Stray Inductance Evaluation of PCB Busbar for Double Pulse Test of SiC Power Modules

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ABSTRACT – SiC power modules provide fast switching characteristics that trend to increase the power conversion performance and efficiency. However, fast switching produces high di/dt that interacting with stray inductance can lead to hazard voltage overshoot. Therefore, special design measures are necessary to decrease the stray inductance in the power loop. Given the conventional power topologies, the busbar is a critical element due to its function as interface between the DC bus capacitors and the power module. Indeed, the busbar can significantly contribute to the total power loop inductance. In this context, this work aims to contribute in the design of busbars by proposing a simplified model of a Printed Circuit Board (PCB) busbar and its experimental evaluation. This experimental validation explores a method to partially characterize the stray inductance of the PCB busbar with two parallel DC inputs using S-parameters. Experimental results are compared with electromagnetic simulations based on the Method of Moments (MoM) in a complementary approach between Ansys Q3D Extractor and Keysight ADS Momentum. Finally, double pulse tests at 800V/500A are carried out to validate the power behavior of the PCB busbar and to quantify its contribution to the power loop inductance.

Keywords— SiC-MOSFET, power module, PCB busbar, stray inductance, S-Parameters, electromagnetic simulation.

1. INTRODUCTION

Nowadays, Silicon Carbridge (SiC) in the power semiconductor market has allowed increasing the performance and power density of power converters. These advantages of SiC-MOSFETs arise from their fast switching characteristics [1]. However, this high-speed switching imposes additional constraints to the associated elements around the power device. For instance, power modules based on SiC-MOSFETs require low stray inductance in the power loop to mitigate the voltage overshoot due to the high di/dt during the device Turn-OFF [1].

The power loop inductance depends on the stray inductance of three main elements identified as the busbar, the DC bus capacitors, and the power module [2]. Nevertheless, stray inductance of the DC bus capacitors and the power modules usually depend on characteristics provided by manufacturers. Therefore, the power electronics designers should optimize the busbar design to take advantage of the SiC-MOSFET features and to increase the system reliability [3].

Additionally, Printed Circuit Board (PCB) busbars play an important role in short time tests of SiC power modules. They offer flexibility in the design stages, relative low-cost implementation, and they are able to carry hundreds of amperes in the double pulse test [4].

In this context, this work aims to contribute to the design of busbar by proposing a simplified model for the stray inductance analysis. The simplified model is intended for PCB busbars with two parallel DC inputs but it can be extended to busbar with more inputs. Additionally, an experimental approach is described to measure the busbar partial stray inductance using a radiofrequency methodology based on S-parameters.

Complementary, the PCB busbar inductance is analyzed by means of two electromagnetic software based on the Method of Moments (MoM) [5]. The electromagnetic analysis tools are Keysight ADS Momentum, oriented to radiofrequency analyses, and Ansys Q3D Extractor, oriented to the extraction of RLCG circuits. Finally, double pulse tests at 800 V/500 A evaluate the power behavior of the analyzed busbar and its contribution to the power loop inductance.

The structure of the paper is as follows: Section II describes the simplified model for the stray inductance of the two DC inputs busbar. Section III illustrates the experimental method for the partial stray inductance measurement using S-Parameters. Section IV describes the electromagnetic simulation of the PCB busbar using the method of moments. Finally, section V rapports the double pulse tests at 800V/500A to evaluate the power behavior of the PCB busbar and its contribution to the power loop inductance.

2. SIMPLIFIED STRAY INDUCTANCE MODEL OF PCB BUSBAR WITH TWO PARALLEL DC INPUTS

This section describes the simplified model proposed to analyze the stray inductance of a PCB busbar.

Power modules can handle hundreds of amperes and the busbar is fundamental for their interconnection with power system and the power distribution. They are several architectures of busbars. Nevertheless, tests of power modules at level of microseconds, such as the double pulse test, can be carried out using PCB busbars. This is a suitable option given the short time current capabilities, design flexibility, and low manufacturing cost of PCBs. However, PCB busbar design requires special attention due to the impact of the stray inductance and the high di/dt. Therefore, this section aims to contribute with a simplified model to describe the stray inductance interactions in a PCB busbar with two DC inputs.

Figure 1a shows a PCB busbar for the interconnection of a power module. As proposed by Geng et al. [6], DC capacitors in short circuit could allow the evaluation of the busbar stray inductance (see Figure 1b). In this study case, the busbar has two parallel DC inputs (DC_{1+} and DC_{2+}) and a common DC-terminal. Figure 2 shows the simplified model where L_1 is the self-inductance between DC_{1+} and DC-, idem for L_2, and M is the mutual inductance between L_1 and L_2.

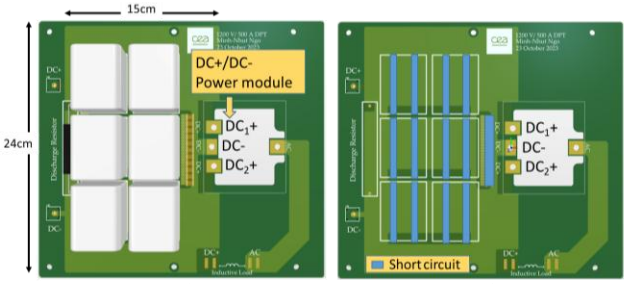

Fig. 1(a) PCB busbar with DC capacitors and (b) capacitors in short circuit

In the simplified circuit of Figure 2, the PCB busbar is unplugged of the power module and connected to a common power supply v_s in DC_{1+} and DC_{2+} terminals. Analysis of circuit in Figure 2 leads to a system of differential equations in matrix form as shown in eq.(1). Solution of this matrix using determinants of eq.(2) provides the differential equation of eq.(3) [7]. Given that an inductance L is usually defined by the expression of eq.(4), the equivalent stray inductance of the PCB busbar with two parallel DC inputs can be deduced as shown by eq. (5).

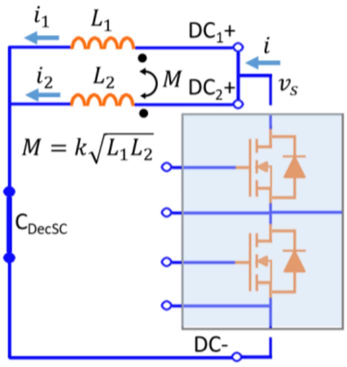

Fig. 2 Simplified model of busbar stray inductance with two DC parallel inputs and DC capacitors in short circuit (C_{DecSC})

$$\begin{bmatrix} v_s \\ v_s \end{bmatrix} = \begin{bmatrix} L_1 & M \\ M & L_2 \end{bmatrix} \begin{bmatrix} \frac{di_1}{dt} \\ \frac{di_2}{dt} \end{bmatrix} \tag{1}$$

$$\Delta = \begin{vmatrix} L_1 & M \\ M & L_2 \end{vmatrix};\ \Delta_1 = \begin{vmatrix} v_s & M \\ v_s & L_2 \end{vmatrix};\ \Delta_2 = \begin{vmatrix} L_1 & v_s \\ M & v_s \end{vmatrix} \tag{2}$$

$$\frac{di}{dt} = \frac{di_1}{dt} + \frac{di_2}{dt} = \frac{\Delta_1 + \Delta_2}{\Delta} = v_s\left(\frac{L_1 + L_2 - 2M}{L_1 L_2 - M^2}\right) \tag{3}$$

$$v_L = L\left(\frac{di}{dt}\right) \tag{4}$$

$$L_{eq} = \frac{L_1 L_2 - M^2}{L_1 + L_2 - 2M} \tag{5}$$

Next section will describe the measurement method to characterize the PCB stray inductance.

3. Partial Stray Inductance Measurement of PCB Busbar Using S-Parameters

Previous section explained the simplified model for the PCB busbar stray inductance. In this section, details about the measurement process are presented by using the S-parameters approach.

S-parameters or scattering parameters are defined by considering a set of high-frequency waves traveling on a network. The equipment that provides the high-frequency waves to measure the S-parameters is known as Vector Network Analyzer (VNA). As shown in Figure 3, when a voltage wave from a VNA port is incident on a DUT, a portion of the voltage wave is transmitted through the DUT. Additionally, the other portion of the wave is reflected back toward the initial VNA port. By definition, S-parameters are the coefficients between these incidents and reflected waves. As described by eq. (6), the S-parameters nomenclature depends on the ports for the incident and reflected waves.

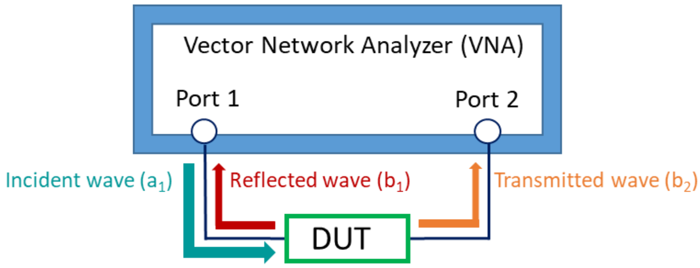

Fig. 3 Vector Network Analyzer (VNA) for S-parameters measurement

$$S_{11} = \frac{b_1}{a_1}\ ;\ S_{21} = \frac{b_2}{a_1}\ ;\ S_{22} = \frac{b_2}{a_2}\ ;\ S_{12} = \frac{b_1}{a_2} \tag{6}$$

The reflected waves result from the interaction between the characteristic impedance Z_0 of the measurement system and the impedance of the device under test (DUT). Usually, the characteristic impedance of the measurement system is Z_0=50Ω. For the PCB busbar under test, the single port approach is followed to decrease the impact of the measurement setup (see Figure 4).

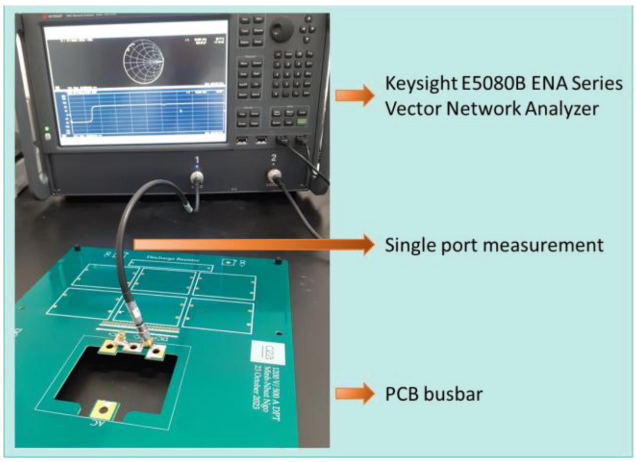

Fig. 4 VNA for measuring PCB busbar S-parameters using a single port

Indeed, the distance between DC_{1+} and DC_{2+} makes challenging an accurate measurement of the total PCB busbar inductance. In contrast, a single port measurement is feasible by using S-parameters to get the busbar partial inductance L_n. Furthermore, the de-embedding method is used to calculate the stray inductance contribution of the test fixture [8]. This de-embedding method refers to the removal of the additional contribution of the test fixture to the measurement. Figure 5 depicts the modeling and characterization of the test fixture that employs a SMA connector as interface between the VNA and the PCB busbar. Figure 6 summaries the stages to measure the partial stray inductance of the busbar (e.g. between DC_{1+} and DC-). Moreover, it considers the de-embedding method to removal the test fixture stray elements.

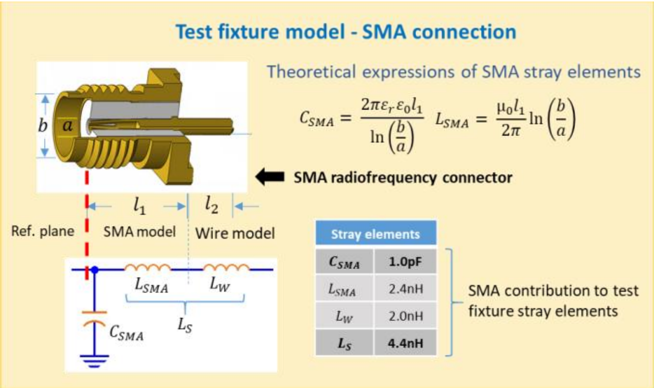

Fig. 5 SMA connection model and stray elements of the test fixture

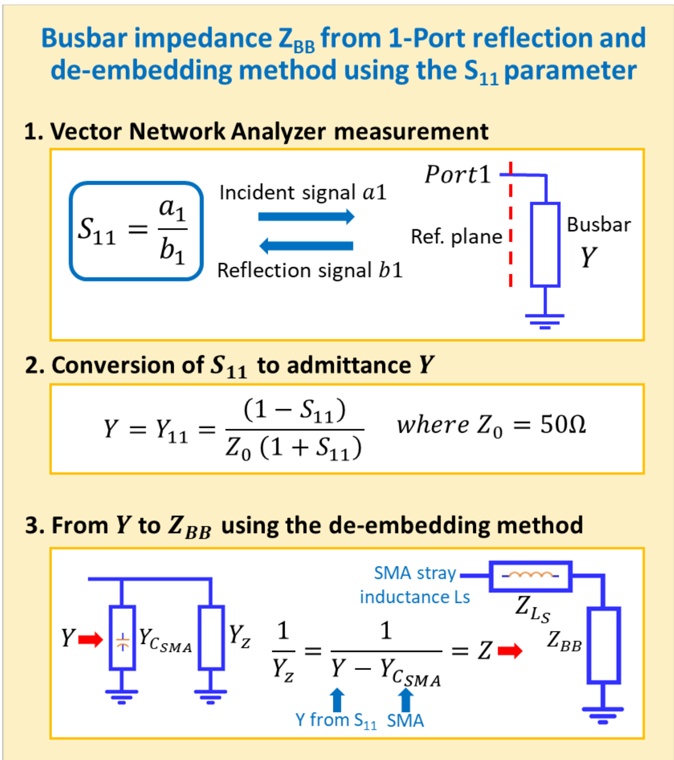

Fig. 6 Stages to measure the busbar partial stray inductance

As describe in Figure 6, the first step is the single port measurement of the busbar with DC capacitors in short circuit. Next, a transformation from S-Parameters to admittance Y-Parameters is carried out to prepare the data for the de-embedding calculation. Then, using the de-embedding method, the contribution of the SMA based test fixture is extracted from the measurements. Finally, a transformation from admittance to impedance is performed to calculated the partial stray inductance of the busbar using eq. (7). Figure 7 shows the busbar partial stray inductance results from VNA measurements and after the de-embedding calculation. The frequency range is from 100kHz to 1MHz.

$$L_n \approx \frac{im(Z_{BB})}{2\pi f} \qquad (7)$$

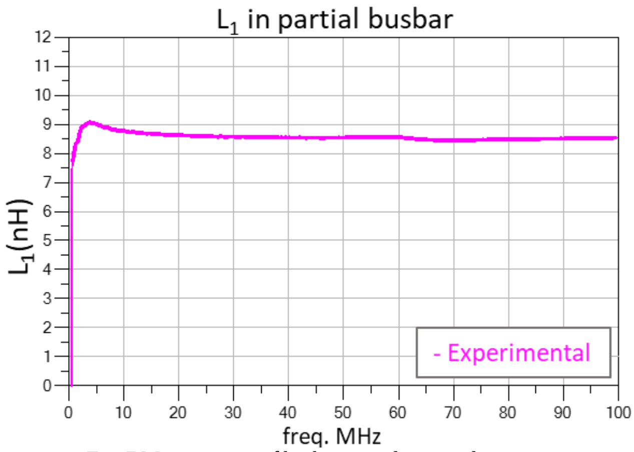

Fig. 7 Measurement of busbar partial stray inductance

Next section will describe a comparison of experimental results with electromagnetic simulation results.

4. Electromagnetic Simulation by Method of Moments

This section provides an overview of an electromagnetic computational method to calculate the stray inductance of the PCB busbar. Most specifically, the Method of Moments (MoM) in the software tools Keysight ADS Momentum and Ansys Q3D Extractor. Furthermore, the electromagnetic simulations are compared with experimental and modeling results to validate the proposed approach.

Computational electromagnetic methods solve electromagnetic problems and perform simulations by the application of Maxwell’s equations. They are several numerical approaches. Nevertheless, the two more common approaches in commercial software tools are the Finite Element Method (FEM) and the Method of Moments (MoM). Table 1 summarizes the main characteristics of these two methods [9].

Table 1. Main characterisitics of computational methods *FEM and MoM*

Method	Solver type	Discretization	Material type
FEM Finite Element Method	Variational form	Volumetric domain	Non-linear, anisotropic
MoM Method of Moments	Integral equations	Surface currents	Linear, homogeneous

As listed in Table 1, the Finite Element Method (FEM) is based on the Maxwell’s equations in variational form. This method divides the full problem space into suitable discrete spaces to find local solutions satisfying the Maxwell’s equations. The local solutions are then merged to obtain the global solution considering the boundary conditions. Moreover, the Finite Element Method (FEM) is suitable to deal with electromagnetic problems that involve non-linear and anisotropic materials [9]. Usually, this method is widely used in computational electromagnetics due to its flexibility in handling complex geometries and arbitrary shapes [10].

The second approach listed in Table 1 is the Method of Moments (MoM). This method is another common numerical technique to solve electromagnetic problems. The Method of Moments (MoM) is an integral equations solver that focuses on the integral form of the Maxwell’s equations. In contrast with the Finite Element Method (FEM), this method discretizes unknown surface currents by meshing planar metallization patterns. Therefore, this technique is more suitable for planar structures embedded in a multilayered dielectric substrate that involves linear and homogeneous materials [11]. As a result, the Method of Moment (MoM) tends to be better adapted for the analyses and electromagnetic simulations of planar structure such as the PCB busbars [11].

There are numerous simulation tools available for the electromagnetic analysis of PCBs [5]. As mention before, we focus on the tools that are mainly based on the Method of Moments (MoM). For this reason, this work considers the computational tools Keysight ADS Momentum and Ansys Q3D Extractor that principally use the Method of Moments (MoM) to carry out the electromagnetic simulations. Nevertheless, this work is not intended for comparing both tools. Instead, we aim to show their complementary to increase the design performance of PCB busbars. Figure 8 shows the complementary approach taking advantages of both tools.

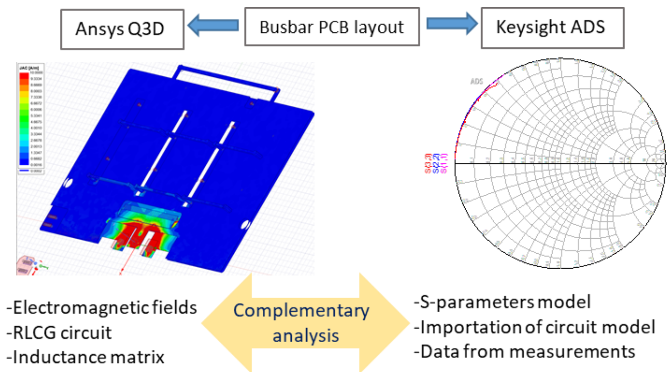

Fig. 8 Complementary analysis using Ansys Q3D Extractor and Keysight ADS Momentum

The computational tool Keysight ADS Momentum is an electromagnetic simulator that computes S-parameters and electromagnetic analysis for general planar circuits such as PCB [12]. This tool is integrated in the Keysight Advanced Design System (ADS) software for the design of electronic systems.

Ansys Q3D Extractor is a parasitic extraction tool for electronics design. Q3D Extractor calculates the parasitic parameter of frequency-dependent resistance, inductance, capacitance and conductance (RLCG) for electronic products. It is ideal for designing electronics packages and connectors. Furthermore, it is used for high-power busbars and power converter components in electrical power distribution, power electronics and electric drive systems [13].

As shown Figure 9, S-parameters measurement and circuit model from Ansys Q3D are imported to Keysight ADS plotting them together to the S-parameters model from Keysight ADS Momentum. Figure 9 depicts the suitable results between experimental and electromagnetic models for the partial stray inductance.

Moreover, for the case of both connected DC_+ inputs, the extracted inductance matrix of Ansys Q3D (eq. (8)) and the simplified model (eq. (5), rewrote in eq (9)) show agreement in Figure 10 and eq. (9) for a busbar stray inductance L_{eq}≈5.5nH.

$$Q3D\ inductance\ matrix = \begin{bmatrix} L_1 & M \\ M & L_2 \end{bmatrix} = \begin{bmatrix} 9.26 & 1.65 \\ 1.65 & 9.50 \end{bmatrix} nH \quad (8)$$

$$L_{eq} = \frac{L_1 L_2 - M^2}{L_1 + L_2 - 2M} = \frac{(9.26)(9.50) - (1.65)^2}{9.26 + 9.50 - 2(1.65)} = 5.5nH \quad (9)$$

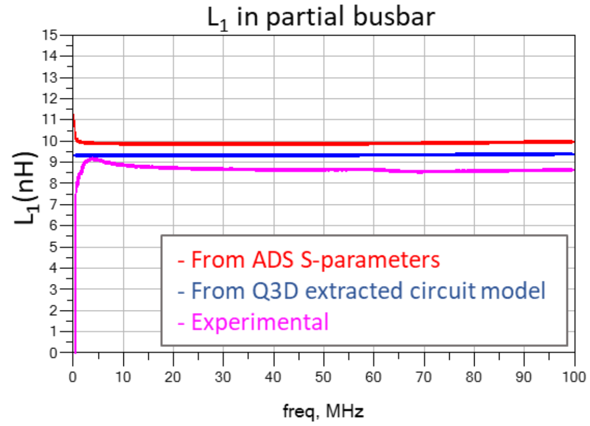

Fig. 9 Simulations and experimental results for partial stray inductance (DC_{1+}, DC-)

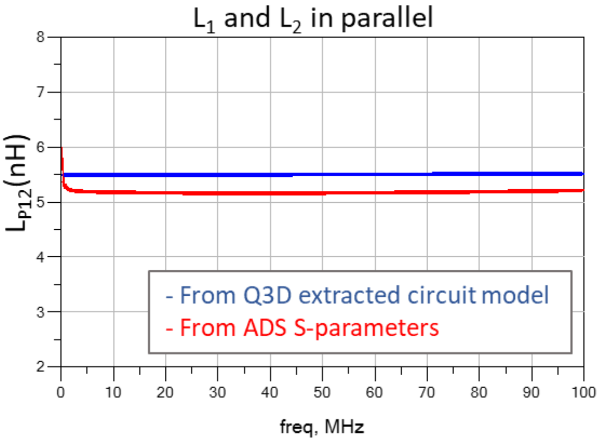

Fig. 10 Stay inductance results for simulation of the PCB busbar with both DC inputs connected in parallel

This section summarized the results of the PCB busbar stray inductance using electromagnetic simulations. Furthermore, these simulation results were compared with experimental and modeling results. Next section will describe some carried out tests to assess the power busbar behavior and the impact of its stray inductance.

5. Double pulse test of SiC power module in PCB busbar

This section describes some experimental power tests performed on the PCB busbar. The test-bench is based on the double pulse test at 800V/500A. Experimental results allows evaluating the power behavior of the PCB busbar. Furthermore, this section aims to estimate the contribution of the PCB busbar stray inductance to the power loop inductance.

Figure 11 shows the double pulse test-bench with the designed PCB busbar. This test-bench is intended for double pulse test at 800V/500A on SiC based power modules. Given the fast switching characteristics of the SiC-MOSFETs, special attention is devoted to the test-bench performance and quality of measurements. Indeed, Figure 12 highlights the suitable waveforms for tests at 800V/500A.

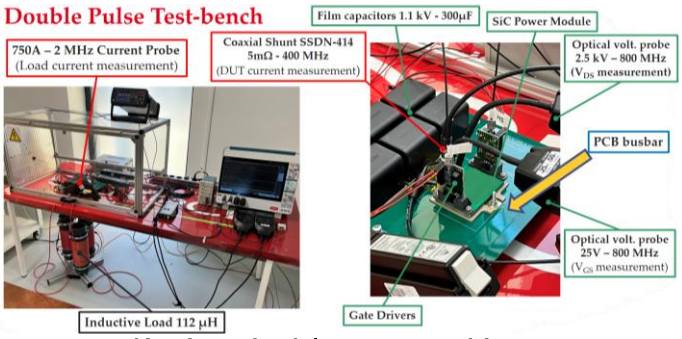

Fig. 11 Double pulse test-bench for SiC power modules at 800V/500A

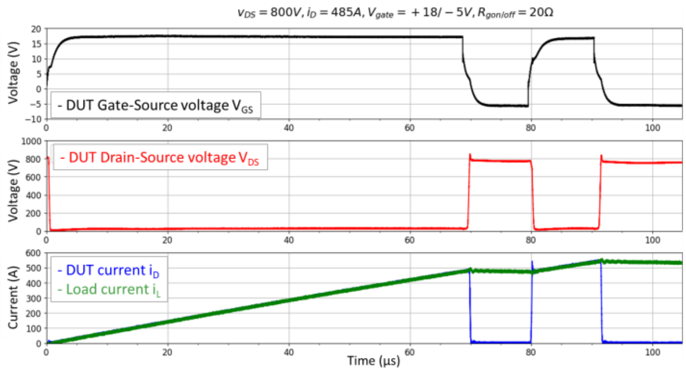

Fig. 12 Double pulse test waveforms for $R_G = 20\Omega$ and V_{GS} = +18V/-5V Test at 800V / 500A

Furthermore, using the Turn-OFF waveforms as shown in Figure 13, the total power loop inductance L_{Total} is calculated for several values of R_G and listed in Table 2. Consequently, the contribution of the busbar is only around 30% to the total power loop inductance according to inductance estimation reported in Table 2.

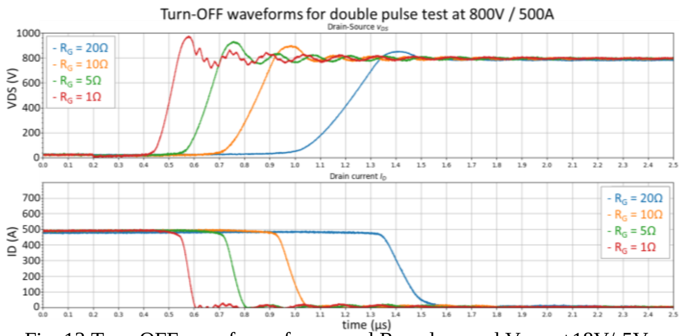

Fig. 13 Turn-OFF waveforms for several R_G values and V_{GS} = +18V/-5V

Table 2. Estimation of total power loop inductance

R_G	20 Ω	10 Ω	5 Ω	1 Ω
ΔV_{ds}	52 V	99 V	131 V	173 V
di/dt_{off}	3.18 kA/µs	4.71 kA/µs	7.51 kA/µs	10.53 kA/µs
L_{tot}	16.4 nH	21 nH	17.4 nH	16.4 nH

6. Conclusions

This work focused on the study of the stray inductance of a PCB busbar with two parallel DC inputs. A simplified model has been proposed considering the mutual inductance and the inductance matrix. Measurements of S-parameters of the partial busbar have been compared with electromagnetic simulations based on the method of moments (MoM) taking advantages of two simulation tools. Validation of the simplified model was carried out using the inductance matrix extracted by Ansys Q3D Extractor. Furthermore, waveforms for double pulse test at 800V/500A have shown the suitable power busbar behavior with a contribution of around 30% to the total power loop inductance. Future work will consider aspects such as the measurement of the total stray inductance, stray capacitances, and resonance frequencies of PCB busbars.

7. Acknowledgements

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