Different parameter values of Gaussian function analysis on EMI reduction and switching loss in active gate drive of SiC MOSFET

Chentao Li, Qishuang Ma*, Ping Xu
School of Automation Science and Electrical Engineering, Beihang University, Beijing 100191, China
*Corresponding author’s e-mail: qsma304@buaa.edu.cn

Abstract—Nowadays, wide bandgap(WBG) devices named SiC and GaN were widely used in power electronics system to improve power density and switching speed, meanwhile, electromagnetic interference(EMI) becomes a major drawback in power electronics system based on wide bandgap devices. This article discusses the influence of different parameter values in Gaussian function on EMI suppression, and a trade-off between EMI and losses was also discussed. Experiments were given in this article to analyze different parameter values effect on EMI reduction. This article can give guidance in the Gaussian function generated when used in active gate drive to reduce EMI.

1. Introduction
With the application of wide bandgap devices, high frequency, and high power density becoming a trend in power electronics. Wide bandgap semiconductors named SiC and GaN have superior characteristics than Si counterparts, the energy gap, electric breakdown field, melting point, and electron velocity are all significantly higher [1]. A comparison of three materials properties can be seen from Table I. Based on WBG devices, the converter switching frequency can be 10X, 20X, or even 50X more than current practice using silicon devices, what has been taken for granted in design practice is being challenged [2].

Meanwhile, superior characteristics also brought new challenges, among which the higher electromagnetic interference(EMI) is a major drawback than Si counterparts due to the high-level $dv/ dt, di/ dt$, generated by the switching of semiconductors. Electromagnetic compatibility(EMC) standards were proposed to restrict EMI emission in the manufacture and design of power electronics converters, such as EN 55011 which is used for industrial, scientific, and medical (ISM)[3].

Next-generation of power supplies using WBG devices need a scientific theory to reduce EMI noise [4]. There are three elements for EMI to occur: noise sources, propagation paths, and sensitive systems. Most popular techniques for suppressing EMI include grounding, electromagnetic shielding, and filtering[5]. Conventionally, EMI filters are used to achieve enough conducted EMI noise attenuation, and shielding is used for radiated EMI[6]. However, the filter has a heavy weight and large volume that can reduce the power density of converters. More importantly, in practice, EMI mitigating mostly according to experience rather than science. The most common solution to overcome EMI is filter yet, however, with the demand for higher density and lower consumption increasing, the EMI filter is not the best choice, the most efficient method for suppressing EMI is reducing the noise sources.
F.C proposed a new method to predict the spectrum envelope of EMI which pays more attention to transient functions of the EMI signal [7]. N.P proposed a spectrum analysis of a PWM signal on the basis of the study of idealized zero (instantaneous switching) and one (non-instantaneous linear switching edges) order model [8], which gives mathematical guidance of EMI reduction. X.Y used the infinitely differentiable characteristics of Gaussian S-shaped transients to reduce EMI of IGBT, but lack of discussion about Gaussian function [9], based on previous research, C.T proposed a practical circuit with a smoothed Gaussian S waveform which reduces EMI effectively optimized shape switching waveform with infinite successive derivatives of Si MOSFETs in [10].

The common wide bandgap devices named GaN HEMTs and, especially SiC MOSFETs related technologies are by far the most mature among WBG semiconductors [11]. Based on [10], this article analyzed the main parameter of "S" waveform influence on EMI reduction in active gate drive of SiC MOSFETs, and different parameters lead to different switching losses. Section II gives the smoothed Gaussian waveform analysis, section III discusses different waveform leads to different EMI reduction effects and different power loss in active gate drive of SiC MOSFET, experiments were designed to verify the proposed theory in section III, section IV gives a conclusion of this article.

| Properties                                      | Bandgap, $E_g$ [eV] | Breakdown electric field, $V_{sat}$ [MV/cm] | Thermal conductivity, $\lambda$ [W/cm·K] | Electron saturation velocity, $V_{sat}$ [$10^7$ cm/s] |
|------------------------------------------------|---------------------|---------------------------------------------|------------------------------------------|-----------------------------------------------------|
| Si                                             | 1.1                 | 0.3                                         | 1.5                                      | 1                                                   |
| SiC                                            | 3.3                 | 2.2                                         | 4.9                                      | 2                                                   |
| GaN                                            | 3.5                 | 2                                           | 1.3                                      | 2.2                                                 |

2. Parameters Optimization of Arbitrary Transient Function

Based on [10], an arbitrary transient function in time-domain shows below:

$$sw(t) = \begin{cases} 0 & t < 0 \\ r(t) & 0 < t < \tau \\ A - r(t - t_0) & t_0 < t < t_0 + \tau \\ 0 & t_0 + \tau < t < T \end{cases}$$

where $T$, $A$, $t_0$, $\tau$, represent waveform period, amplitude, pulse width and switching time, duty cycle is $D = t_0 / T$, $r(t)$ is a switching transient function. Convolution form of Equation (1) is:

$$sw(t) = sq(t) * \left( \frac{1}{A} \cdot \frac{dr(t)}{dt} \right) = sq(t) * g(t)$$

In order to make sure $sq(t)$ and $sw(t)$ has the same amplitude, there are two conditions need to be satisfied:

$$\int_0^\infty g(t)dt = 1$$

$$r(0) = 0, r(\tau) = A$$

In [8], there is an infinitely differentiable switching waveform given based on $g(t)$, which shows as below:

$$g(t) = \varphi(t) * \lambda(t) = \varphi(t) * \left[ \frac{1}{\sigma_{\varphi} \sqrt{2\pi}} \cdot \exp\left(\frac{-t^2}{2\sigma_{\varphi}^2}\right) \right]$$

Table 1. Comparison of three materials properties.
where \( \varphi(t) \) is a pulse function with pulse width \( t_1 \), \( \lambda(t) \) is a Gaussian function with pulse width \( t_2 \), \( \sigma_t \) is a parameter which can influence Gaussian function waveform, different \( \sigma_t \) leads to different Gaussian waveform, the time domain and frequency domain waveform can be seen from Figure 1. Mathematically, in order to reach \( \lambda(t) \to 0 \), according to pauta criterion, \( \sigma_t \leq \frac{t_2}{4} \), however, there is less discussion about the value of \( \sigma_t \) influence in EMI reduction. Moreover, a series of experiments were designed in section III to analyze this issue.

![Figure 1. Gaussian function time domain and frequency domain waveform of different \( \sigma_t \)](image)

(a) time domain waveform of different \( \sigma_t \)  
(b) frequency domain waveform of different \( \sigma_t \)

3. Experiment Results and Discussions

In order to analyze different \( \sigma_t \) effect on EMI reduction, there is a test bench designed as shown in Figure 2.

![Figure 2. Active gate drive test bench of SiC MOSFET](image)

The parameter of main components in test bench circuit as shown in Table 2.

| Manufacturer | Voltage | Resistor/ Capacitance |
|--------------|---------|-----------------------|
| SCT2450KE    | 1200V/\( V_{DSS} \) | 450 m\( \Omega \) |
| C4D05120A    | 1200V/\( V_{RBM} \) | 27pF |

In this test bench, the SiC MOSFET is SCT2450KE, having an on-state 0.45\( \Omega \), the freewheeling diode is C4D05120A, which is a SiC-based Schottky diode, moreover, by using a coaxial shunt named SDN-414-01 to measure current to analyze power loss in this test bench. When \( \sigma_t = \frac{t_2}{16} \), Gaussian
function spectrum is not good as other values (when $\sigma_t = t_2/8$, $\sigma_r = t_2 / 4$), the experiment was designed to analyze these two $\sigma_r$ values effect on EMI reduction in active gate drive of SiC MOSFET.

3.1. Different $\sigma_t$ effect analysis on EMI reduction

When switching frequency of active gate drive waveform generated by Gaussian function is 100kHz and 200kHz, the experiment result can be seen from Figure 3, Figure 4.

![Figure 3. Experiment result of $V_{ds}$ time domain](image-url)

Figure 3 shows the time domain waveform of reference voltage $V_{ref}$ and drain-source voltage $V_{ds}$. In order to satisfy zero-voltage turning off, the reference voltage must be lower than $0V$, regardless of the switching frequency. From Figure 3, it can be seen that the following effect matches what was expected in this experiment. According to the spectrum analysis of $V_{ds}$ as shown in Figure 4, it is possible to draw a conclusion: there is a little different effect on EMI reduction between these two $\sigma_t$, however, there is an over 5 dBμV reduction in some certain frequency when $\sigma_t = t_2 / 4$ as shown in green circle below.

![Figure 4. Experiment result of $V_{ds}$ frequency domain](image-url)

3.2. Different $\sigma_t$ effect on power loss

Although, there is less different between these two $\sigma_t$ in EMI reduction, the loss need to be concerned as well. The main source of power loss in a power electronics system is the switching transient of a SiC MOSFET, which can be estimated with an equation:

$$E_T = \int_{t_{on}}^{t_{off}} V_{ds}(t)I_d(t)dt + \int_{t_{on}}^{t_{off}} V_{ds}(t)I_d(t)dt$$

(6)
where $t_{on}$ denotes the rise time when the drain current ($I_d$) begins to rise and $t_{on}$ represents the time when the drain current ($I_d$) drops to the end of turning on transient, $t_{off}$ denotes the rise time when the drain current ($I_d$) begins to rise and $t_{off}$ represents the time when the drain current ($I_d$) drops to the end of turning off transient. $V_{ds}$ denotes drain-source voltage of MOSFET. The drain current ($I_d$) data came from a coaxial shunt named SDN-414-01 shown in Figure 2. The $V_{ds}$ and $I_d$ experimental waveforms can be seen in Figure 5.

Through equation (6), using MATLAB can calculate the power loss in this experiment, compared with $\frac{t_2}{4}$, when $\frac{t_2}{8}$, there is a result shown that the loss can be reduced by 10.1% in 100kHz and 6.5% in 200kHz.

![Figure 5. Turning on and turning off $V_{ds}$ and $I_d$ transient waveform](image)

### 4. Conclusion and perspectives

This article discusses the effect of different $\sigma_t$ on EMI reduction and switching loss, gives a series of experiments to functional verification on active gate drive bench. Through spectrum and switching loss analysis, there are some conclusions obtained:

Different $\sigma_t$ has less effect on EMI reduction when $\sigma_t$ already less than $\frac{t_2}{4}$, however, in some certain frequency, there is an obvious difference can be found. This phenomenon can be analyzed in a follow-up study to select the more fit value of $\sigma_t$ in different switching frequency in active gate drive. In addition, switching loss has an obvious difference, the main reason is the lower the $\sigma_t$, the shorter the switching time, due to that, the switching loss was lower. As long as the EMI amplitude is fit to the EMC standard, the $\sigma_t$ value can be less than proposed in previous research. It is necessary to propose an index to evaluate the effect of EMI reduction from different dimensions instead of only evaluating amplitude attenuation.

### References

[1] Chen J, Du X, Luo Q, et al. (2020) A Review of Switching Oscillations of Wide Bandgap Semiconductor Devices. *IEEE Transactions on Power Electronics* 35: 13182–13199.

[2] Lee FC, Li Q, Liu Z, et al. (2016) Application of GaN devices for 1 kW server power supply with integrated magnetics. *CPSS Transactions on Power Electronics and Applications* 1: 3–12.

[3] EN 55011 (2016) Industrial, scientific and medical equipment -Radio-frequency disturbance characteristics -Limits and methods of measurement:12-87.

[4] Lee FC, Wang S, Li Q (2020) Next Generation of Power Supplies-Design for Manufacturability. *IEEE Journal of Emerging and Selected Topics in Power Electronics* 1–1.

[5] Mainali K, Oruganti R (2010) Conducted EMI Mitigation Techniques for Switch-Mode Power Converters: A Survey. *IEEE Transactions on Power Electronics* 25: 2344–2356.
[6] Wang S, Lee FC, Chen DY, et al. (2004) Effects of parasitic parameters on EMI filter performance. IEEE Transactions on Power Electronics 19: 869–877.

[7] Costa F, Magnon D (2005) Graphical analysis of the spectra of EMI sources in power electronics. IEEE Transactions on Power Electronics 20: 1491–1498.

[8] Patin N, Viñals ML (2012) Toward an optimal Heisenberg’s closed-loop gate drive for Power MOSFETs, IECON 2012 - 38th Annual Conference on IEEE Industrial Electronics Society, 828–833.

[9] Yang X, Yuan Y, Zhang X, et al. (2015) Shaping High-Power IGBT Switching Transitions by Active Voltage Control for Reduced EMI Generation. IEEE Transactions on Industry Applications 51: 1669–1677.

[10] Cui T, Ma Q, Xu P, et al. (2017) Analysis and Optimization of Power MOSFETs Shaped Switching Transients for Reduced EMI Generation. IEEE Access 5: 20440–20448.

[11] Millán J, Godignon P, Perpiñà X, et al. (2014) A Survey of Wide Bandgap Power Semiconductor Devices. IEEE Transactions on Power Electronics 29: 2155–2163.