A novel application kit design accelerating the performance of Danfoss' 1.2 kV SiC DCM™1000X for EV drivetrains

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Abstract

Commutation loop stray inductances and layout asymmetries cause multiple complications in high speed switching devices and should be minimized during the design stage to avoid subsequent power module de-rating. Such complications can include large voltage overshoot, ringing with semiconductor parasitic capacitance and current sharing mismatch, to name a few.

This paper considers the design, simulation and experimental validation of a fully integrated DC-link capacitor and busbar "application kit" exclusively designed to enhance the performance of Danfoss' direct cooled molded DCM™1000X platform, utilizing the latest generation of 1200 V SiC MOSFET with a current rating ranging from 200 A up to 800 A.

Electromagnetic simulation using Ansys Q3D Extractor has been carried out to extract and evaluate the total commutation inductance and current density distribution on a classic 2-level inverter structure. Dynamic switching and full frequency test have been performed to validate the overall design.

1 Introduction

Next generation 1.2 kV SiC-MOSFET power modules for electric vehicle applications are targeting increased power density and efficiency to reduce the overall drive train and on/off board charger costs [1].

The critical design factors to consider are:

1) maximizing current density capability;
2) minimizing stray inductance at the power terminal connection – (without violating clearance, creepage and partial discharge requirements);
3) symmetrizing the connection point of the capacitors in relation to the power module's terminals.

The Danfoss DCM™1000X platform [2], represents a new state of the art - fully integrated - 1.2kV SiC-MOSFET chip technology. It utilizes a specific transfer mold package material (Epoxy-Raisin) and Danfoss Bond Buffer® technology (DBB®) enabling stable operation at elevated junction temperatures [3]. The half bridge power Module, as shown in Fig. 1, has unique 3x DC power terminals designed to minimize the module's stray inductance, allowing fast turn-off within the device's SOA (Safe Operating Area) as well as reducing turn-off losses.

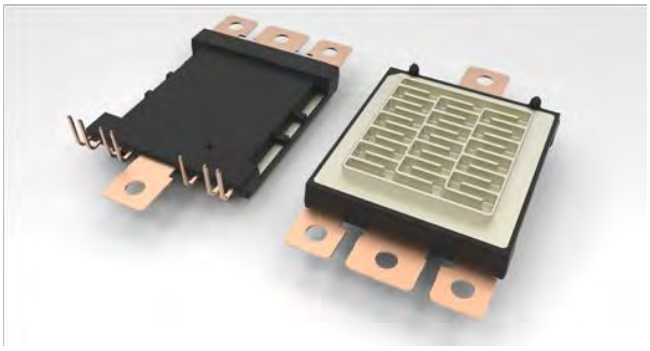

Fig. 1: DCM™1000X Half-bridge Power Module: top-view and bottom-view.

For cooling, the power module is equipped with a unique ShowerPower®3D technology already validated on the DCM1000 Si platform version [4]. Since the ShowerPower®3D is an integral part of the baseplate, supporting the structure, it allows for a thinner baseplate, better thermal performance and full mechanical integration with the application kit as illustrated in Fig. 2.

Various capacitor and bus structure concepts could be applied to increase the power density and to decrease the commutation loop inductance,

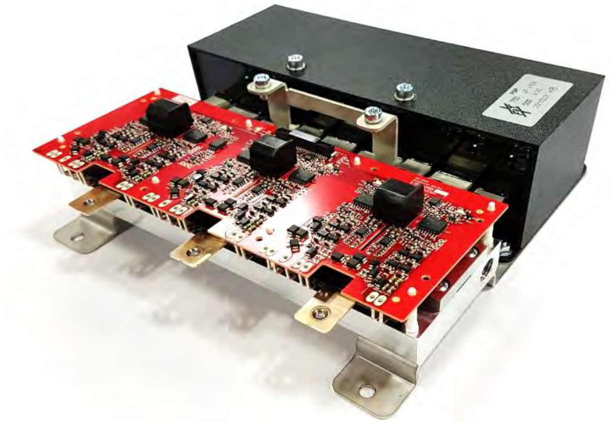

Fig. 2: Example like DCM™1000 application kit.

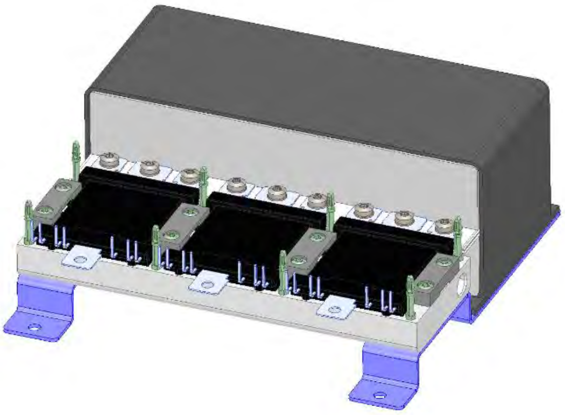

Fig. 3: Novel DCM™1000X 3-phase application kit.

however, as shown in this paper, an optimal, dedicated application kit has been designed and constructed to allow the connection of 3 half-bridge modules to create a classic 2-level inverter using the latest DCM™1000X technology platform.

In the first section of the article, the novel application kit is described briefly; inductance simulation results are presented and validated by experimental results.

In the second section of this paper the current sharing of the DCM™1000X using a standard "on shelf" application kit will be compared with the novel one.

In the last section, the internal temperature evolution of the novel application kit is shown being subjected to continuous, high frequency, back-to-back tests - to validate the effectiveness of the design.

2 Novel application kit layout

The Danfoss DCM™1000X High Power drive requires a DC-link capacitor capable of the following parameters:

V_{dc}	C	$I_{cap,rms}$	ESL	ESR	$T_{coolant}$
[V]	[uF]	[A]	[nH]	[mΩ]	[°C]
1000	300	300	<6	<0.5	65

Tab. 1: application kit target specification.

Additionally, a lifetime requirement of 10.000 hours typical of an EV drive cycle was specified. The evaluation kit consists of 6 standard (metalized polypropylene) capacitor windings connected back to back on a two-layer, low inductive bus structure to achieve; the total required capacitance as well as the ripple current at the rated temperature.

The back to back structure was especially designed to obtain circuitry symmetry at the device's terminals, avoiding static and dynamic current sharing mismatch during fast switching transients and steady state operations.

Fig.3 shows the overall assembly of the application kit layout. Capacitors windings and bus structure are contained in a glastic housing within 1.7 liters.

Each capacitor - placed in front of the power module - acts like a local snubber element and provides the charge required to support the fast switching transient locally. The DC power terminals of the bus structure have been specially designed and constructed to minimize stray inductance; providing a symmetrical current path as well as avoiding creepage (7.6 mm) and clearance (4.3 mm) violation by the DCM™1000X. For the bus structure and bushing connections, a max current density of 2.5 A/mm^2 was considered.

2.1 Finite Element simulation

In order to perform additional parasitic extraction, application kit geometry was imported and meshed in Ansys Q3D extractor. Fig.4 shows the total commutation inductance distribution simulated at 10 MHz (well above the upper frequency limit of 10 kHz given by the thinnest conductive element in the simulated model).

As illustrated, the total commutation inductance is below 4 nH for any phase position simulated. Additionally, the distribution is within the 0.25 nH.

Fig.5 shows an additional simulation on current density distribution. The simulation work confirms the design efficiency: adhering to the max allowed current density and respecting the geometrical distribution from the capacitor connections towards power module's entry points [5].

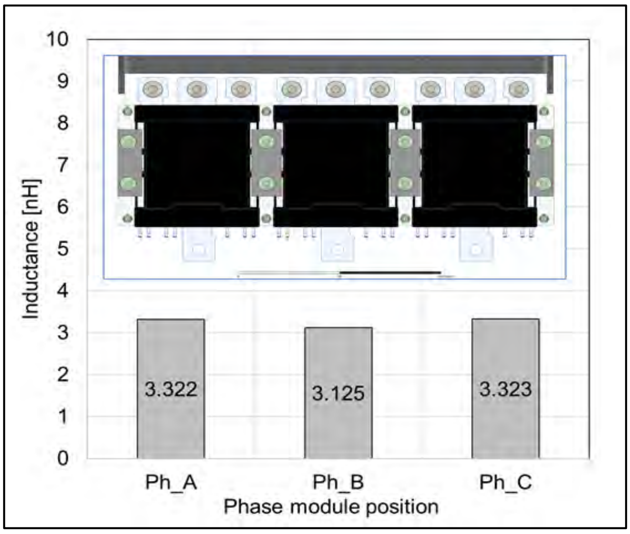

Fig. 4: Simulated stray inductance distribution.

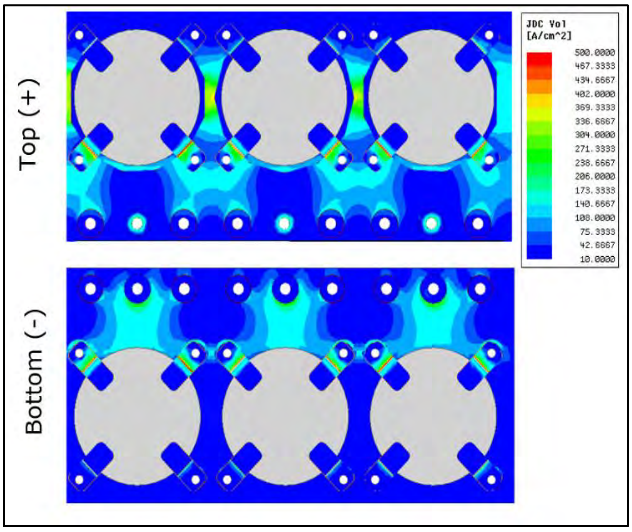

Fig. 5: DC-current density distribution.

2.2 Stray inductance validation

To verify simulation work experimentally, a prototype was built and dynamically tested using double-pulse tester. Measurements were performed using calibrated high bandwidth voltage (120 MHz) and current probes (30 MHz). In this test setup, turn-off and turn-on switching transients were recorded.

The typical waveforms during turn-on event is shown in Fig.6. The voltage was measured at the sensing terminals of the DUT (low side SiC-MOSFET). The total drain current was directly measured at the minus terminal.

The measuring principle for partial stray inductance is based on the inductance voltage integral method [6]. Under high frequency, the stray inductance is determined by the inductance outside the conductor, which tends to be constant.

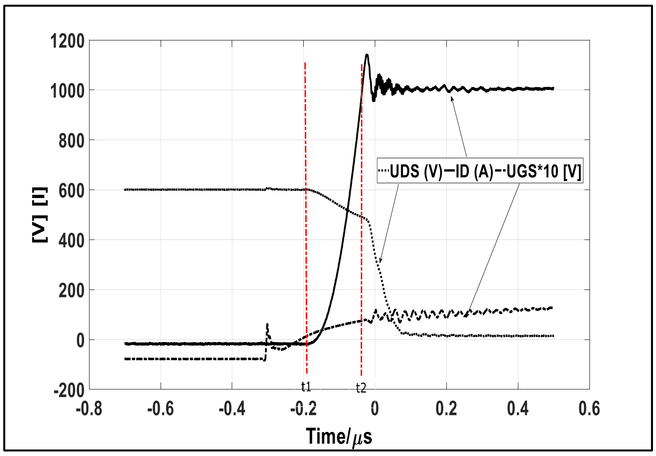

Fig. 6: Danfoss DCM™1000X turn-on transient on Phase A (Lσ=8 nH including module).

The inductance is then evaluated by calculating the definite integral at t_1–t_2 of the voltage across the switching device, divided by the corresponding current variation.

A total commutation inductance of 8 nH has been confirmed experimentally - which is perfectly aligned with the simulation results (considering that the DCM™1000X power module has an internal inductance of approximately 4.5 nH). Several operating points performed at different voltage and current levels have been tested and post processed in MATLAB to confirm the aforementioned value.

Moreover, the insignificant total loop inductance value confirms that the application kit design - developed with the Danfoss DCM™1000X platform - is suitable for fast switching operations used in next generation high-power density drivetrain inverters.

2.3 Current sharing validation

To experimentally verify the current sharing on a three terminal power module, a dynamic test (similar to the stray inductance validation) was performed, although the high-side MOSFET was chosen as device under test to measure the drain current entering the two outer terminals of the DCM™1000X. Several tests were performed to the proposed design with a standard commercially available application kit.

Fig.7 shows a comparison between two switching tests performed.

As illustrated, a small asymmetry in the parallel commutation paths result in a severe current sharing mismatch. In order to verify the

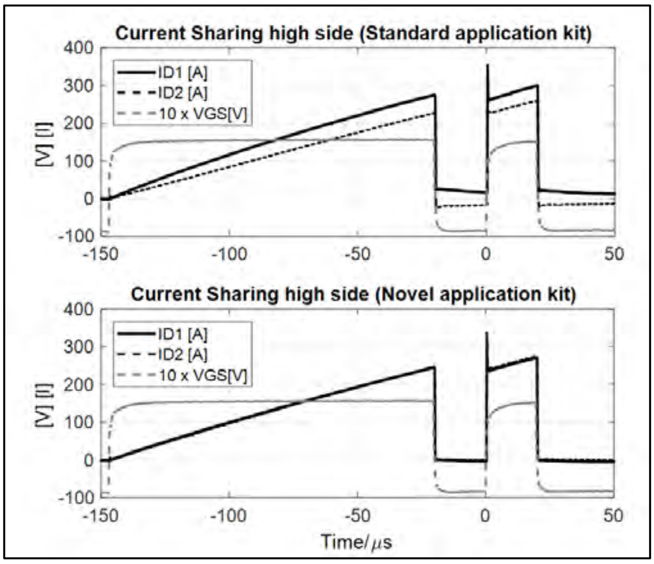

Fig. 7: Current sharing transient comparison (Standard vs. Novel application kit).

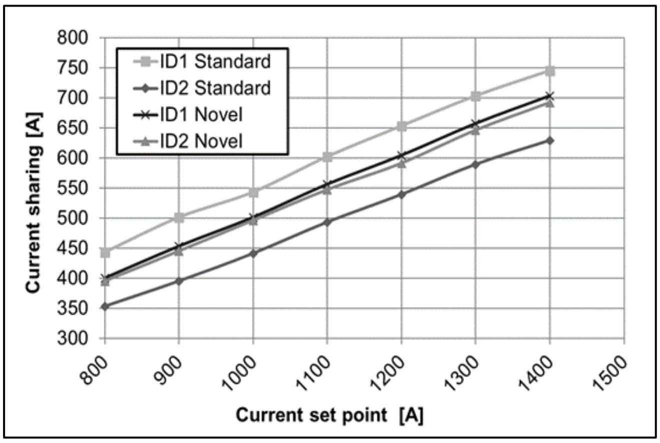

Fig. 8: Current sharing comparison vs. turn-off current set point (Standard vs. Novel application kit).

effectiveness of the proposed application kit; several operating points at different turn-off current values (up to double the device nominal drain current) have been tested and summarizes in the graph shown if Fig.8.

The data shows that a difference in current sharing of up to 120 A can occur if the application kit improperly designed.

On the other hand, the proposed application kit exhibited a max current deviation of 13 A at the 1200 A operating point, which is just within the 1% error margin.

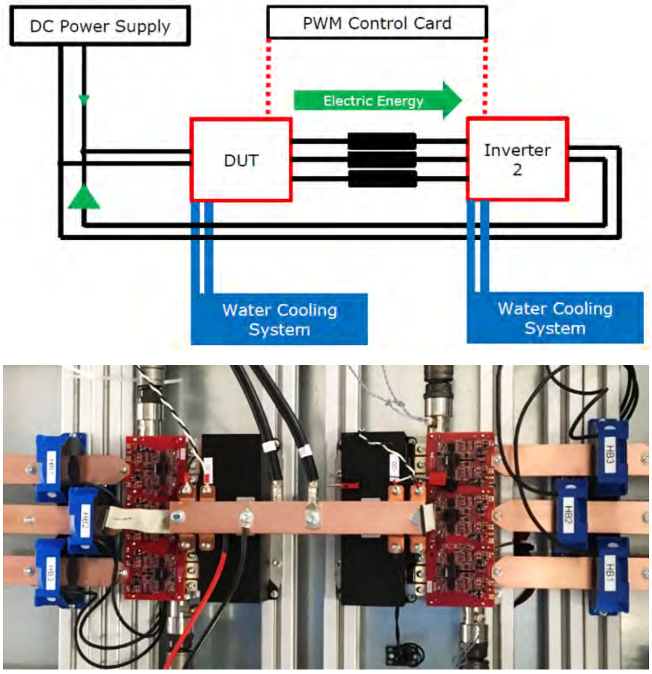

Fig. 9: System level back to back layout.

3 System level testing

To validate the application kit on a complete system level, a back to back test bench was built in the laboratory. The main goal was to thermally validate the application kit design and to demonstrate the overall system performance.

The inverter (DUT) was feeding a three-phase ohmic-inductive load where a second unit, acting as rectifier, forces the energy back into the DC-link.

Fig.9 shows the simple schematic used as well as the actual hardware layout.

Fig.10 shows a thermal image of the power terminals of the application kit (phase A) after steady state thermal conditions were reached, while about 200 kW of power was circulated.

A uniform distribution of the temperature at the outer terminals is evident, indicating proper current

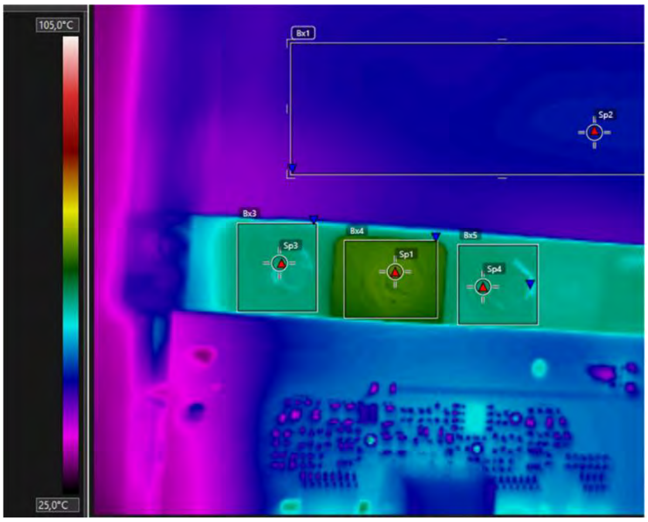

Fig. 10: Application kit (phase A) thermal image during steady state operation.

sharing as already experimentally validated in the previous paragraph.

A maximum temperature hotspot of 73°C was observed on the minus terminal (low-side source) handling the total retuning current to the windings.

Ultimately, as Fig.10 shows, the application kit case temperature revealed a uniform temperature distribution as well as an average temperature of 48°C, allowing a significant margin that can be used for overload conditions.

During all operating points, the capacitor winding's temperature (observed via temperature sensor) was far below the max allowed hotspot specified by the manufacturer and insulation materials used in the bus lamination - with about 25°C margin, thus enabling the targeted 10.000 hours of life for the typical drive cycle.

4 Conclusions

In this paper, an innovative application kit, expressly design for the Danfoss' DCM™1000X half bridge 1200 V SiC MOSFET, was presented and validated.

The estimation of the total loop inductance was first simulated and then validated by dynamic switching test. A total inductance of 8 nH including module was achieved which is significantly lower than any conventional application kit for EV power train and chargers, enabling minimization of voltage overshoot as well as minimization of turn-off losses.

The overall L-R parasitic (caused by the design) was totally suitable in achieving proper current distribution. Moreover, it minimized current mismatch at the power module terminals compared to commercially available application kits.

Ultimately continuous switching testing in a back to back configuration, performed on a classic 2-level inverter structure, revealed a uniform temperature distribution and max temperature far below the allowed hotspot, enabling a significant margin for safety in addition to overload conditions.

The tests prove that the proposed application kit design matches the target specifications, empowering the high switching performance of Danfoss' 1.2 kV SiC DCM™1000X for automotive applications.

5 References:

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