible dark area around 20 MHz. This frequency corresponds to one of the ringing frequencies of the switching unit. Faster switching leads to higher ringing magnitudes that in turn propagate back to the mains. These results are in good report with simulation. The high peaks in the conducted EMI measurements are not a concern for the final application as optimization the of EMI filter including management of E fields in the converter can significantly change and improve the EMI signature.

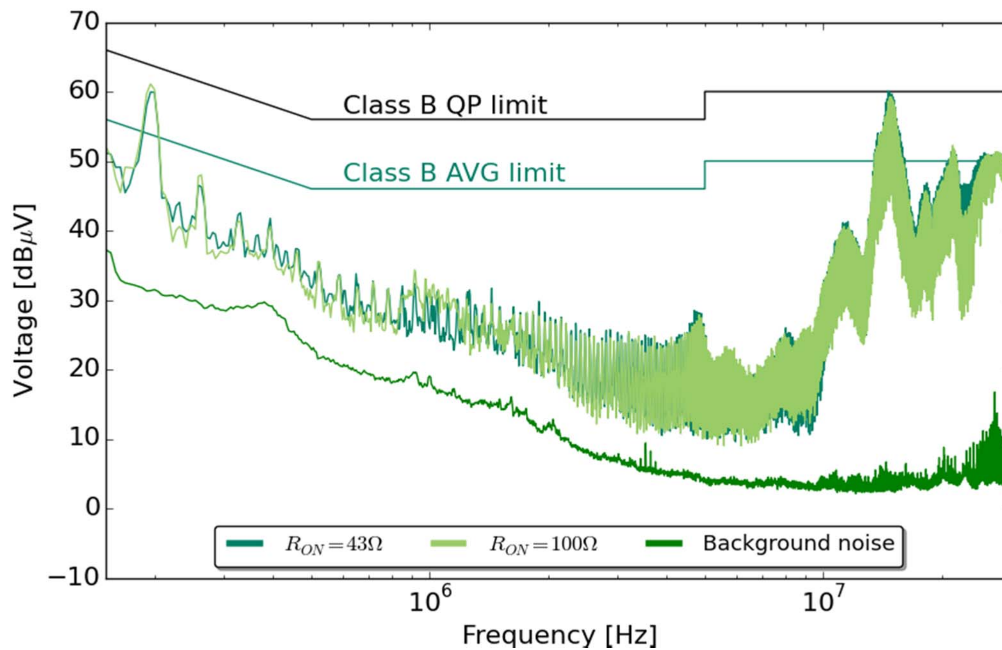

Figure 11. Measured EMI emissions of the converter with indicated allowable emission levels for EN55022 class B. The converter is operating at 800 W output power and R_{ON} = R_{OFF} = 43 or 100.

Conclusion

The work reported in this paper showed the effect of changing gate resistors and adding a Zener diode to the gate circuit of a GaN eHEMT. The Zener diode can protect the GaN eHEMT from overvoltages, as the voltage requirements such devices are very strict. The effects on the switching waveforms is investigated in simulation and verified by experimental results. The Zener diode junction capacitance results in a time delay for the switching transient, yet mainly for the device turn-on. The effects are prominent only for high gate resistance values. For low resistance values, the effects are negligible. Nonetheless, for application where delay time is significant, this effect should be accounted for if use of Zener diodes is considered. An example of such an application is dead time control.

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