Proceedings of the 30th International Symposium on Power Semiconductor Devices & ICs
May 13-17, 2018, Chicago, USA

# Dynamic Stability Analysis based on State-space Model and Lyapunov's Stability Criterion for SiC-MOS and Si-IGBT Switching

Xiao Zeng, Zehong Li, Yuzhou Wu, Wei Gao, Jinping Zhang, Min Ren, Bo Zhang
The State Key Laboratory of Electronic Thin Films and Integrated Devices
University of Electronics Science and Technology of China (UESTC)
Chengdu, China

***Abstract*—This paper proposes a new stability evaluation method for SiC-MOS and Si-IGBT in switching transient state. This method is based on Lyapunov's stability criterion and statistics. A state-space model is established based on SiC-MOS equivalent circuit with consideration of straw parameters. The system matrix in the state-space model can be used for stability analysis by Lyapunov's stability criterion for the samples that include the parameters in system matrix. The statistical method is implemented for the stability results of the samples in device switching transient state and the unstable level which is used to descript the stability performance during transient state has been defined. From the simulation and experimentation results, the unstable level has the capability to evaluate the EMI performance for comparing the impact of parasitic parameters in design of package, module and chip, even the suitability of the application circuits to suppress device self-excited oscillation.**

***Keywords—SiC-MOS; IGBT; stability; self-excited oscillation***

## I. Introduction

SiC-MOS has become a hotspot both in research and engineering application in recently years due to its higher power density, higher switching frequency and lower switching loss. It has the trend to replace Si Insulated Gate Bipolar Transistor (Si-IGBT) in design of middle power system in the near future, especially in automotive power solutions, such as the electrical drive in electrical automobile. In engineering application, self-excited oscillation is a common problem in the power system based on SiC-MOS or Si-IGBT. The self-excited oscillation is a significant contributor of the EMI issue during SiC-MOS and Si-IGBT switching. Many factors can be the candidates of the self-excited oscillation, such as the parasitic inductance, capacitance and resistance from external circuits, device package and chip. Moreover the working condition also impacts. The system level analysis should be performed to find the proper parameters or working condition to eliminate the EMI issue to improve the switching performance.

Many previous literatures are focusing on characteristic equation of device equivalent circuits with consideration of parasitic parameters to work out suitable range of parameters. In [1], a characteristic equation has been derived from differential mode circuit of a single IGBT in a parallel connected IGBT typology. All the parameters in this equation are parasitic parameters, including some variable parameters that highly depend on collector voltage, collector current and temperature, except for the gate resistor. The Routh-Hurwitz criterion is used to define the stability of the system based on the characteristic equation. Same analysis method can be found in [2] to guide the package design for SiC-MOS and Si-IGBT to suppress EMI issue. The only way to make the system stable is to find the minimum gate resistor after finding other parameters in whole range condition. Related analysis can also be found in [3] and so forth. Nowadays, from the application of power semiconductor device, the active gate control (AGC) technology has been adopted by more and more power system design to improve switching performance of device, such as [4]. So the AGC can be implemented during device switching to perform stability control based on feedback signal by measuring methods, such as [5]. So finding an effective way to do stability evaluation during device switching based on particular computational resource is absolutely necessary. This can also benefit to device design during simulation loop as well as the package and application circuit design.

In order to solve this problem, this paper proposed a dynamic stability analysis method based on state-space model and Lyapunov's stability criterion for SiC-MOS and Si-IGBT switching. Section II will explain the establishment of state-space model and the proposed method of stability analysis. Section III will discuss the simulation and experimentation. At last, section IV will summarize the whole study.

## II. The Priciple of Proposed Dynamic Stability Evaluation

The switching of SiC-MOS or Si-IGBT is a significant non-linear process. So many physical parameters are variable during the switching. For example, the gate-drain capacitor $C_{gd}$ of SiC-MOS and gate-collector capacitor $C_{gc}$ of Si-IGBT are highly depended on drain voltage and collector voltage, respectively, as well as the drain-source capacitor $C_{ds}$ of SiC-MOS and collector-emitter capacitor $C_{ce}$ of Si-IGBT, and so on. These variable parameters and the parasitic parameters from package, external circuits make the switching system time-varied. The state-space model is suitable for descripting this kind of system. Once the state-space model is established,

This work was supported in part by the National Natural Science Foundation of China (Grant No. 61474017; Grant No. 61404023) and the Project of National Energy Application Technology Research and Engineering Demonstration (Grant No. NY20150703).

the system matrix is available for stability analysis by Lyapunov's stability criterion, but the state-space model establishment for time-varied system is complex, but the system for one of the samples from device switching process is time-invariant. So the state-space model establishment for one of the samples during device switching is easy, but this space-model cannot be suitable for all samples during device switching process due to mentioned above variable parameters. If the variation of these variable parameters is worked out, the space-model can be used for other samples with changes of the variable parameters, because the circuit is same for all samples in device switching process and this means the structure of state-space model is the same. The difference of state-space model is induced by these variable parameters. Based on mentioned above analysis, the time-varied state-space model for device switching process can be equivalent to time-invariant system space-model for one sample with the curves of variable parameters that in system matrix.

### *A. State-space Model Establishment*

The establishment of state-space model for one sample is based on MOS equivalent circuit, as shown in Fig. 1, with consideration of parasitic parameters. In Fig.1, the $R_G$, $R_S$ and $R_D$ are parasitic resistance in gate, source and drain, respectively. The $L_G$, $L_S$ and $L_D$ are parasitic resistance in gate, source and drain, respectively. The device is equivalent to gate-source capacitance $C_{gs}$, $C_{gd}$, $C_{ds}$, on resistance $R_{on}$ and controllable current source $g_m V_{GS}$.

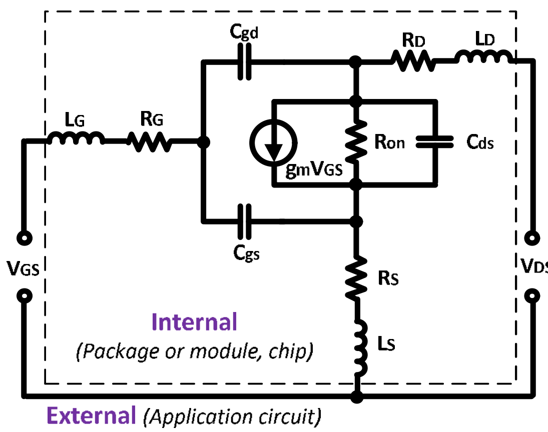



Fig. 1. MOS equivalent circuit.

The method in [1] can also be referred to get the transfer function of the circuit in Fig.1, as shown below:

$$G(s)=\frac{V_{DS}}{V_{GS}}$$
$$=\frac{C_{gd}R_{on}g_m(LL)s^3+C_{gd}R_{on}g_m(LR)s^2+R_{on}g_m(L_S+C_{gd}(RR))s+R_S}{\begin{array}{l}R_{on}(LL)(CC)s^4+[((LL)(C_{gd}+C_{gs})+R_{on}(LR)(CC)]s^3+\\ [(C_{gd}+C_{gs})(LR)+R_{on}(C_{ds}(L_D+L_S)+C_{gd}(L_D+L_G)+C_{gs}(L_G+L_S)+(CC)(RR))]s^2+\\ [L_D+L_S+(C_{gd}+C_{gs})(RR)+R_{on}(R_D(C_{ds}+C_{gd})+R_G(C_{gd}+C_{gs})+R_S(C_{ds}+C_{gs})]s+\\ R_D+R_S+R_{on}\end{array}} \quad (1)$$

where

$$\begin{aligned} LL &= L_D L_G + L_D L_S + L_G L_S \\ RR &= R_D R_G + R_D R_S + R_G R_S \\ CC &= C_{ds} C_{gd} + C_{ds} C_{gs} + C_{gd} C_{gs} \\ LR &= L_D R_G + L_G R_D + L_D R_S + L_S R_D + L_G R_S + L_S R_G \end{aligned} \quad (2)$$

This transfer function can be converted to state-space model, as shown in (3).

$$\begin{cases} \dot{x} = Ax + Bu \\ y = Cx \end{cases} \quad (3)$$

where

$$A=\begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -\frac{R_D+R_S+R_{on}}{R_{on}(LL)(CC)} & -\frac{\begin{array}{l}R_D(C_{ds}+C_{gd})+\\ R_G(C_{gd}+C_{gs})+\\ R_S(C_{ds}+C_{gs})\end{array}}{(LL)(CC)} & -\frac{\begin{array}{l}(C_{gd}+C_{gs})(LR)+\\ R_{on}[C_{ds}(L_D+L_S)+\\ C_{gd}(L_D+L_G)+\\ C_{gs}(L_G+L_S)]+(CC)(RR)\end{array}}{R_{on}(LL)(CC)} & -\left(\frac{C_{gd}+C_{gs}}{R_{on}(CC)}+\frac{(LR)}{(LL)}\right) \end{pmatrix} \quad (4)$$

$$B=\begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix} \quad (5)$$

$$C=\begin{pmatrix} \frac{R_S R_{on} g_m}{R_{on}(LL)(CC)} & \frac{(L_S+C_{gd}(RR))R_{on}g_m}{R_{on}(LL)(CC)} & \frac{C_{gd}(LR)R_{on}g_m}{R_{on}(LL)(CC)} & \frac{C_{gd}}{(CC)} \end{pmatrix} \quad (6)$$

$A$ is system matrix, $B$ is input matrix and $C$ is output matrix.

### *B. Stability Analysis by Lyapunov's Stability*

The system matrix $A$ can be used to solve the Lyapunov's equation, as shown in (7) to get the matrix $P$.

$$A^T P + PA + I = 0 \quad (7)$$

where $I$ is unit matrix. Then, judge $P$ is positive definite or not by Sylvester criterion to know the SiC-MOS or Si-IGBT based system is stable or not.

Some of the parasitic parameters which mentioned above in matrix $A$ are changing with external conditions as well as some electrical parameters, so the $A$ is variable and it needs to perform above mentioned steps for all samples in device switching dynamically to get the binomial probability distribution of stability. The unstable level is defined by the percentage of unstable samples to indicate the overall stability level of device with different parasitic parameters in package and chip or external circuits.

### *C. Acquiring Parameters in System Matrix A*

The time-invariant parameters, such as resistance and inductance can be obtained from device datasheet, SPICE model file or parameter extraction experiment. The time-varied parameter $C_{gd}$, $C_{ds}$ can be obtain from the capacitance test curve from datasheet and perform curve fitting to get an equivalent equation. The $R_{on}$ can be calculated by (8) or by curve fitting from I-V characteristics on device datasheet.

$$R_{on} = V_{DS} / I_{DS} \tag{8}$$

## III. SIMULATION AND EXPERIMENTATION

Before simulation and experimentation, a stability algorithm which runs in Mathworks/Matlab has been developed according to proposed method, which is used for stability evaluating in simulation and experimentation. The SiC-MOS device is implemented for simulation while the Si-IGBT device is implemented for experimentation.

### *A. Simulation*

The SiC-MOS (CREE C2M0045170D) based BUCK DC-DC converter is implemented in simulation circuit, as shown in Fig.2. The acquired the time-invariant parameters in matrix $A$ are shown in TABLE I. The curve fitting equations of $C_{gd}$ and $C_{ds}$ are shown in (9) and (10).

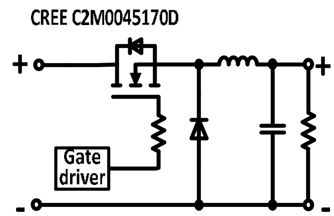



Fig. 2. SiC-MOS based BUCK DC-DC converter in simulation.

TABLE I. TIME-INVARIANT PARAMETERS (C2M0045170D)

| Para. | Value (unit) |
|---|---|
| $L_G$ | 15e-9 H |
| $L_S$ | 9e-9 H |
| $L_D$ | 6e-9 H |
| $R_G$ | 1.3 Ω |
| $R_S$ | 2e-3 Ω |
| $R_D$ | 2e-3 Ω |
| $Cgs$ | 3.9e-9F |

$$C_{gd} = (13.76e-12) - (0.1281e-9)/V_{DS} + (7.6648e-9)/V_{DS}^2 \tag{9}$$

$$C_{ds} = (0.2209e-9) - (16.093e-9)/V_{DS} + (43.767e-9)V_{DS}^2 \tag{10}$$

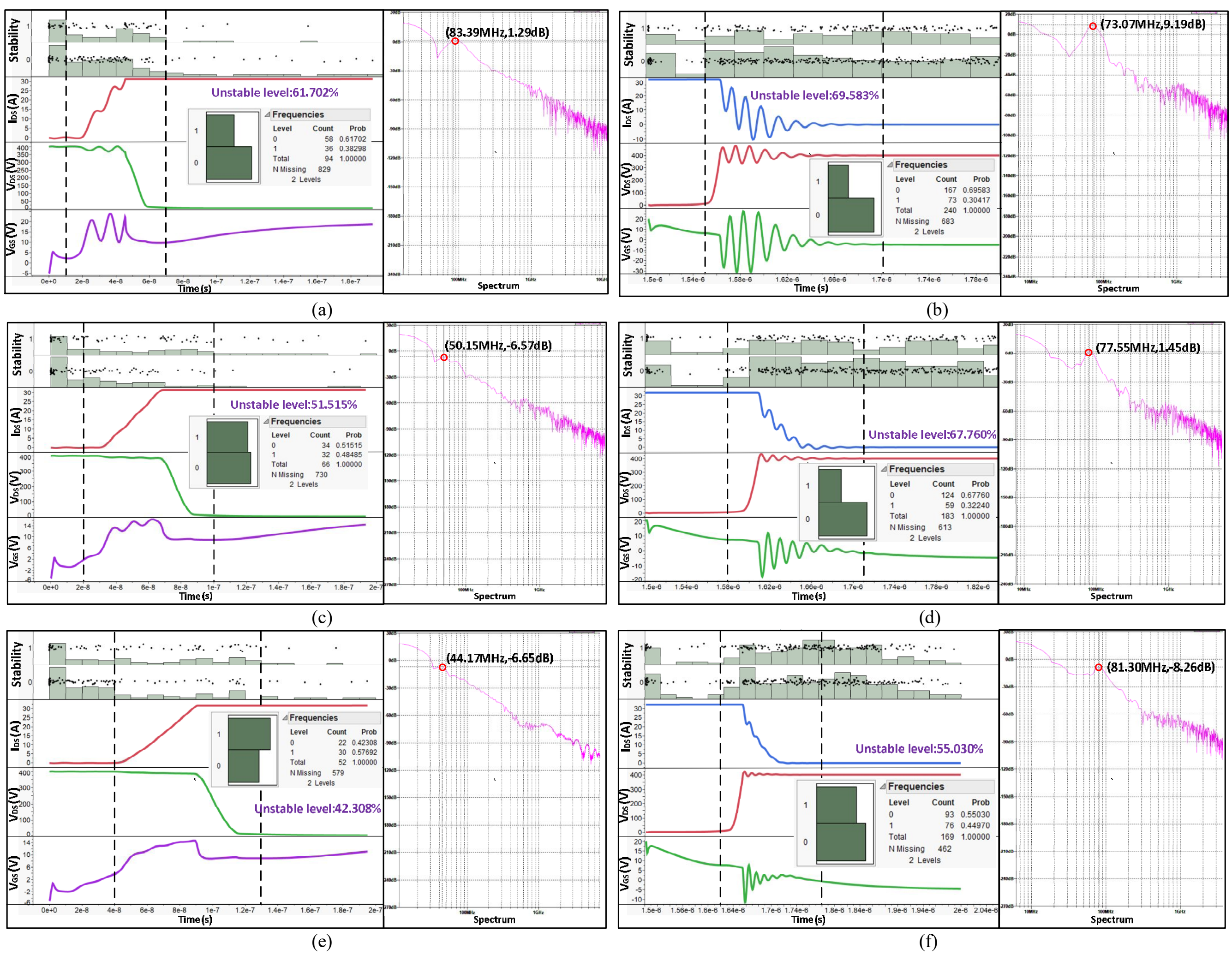
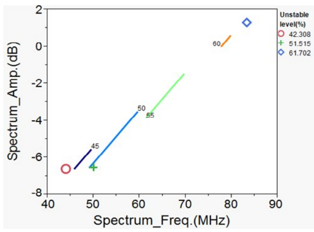
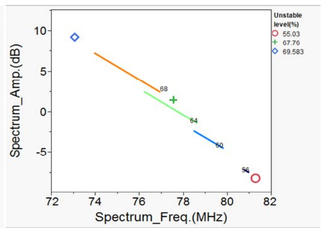



Fig. 3. SiC-MOS based BUCK DC-DC converter simulation results per round, (a) $R_{G\_EXT}$=10Ω turn-on;(b) $R_{G\_EXT}$=10Ω turn-off;(c) $R_{G\_EXT}$=20Ω turn-on;(d) $R_{G\_EXT}$=20Ω turn-off;(e) $R_{G\_EXT}$=30Ω turn-on;(f) $R_{G\_EXT}$=30Ω turn-off.

There are 3 rounds in the simulation with different external gate resistor $R_{G\_EXT}$, as shown in Fig.3. The summary of the simulation can be found in Fig. 4 and it concludes that the proposed method is effective to evaluate the EMI level or stability during SiC-MOS switching.



(a)



(b)

Fig. 4. The summary of relationship between unstable level and EMI performance, (a) relationship between turn-on unstable level and spectrum; (b) relationship between turn-off unstable level and spectrum.

## B. Experimentation

The experimentation of stability evaluating for Si-IGBT (Infineon IKW40N65H5) is performed on power semiconductor device dynamic tester (ITC 57240 test head), as shown in Fig.5 and the time-invariant parameters are shown in TABLE II. The curve fitting equations of $C_{gc}$, $C_{ce}$ and $R_{on}$ are shown in (11), (12) and (13).

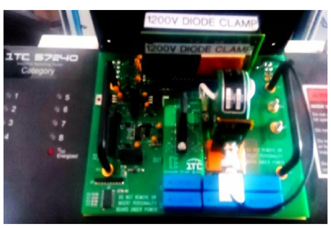


Fig. 5. Si-IGBT test platform (ITC57240).

TABLE II. TIME-INVARIANT PARAMETERS (C2M0045170D)

| Para. | Value (unit) |
|---|---|
| $L_G$ | 5e-9 H |
| $L_E$ | 5e-9 H |
| $L_C$ | 3e-9 H |
| $R_G$ | 1.3 Ω |
| $R_E$ | 2e-3 Ω |
| $R_C$ | 2e-3 Ω |
| $Cge$ | 2.5e-9F |

$$C_{gc} = (8.539e-12) - (55.82e-12)/V_{CE} + (5.553e-14)/V_{CE}^2 \quad (11)$$

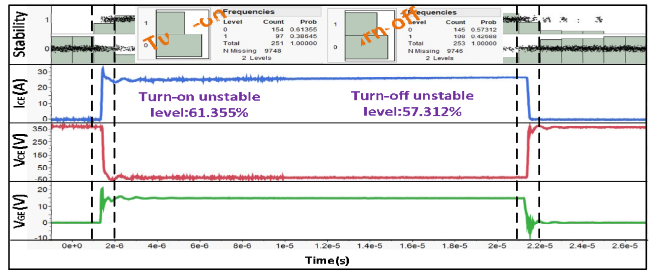
$$C_{ce} = (9.941e-12) - (0.3236e-9)/V_{CE} + (0.3225e-12)/V_{CE}^2 \quad (12)$$

$$R_{on} = 0.0234448 - 0.8637419/I_{DS} + 0.1843049/I_{DS}^2 \quad (13)$$

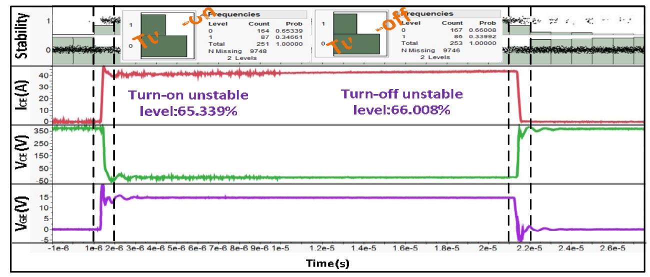
There are two rounds with different loads (load2>load1) in the experimentation, the results are shown in Fig. 6. The unstable level of load2 is higher than load1 and load2 deserves worse EMI performance. It proves that the proposed method can evaluated the EMI performance by unstable level for Si-IGBT switching.

## IV. CONCULSION

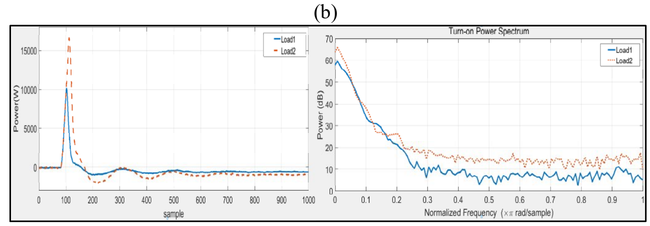
A dynamic stability evaluation method based on Lyapunov's stability criterion is proposed for SiC-MOS and Si-IGBT. The simulation and experimentation results show that this method is capable to evaluate and compare the device EMI performance with different internal (package and chip) or external (application, drive circuits) parameters. It can be used for on-line stability investigation as well as device design and application circuit design to improve EMI performance.



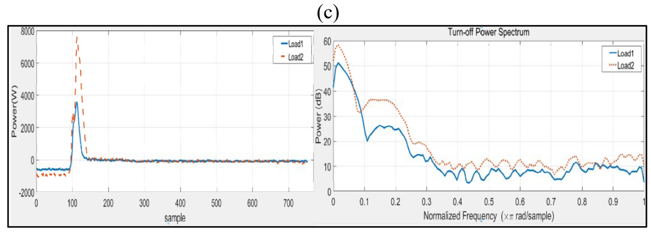
(a)



(b)



(c)



(d)

Fig. 6. Si-IGBT experimental results (load2>load1), (a) load1 switching waveform; (b) load2 switching waveform; (c) turn-on power loss and spectrum; (d) turn-off power loss and spectrum.

## REFERENCES


[1] John C. Joyce, "Current sharing and redistribution in high power IGBT modules," University of Cambridge, pp. 53, May. 2001.

[2] K. Saito, T. Miyoshi, D. Kawase, S. Hayakawa, T. Masuda and Y. Sasajima, "Suppression of self-excited oscillation for common package of Si-IGBT and SiC-MOS," 2017 29th International Symposium on Power Semiconductor Devices and IC's (ISPSD), Sapporo, 2017, pp. 427-430

[3] M. Spang, S. Buetow and G. Katzenberger, "Differential-mode oscillations between parallel IGBTs in power modules," 2015 17th European Conference on Power Electronics and Applications (EPE'15 ECCE-Europe), Geneva, 2015, pp. 1-10.

[4] X. Yang, X. Zhang and P. R. Palmer, "IGBT converters conducted EMI analysis by controlled multiple-slope switching waveform approximation," 2013 IEEE International Symposium on Industrial Electronics, Taipei, Taiwan, 2013, DOI: 10.1109/ISIE.2013.6563663, pp. 1-6.

[5] X. Zeng et al., "A Novel Virtual Sensing with Artificial Neural Network and K-means Clustering for IGBT Current Measuring," in IEEE Transactions on Industrial Electronics, in press.