Imbalance Current Analysis and Its Suppression Methodology for Parallel SiC MOSFETs With Aid of a Differential Mode Choke

Zeng, Zheng; Zhang, Xin; Zhang, Zhe

Published in:
IEEE Transactions on Industrial Electronics

Link to article, DOI:
10.1109/TIE.2019.2901655

Publication date:
2020

Document Version
Peer reviewed version

Link back to DTU Orbit

Citation (APA):

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.
Imbalance Current Analysis and Its Suppression Methodology for Parallel SiC MOSFETs With Aid of a Differential Mode Choke

Zheng Zeng, Member, IEEE, Xin Zhang, Member, IEEE, and Zhe Zhang, Senior Member, IEEE

Abstract—Parallel connection of SiC MOSFETs is a cost-effective solution for high-capacity power converters. However, transient imbalance current, during turn-on and off processes, challenges the safety and stability of parallel SiC MOSFETs. In this paper, considering the impact factors of device parameters, circuit parasitics, and junction temperatures, in-depth mathematical models are created to reveal the electro-thermal mechanisms of the imbalance current. Moreover, with the incorporation of a differential mode choke (DMC), an effective approach is proposed to suppress the imbalance current among parallel SiC MOSFETs. Physic concepts, operation principles, and design guidelines of the DMC suppression method are fully presented. Besides, to reduce the equivalent leakage inductance and equivalent parallel capacitance of the DMC, winding patterns of the DMC are comparatively studied and optimized to suppress turn-off over-voltage and switching ringing. Concerning the influence of winding patterns, load currents, gate resistances, and junction temperatures, experimental results are comprehensively demonstrated to confirm the validity of theoretical models and the function of the proposed DMC suppression method. It is turned out the low-cost DMC is easy to design and utilize without complex feedback circuits or control schemes, which is a cost-effective component to guarantee consistent and synchronous on-off trajectories of parallel SiC MOSFETs.

Index Terms—Parallel SiC MOSFETs, mechanism of imbalance current, consistency and synchronization of on-off trajectories, differential mode choke.

I. INTRODUCTION

HIGH-frequency and high-capacity power converters are increasingly demanded for transportation electrification and smart grid applications to reduce cost, improve power-density, and save manpower [1]–[3]. Thanks to the high switching speed and low switching loss, SiC MOSFET device becomes more and more popular for high-frequency power converters [4]–[6]. However, due to the low yield rate in the wafer and high thermal-mechanical stress in the device, the active area of SiC chip is limited, and the current rating of commercial SiC chip is within 100A [4], generally. Parallel connection of SiC MOSFETs is an invertible approach to elevate the current rating of the power device and pursue the high capacity of the power converter. However, the unacceptable imbalance current among parallel SiC MOSFETs poses unsolved challenges [1], [2].

Static and transient imbalance current among parallel SiC MOSFETs may lead to over-current, over-temperature, even thermal runaway, which challenges the safety of parallel devices and limits the usable current rating [7]. The static imbalance current might be automatically suppressed by the positive temperature-dependent on-resistance of device. However, compared with Si counterpart, the on-resistance of SiC MOSFET is not sensitive to junction temperature [8]. The inherent current-sharing capability of SiC MOSFET by using on-resistance is restricted. Besides, the transient imbalance current cannot be self-suppressed by the parallel devices [9], [10]. In contrast, the negative temperature-dependent threshold voltage undesirably increases the transient imbalance current. Due to the challenge of imbalance current, current de-rating is inevitable to design and use the parallel SiC MOSFETs. Current capacities of parallel devices are not fully utilized, which is undesired and uneconomical [11], [12]. Therefore, the transient imbalance current should be carefully addressed for high-capacity applications of parallel SiC MOSFETs.

Some researches focus on the reasons of imbalance current among parallel SiC MOSFETs. From the viewpoint of manufacturing and material, SiC MOSFETs are not as mature as their Si counterparts. Differences in electrical parameters of parallel SiC MOSFETs may lead to imbalance current [13], [14]. For instance, inconsistent threshold voltages of parallel SiC MOSFETs result in asynchronous turn-on and off trajectories, as well as the imbalance current. Besides, an asymmetrical circuit layout results in mismatched parasitics in power loops, common source loops, and gate loops among parallel SiC MOSFETs [15], [16]. The mismatched parasitic inductances result in asymmetrical impedances and increase the imbalance current among parallel branches [17], [18].
Furthermore, unequal junction temperatures of parallel SiC MOSFETs also lead to imbalance current by the electro-thermal coupling of temperature-sensitive electrical parameters [19]–[21]. However, how the imbalance current generated and expanded is still poorly modeled. In-depth principles and mathematical models of the imbalance current should be carefully concerned to suppress it better.

Recently, some existing approaches have been reported to overcome the imbalance current [22]–[32]. Series resistor inserted into the parallel branches can limit the static imbalance current, but it does not affect on the transient imbalance current. Some researches focus on the optimal layout of direct bonding copper (DBC) to guarantee consistent parasitics and balance currents of parallel SiC MOSFETs [22], [23]. Generally, it is costly and time-consuming to design novel and effective DBC layouts for parallel SiC MOSFETs. Additionally, an absolutely symmetrical DBC layout does not exist, so it is a very challenging task to suppress the imbalance current by using optimized DBC. With the aid of differential current sensor and analog time-delay controller, the active gate driver is a practical approach to handle the imbalance current and ensure the synchronous trajectories of parallel MOSFETs [24]–[26]. By using active gate driver, the differential current sensor with multi-channel and high-bandwidth property is difficult to fabricate. Besides, the analog feedback control is complicated to design. Therefore, to overcome the imbalance current, some simple approaches based on passive elements should be further investigated. Inductance-based passive balancing is a creative solution, which has been proposed to reshape the loop impedance and limit the imbalance current [27]–[31]. The inserted passive inductances and gate resistances change the impedance of gate-source loops, the stability of parallel SiC MOSFETs in transient processes ought to be further addressed [32]–[34]. However, thanks to the benefits of low cost, fast dynamics, and easy design, passive-based approaches to suppress the imbalance current are promising solutions and need more concerns.

Revisiting the imbalance current issue of parallel SiC MOSFETs, the imbalance current is a kind of differential mode current, essentially. Inspired by the successfully used common mode chokes to attenuate common mode current in high-frequency power supplies, an interesting idea is naturally generated as: the imbalance current can be suppressed by a simple differential mode choke (DMC).

In this paper, in-depth mathematical models are proposed to reveal the electro-thermal principles of imbalance current among parallel SiC MOSFETs. After that, a DMC-based suppression methodology is proposed, designed, and verified to guarantee the consistent and synchronous on-off trajectories of parallel SiC MOSFETs. The rest of this paper is organized as follows. The phenomenon of imbalance current issue is briefly described and analyzed in Section II. In Section III, to understand the imbalance current, electro-thermal mechanisms of the imbalance current are comprehensively modeled and analyzed. In Section IV, the DMC-based method is proposed to suppress the imbalance current. Physic concepts, operation principles, and design guidelines of the DMC are also presented. In Section V, considering multiple impact factors, extensive experiments are provided to confirm the validity of the proposed approach. Extension and comparison of proposed DMC suppression method are illustrated in Section VI. Finally, Section VII summarizes this paper.

II. PROBLEM DESCRIPTION: IMBALANCE CURRENT AMONG PARALLEL SiC MOSFETs

The configuration of parallel SiC MOSFET devices under test (DUTs) is shown in Fig. 1. Some key variables are listed in TABLE I. \( i_1 \) and \( i_2 \) are drain currents, where subscripts 1 and 2 respectively represent DUT 1 and DUT 2. Typically measured imbalance current issue of parallel SiC MOSFETs is demonstrated in Fig. 2.

![Fig. 1. Schematic circuit of parallel SiC MOSFETs.](image)

![Fig. 2. Imbalance current issue of parallel SiC MOSFETs.](image)

<table>
<thead>
<tr>
<th>Table I</th>
<th>PARAMETERS OF TEST RIG</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_{dc} )</td>
<td>DC-link voltage</td>
</tr>
<tr>
<td>( C_{dc} )</td>
<td>DC-link capacitance</td>
</tr>
<tr>
<td>( v_{ds} )</td>
<td>Drain-source voltage</td>
</tr>
<tr>
<td>( L )</td>
<td>Load inductance</td>
</tr>
<tr>
<td>( i_{d1} )</td>
<td>Drain current</td>
</tr>
<tr>
<td>( V_{G} )</td>
<td>Output voltage of gate driver</td>
</tr>
<tr>
<td>( R_{g} )</td>
<td>Gate resistance</td>
</tr>
</tbody>
</table>

Compared SiC MOSFET C2M0080120D from Wolfspeed to Si MOSFET IXFK32N100Q3 from IXYS, the temperature-dependent \( R_{dson} \) and threshold voltage \( V_{th} \) are depicted in Fig. 3. The \( R_{dson} \) of SiC device is less sensitive to temperature than Si device. The self-current-sharing capability of SiC MOSFET is limited. In contrast, the negative temperature-dependent \( V_{th} \) degrades the current-sharing performance. Therefore, the imbalance current of parallel SiC MOSFETs is more severe than Si ones. Mechanism models and physic methods are urgently needed to understand and suppress the imbalance current.

![Fig. 3. Comparison of SiC and Si MOSFETs. Temperature-dependent (a) on-resistance \( R_{dson} \) and (b) threshold voltage \( V_{th} \).](image)
III. MATHEMATICAL MECHANISMS OF IMBALANCE CURRENT FROM ELECTRO-THERMAL PERSPECTIVE

The imbalance current among parallel SiC MOSFETs is mainly influenced by three factors: inconsistent device parameters, asymmetrical circuit layouts, and unequal junction temperatures. These inevitable factors jointly result in the imbalance current \( \Delta i_i = i_{i1} - i_{i2} \), which can be expressed as

\[
\Delta i_i = F(\Delta V_{th}, \Delta \beta, \Delta L_d, \Delta L_s, \Delta T_f),
\]

where \( F(\cdot) \) is a nonlinear function; \( \Delta V_{th} \) and \( \Delta \beta \) are dispersing threshold voltage and transconductance coefficient of parallel devices; \( \Delta L_d \) and \( \Delta L_s \) are mismatched stray inductances at drain and source terminals; \( \Delta T_f \) is junction temperature difference of parallel devices.

Although the impact of individual factor may be small, the entire imbalance current \( \Delta i_i \) might be unacceptable. Lacking of mechanism models to characterize the imbalance current, it poses an unsolved challenge to rebalance the load currents of parallel SiC MOSFETs.

The imbalance current is nonlinearly influenced by many factors as indicated in (1). It is not possible to consider all the impacts at the same time. Based on the small-signal analysis methodology, some essential principles of imbalance current are mathematically modeled considering the electro-thermal factors one-by-one as follows.

A. Impact of Dispersing Device Parameters

Drain current of either SiC MOSFET in Fig. 1 can be expressed as

\[
i_d = \begin{cases} 
0 & \text{if } v_{gs} < V_{th} \\
G_m(v_{gs} - V_{th}) = \beta(v_{gs} - V_{th})^2 & \text{if } v_{gs} \geq V_{th}
\end{cases}
\tag{2}
\]

where \( G_m \) and \( V_{th} \) are the transconductance and threshold voltage. Transconductance coefficient is \( \beta \) determined by the structure size of chip [35], which can be written as

\[
\beta = \frac{\mu_n C_{OX} Z_{CH}}{2 L_{CH}},
\tag{3}
\]

where \( \mu_n \) is the majority-carrier mobility, \( C_{OX} \) is the gate oxide capacitance per unit area, \( Z_{CH} = \varepsilon_{OX} t_{OX} \), \( t_{OX} \) is the dielectric constant of the silicon dioxide, \( \varepsilon_{OX} \) is the thickness of the gate oxide. \( Z_{CH} \) and \( L_{CH} \) are channel width and length.

According to Fig. 1, the transfer function model from gate drive voltage \( V_{gs} \) to gate-source voltage \( V_{gs} \) can be written as

\[
V_{gs}(s) = \frac{1}{(L_d + L_s)C_{gs}s^2 + R_d s + 1} V_i,
\tag{4}
\]

where \( s = j 2 \pi f \) is the Laplace operator; \( f \) is the specific frequency; \( C_{gs} \) is the gate-source capacitance of SiC MOSFET; \( L_d \) and \( L_s \) are parasitic inductances at gate and source terminals; \( R_d \) is gate resistance of gate driver, as summarized in TABLE I. \( V_{gs}(s) \) is the gate-source voltage in frequency domain. The gate-source voltage in time domain can be derived from (4) by using inverse Laplace transform, \( v_{gs} = \mathcal{L}^{-1}[V_{gs}(s)] \).

If the parameter variation of \( V_{th} \) is \( \Delta V_{th} \), the transient imbalance current caused by \( \Delta V_{th} \) can be expressed as

\[
\Delta i_i(\Delta V_{th}) = \frac{\partial \beta}{\partial V_{th}} \Delta V_{th} = -2 \beta(v_{gs} - V_{th}) \Delta V_{th}. \tag{5}
\]

According to (4), during turn-on and -off processes, because the impedances of stray inductances and capacitance are affected by specific frequency, the gate-source voltage \( v_{gs} \) in time domain can be analyzed in frequency domain to understand the frequency-related principles of imbalance current.

Similarly, transient imbalance current caused by dispersing parameter \( \beta \) can be derived as

\[
\Delta i_i(\Delta \beta) = \frac{\partial \beta}{\partial \Delta \beta} \Delta \beta = (v_{gs} - V_{th})^2 \Delta \beta, \tag{6}
\]

where \( \Delta \beta \) is the parameter variation of \( \beta \).

Taking C2MO080120D as an example, in (2) - (6), \( V_G = 20 \text{ V}, \quad V_{th} = 2.6 \text{ V}, \quad \beta = 1.11 \text{ A/V}^2, \quad R_d = 20 \Omega, \quad C_{gs} = 1980 \text{ pF} \text{ at 600 V} \) [36], parasitics \( L_d = 9.2 \text{ nH}, \quad L_s = 7.5 \text{ nH} \) [37]. According to (4) and (5), the numerical results of \( \Delta i_i \) caused by \( \Delta V_{th} \) and influenced by \( v_{gs} \) is illustrated in Fig. 4 (a). It can be found the magnitude of transient imbalance current \( \Delta i_i \) dramatically increases with \( v_{gs} \), \( \Delta V_{th} \), and \( \beta \).

The transient imbalance current in frequency domain is depicted in Fig. 4(b). The imbalance current in three-dimension space can be mapped to two-dimension space as shown in Fig. 4(c) and (d).

Although the maximum switching frequency of SiC MOSFET may be up to several MHz, the commonly used switching frequency of SiC MOSFET is from several dozens of kHz to several hundreds of kHz. As shown in Fig. 4(b) to (d), frequency-dependent transient imbalance current is attenuated above 1 MHz, considering the frequency range from switching frequency to ten times of switching frequency. Due to the un-negligible imbalance current, the imbalance current in the considered frequency range should be paid enough attention.

Besides, in Fig. 4, it can be concluded that small \( \beta \) is useful to reduce the transient imbalance current. The imbalance current \( \Delta i_i \) can be eliminated if and only if \( \Delta V_{th} = 0 \). However, due to the difficulty of device fabrication, the parameter variation of SiC MOSFET is inevitable.
B. Impact of Mismatched Stray Inductances

Caused by asymmetrical layouts of parallel devices in power package or power circuit, mismatched stray inductances also lead to transient imbalance current. The mismatched parasitics mainly come from power drain inductance $L_d$ and common source inductance $L_s$ in power loops.

Accounting for the mismatched $L_d$, parallel branches in Fig. 1 satisfy Kirchhoff’s voltage law, which can be expressed as

$$L_d \frac{di_d}{dt} + L_s \frac{di_s}{dt} + V_{th} = L_s \frac{di_s}{dt} = i_s R_{son} = v_{th},$$

where $R_{son1}$ and $R_{son2}$ are on-resistances of parallel SiC MOSFETs. Supposing $R_{son1} = R_{son2} = R_{son}$, $L_s = L_d = L_s$, and $L_d = L_d + \Delta L_d$, where $\Delta L_d$ is the difference of drain stray inductances between parallel branches, (7) can be rewritten as

$$\Delta L_d \frac{di_d}{dt} + (L_d + L_s) \frac{di_s}{dt} + R_{son} \Delta i_d = 0. \quad (8)$$

The slope of drain current $i_d$ is determined by the performance of SiC MOSFET, which can be approximately expressed as

$$\frac{di_d}{dt} \approx \frac{I_L}{2 \tau}, \quad (9)$$

where $I_L$ is the load current in load inductor, $\tau$ is the transient time of device’s drain current rising from 0 to $I_L/2$.

Therefore, $\Delta i_d$ caused by mismatched $L_d$ can be expressed as

$$\Delta i_d(\Delta L_d) = \frac{I_L}{2[(L_d + L_s)\tau + R_{son}]} \Delta L_d. \quad (10)$$

It can be seen $\Delta i_d$ is proportional to $I_L/\tau$, which means slow switching speed is useful to reduce the transient imbalance current caused by $\Delta L_d$. Additionally, the maximum value of transient imbalance current occurs at $s = 0$, which can be expressed as

$$\Delta I_d(\Delta L_d) = \Delta i_d|_{s=0} = \frac{I_L}{2R_{son}\tau} \Delta L_d. \quad (11)$$

Taking $L_d = 5.9 \text{nH}$, $R_{son} = 80 \text{m} \Omega$, $L_s = 7.5 \text{nH}$, and $g_m = 2.4 \text{S}$ for example, the imbalance current $\Delta i_d$ versus $\Delta L_d$ and $\tau$ is depicted in Fig. 6. Transient imbalance current should be paid more attention for high-frequency application of SiC MOSFET with very small $\tau$.

Similarly, considering the influence of mismatched $L_s$, the drain currents in (2) can be written as

$$\begin{align*}
\dot{i}_{s1} &= g_m(v_s - v_{th1}) + \dot{v}_{th1} \\
\dot{i}_{s2} &= g_m(v_s - v_{th2}) + \dot{v}_{th2},
\end{align*} \quad (12)$$

where $v_{th1} = V_{th1} + \Delta V_{th1}$ and $v_{th2} = V_{th2} + \Delta V_{th2}$ are the induced voltages by common source inductances of the SiC MOSFETs. If the threshold voltage and transconductance are matched ($V_{th1} = V_{th2} = V_{th}$, $g_m = g_{m1} = g_{m2}$), (12) can be simplified to

$$\Delta L_s \frac{di_d}{dt} + (L_d + L_s) \frac{di_s}{dt} = \frac{1}{g_m} \Delta i_d, \quad (13)$$

where $\Delta L_s = L_{d1} - L_{d2}$. Transient imbalance current can be derived as

$$\Delta i_d(\Delta L_s) = \frac{g_m i_d}{2L_s(g_m L_s + 1)} \Delta L_s. \quad (14)$$

Similar to (11), the maximum value of transient imbalance current appears at $s = 0$, which can be expressed as

$$\Delta I_d(\Delta L_s) = \Delta i_d|_{s=0} = \frac{g_m I_d}{2L_s} \Delta L_s. \quad (15)$$

In the condition of $L_d = 7.5 \text{nH}$ and $g_m = 2.4 \text{S}$, the impact of mismatched $L_s$ is illustrated in Fig. 7. Compared (14) to (10),
because \( 1/g_m > R_{\text{Ron}} \), the imbalance current caused by \( \Delta I_d \) is smaller than that by \( \Delta L_d \).

C. Impact of Unequal Junction Temperatures

Electrical characteristics of SiC MOSFETs are highly temperature-dependent. The asymmetrical layout of parallel SiC MOSFETs on a heat-sink or DBC results in unequal thermal resistances and junction temperatures. Based on (2), how temperature affects the drain current through the temperature-dependent \( g_m \) and \( V_{th} \) can be derived, which can be expressed as

\[
\frac{\partial I_d}{\partial T_j} = (v_{ps} - V_{th}) \frac{\partial g_m}{\partial T_j} - g_m \frac{\partial V_{th}}{\partial T_j},
\]

where \( T_j \) is the junction temperature of the SiC MOSFET. The transient imbalance current, caused by the junction temperature difference \( \Delta T_j \) of parallel SiC MOSFETs, can be derived as

\[
\Delta I_d(\Delta T_j) = \frac{\partial I_d}{\partial T_j} \Delta T_j.
\]

The typical temperature-dependent \( g_m \) and \( V_{th} \) of the SiC MOSFET device C2M0080120D can be expressed as [38]

\[
\begin{align*}
V_{th} &= 2.71 - 6.37 \times 10^{-3} T_j, \\
g_m &= 2.39 + 1.62 \times 10^{-3} T_j.
\end{align*}
\]

According to (16)–(18), Fig. 8 demonstrates the transient imbalance current caused by unequal junction temperatures, in case of \( V_{th} = 2.7 \) V, \( g_m = 2.4 \) S, \( T_j = 25 \) °C, and \( I_d = 30 \) A. It can be found that the imbalance current \( \Delta I_d \) increases with \( \Delta T_j \) and \( v_{ps} \). Big \( V_{th} \) is helpful to suppress the transient imbalance current. Besides, it is evident that the transient imbalance current has a positive temperature-dependent coefficient, which may lead to thermal runaway among parallel SiC MOSFETs and cause damages.

![Fig. 8. Imbalance current affected by unequal \( T_j \) at \( I_d = 30 \) A. (a) \( \Delta I_d \) versus \( \Delta T_j \) and \( v_{ps} \), (b) \( \Delta I_d \) versus \( \Delta T_j \), and (c) \( \Delta I_d \) versus \( f \) at \( V_{th} = 2 \) V, and (d) \( \Delta I_d \) versus \( f \) at \( V_{th} = 4 \) V.](image)

According to the before mentioned mechanisms of imbalance current, multiple inevitable electro-thermal factors jointly result in the imbalance current among parallel SiC MOSFETs, it is difficult to eliminate all these factors. Therefore, some auxiliary circuits should be addressed to suppress the imbalance current.

IV. PROPOSED DMC METHOD FOR IMBALANCE CURRENT SUPPRESSION

A. Physic Concept of the Proposed DMC

Schematic diagram of the DMC is illustrated in Fig. 9. As shown in Fig. 9(a), the balance load current is common mode current, and the magnetic flux density \( B_s \) in the core is zero. \( i_{d1} \) and \( i_{d2} \) are affected by leakage inductance caused by leakage magnetic flux density \( B_t \) in the air. As depicted in Fig. 9(b), the imbalance current is differential mode current, and it activates the \( B_s \). The corresponding magnetizing inductance is big enough to limit the imbalance current.

![Fig. 9. Magnetic flux densities of DMC induced by (a) balance current \( i_{d1} = i_{d2} \) and (b) imbalance current \( i_{d1} > i_{d2} \).](image)

From the viewpoint of impedance, the imbalance current, caused by the before mentioned impact factors, can be modeled as

\[
\Delta I_d = \frac{v_{ps}/Z_1 - V_{th}/Z_2}{Z_1 - Z_2},
\]

where \( Z_1 \) and \( Z_2 \) are equivalent impedances in parallel branches.

Operation principles of the DMC to suppress imbalance current can be characterized as 4 dynamic intervals, as illustrated in TABLE II and Fig. 10.

1. Interval 1: At the beginning, assuming \( Z_1 = Z_2 \), so \( i_{d1} = i_{d2} \), currents of parallel SiC MOSFETs are balanced.

2. Interval 2: If \( Z_1 \neq Z_2 \), for instance, \( Z_1 < Z_2 \), the corresponding imbalance current in (19) circulates between the parallel branches, i.e., \( i_{d1} > i_{d2} \) in Fig. 10.

3. Interval 3: According to the dot convention of DMC, the induced voltages in parallel branches are opposite (i.e., \( v_m = -v_m \)) in Fig. 10, where \( v_m = L_d\Delta i_d/dt \).

4. Interval 4: Induced voltages regulate the imbalance current (i.e., \( i_{d1} \uparrow, i_{d1} \downarrow, \Delta i_d \rightarrow 0 \)) until the currents are balanced again.

<table>
<thead>
<tr>
<th>TABLE II</th>
<th>INTERVALS DURING IMBALANCE CURRENT SUPPRESSION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interval 1</td>
<td>Currents are balance, ( i_{d1} = i_{d2} )</td>
</tr>
<tr>
<td>Interval 2</td>
<td>Currents are imbalance, i.e., ( i_{d1} &gt; i_{d2} )</td>
</tr>
<tr>
<td>Interval 3</td>
<td>Due to induced voltage ( v_m ), ( i_{d1} ) decreases and ( i_{d2} ) increases</td>
</tr>
<tr>
<td>Interval 4</td>
<td>Currents are balance again</td>
</tr>
</tbody>
</table>

![Fig. 10. Schematic diagram for imbalance current suppression by DMC.](image)
It should be noted, by using the DMC to suppress imbalance current, one winding observes energy $P_m = \nu_0 \Delta i_d$ and converts electric energy to magnetic energy. However, the other winding generates energy $P_a = \nu_0 \Delta i_a$ and converts magnetic energy to electric energy. Therefore, DMC utilizes magnetic flux as a media to transfer current from one branch to the other, and it can eliminate the imbalance current without energy loss in ideal condition.

B. Theory Foundation of the Proposed DMC

(1) Mathematical Models of the Proposed DMC Method

Fig. 11(a) demonstrates a test rig for current sharing of parallel SiC MOSFETs by incorporating the DMC. According to the configuration of the DMC by using sectional winding in Fig. 11(b), the magnetic flux density $B_c$ in the core caused by the transient imbalance current can be expressed as

$$B_c = \frac{2n\mu_0\mu_r}{\pi(D_{\max} + D_{\min})} \Delta i_d,$$

where $n$ is the turns of winding, $\mu_0$ and $\mu_r$ are the vacuum permeability and relative permeability, respectively. $D_{\max}$ and $D_{\min}$ are external and inner diameters of the core. The leakage magnetic flux density $B_l$ in the air can be expressed as

$$B_l = n \mu_0 \mu_r \Delta i_l.$$

(20)

(21)

where

$$\gamma = \frac{\Delta i_d}{I_s} = \frac{\Delta R_m + (\Delta L_1 + \Delta L_0)I_s}{I_s}.$$

(26)

Therefore, according to (24), $\Delta i_d$ can be expressed as

$$\Delta i_d = \frac{-\Delta R_m + (\Delta L_1 + \Delta L_0)I_s}{I_s}.$$

(25)

Therefore, according to (24), $\Delta i_d$ can be expressed as

$$\Delta i_d = \frac{-\Delta R_m + (\Delta L_1 + \Delta L_0)I_s}{I_s}.$$

(25)

The maximum imbalance current $\Delta i_{\max}$ is theoretically determined by the equivalent impedance $\Delta R_{\text{son}} + (\Delta L_1 + \Delta L_0)\gamma$.

According to (25), the ratio of imbalance current, which is defined as $\gamma$, can be expressed as

$$\gamma = \frac{\Delta i_d}{I_s} = \frac{\Delta R_m + (\Delta L_1 + \Delta L_0)I_s}{I_s}.$$

(27)

In the condition of $\Delta L_0 = 2 \text{nH}$, $L_m = 1 \text{nH}$, and $\Delta L_1 = 10 \text{nH}$, the $\gamma$ greatly decreases with the increased $L_m$, as indicated in Fig. 12(a). However, big $L_m$ also means bulk volume, heavy weight, and more cost. Therefore, there is a trade-off to determine $L_m$.

(2) Operation Principles of the Proposed DMC Method Ignoring the EPC, based on the proposed DMC suppression solution, according to the schematic diagram in Fig. 11(c), controlled currents in parallel branches satisfy

$$\left( L_m + L_{\text{dson}} + L_a \right) \frac{di_{\text{dson}}}{dt} + L_m \frac{di_a}{dt} + R_{\text{dson}} \frac{v_{\text{dson}}}{l_{\text{dson}}} = \left( L_m + L_{\text{dson}} + L_a \right) \frac{di_{\text{dson}}}{dt} - L_m \frac{di_a}{dt} + R_{\text{dson}} \frac{v_{\text{dson}}}{l_{\text{dson}}}.$$

(23)

If $R_{\text{dson}} = R_{\text{dson2}} + \Delta R_{\text{ac}},$ (23) can be simplified to

$$\left( 2L_m + L_a + L_{\text{dson}} + L_{\text{dson2}} \right) \frac{di_{\text{dson}}}{dt} + \left( \Delta L_1 + \Delta L_0 \right) \frac{di_a}{dt} + R_{\text{dson2}} \Delta i_d = 0.$$

(24)

Therefore, according to (24), $\Delta i_d$ can be expressed as

$$\Delta i_d = \frac{-\Delta R_m + (\Delta L_1 + \Delta L_0)I_s}{I_s}.$$

(25)

It can be seen $\Delta i_d$ increases with $I_s$. To avoid saturation of DMC, the DMC core material and winding turns should be optimally designed. In dynamic state, $s \neq 0$, because $L_m >> L_a + L_{\text{dson}} + L_{\text{dson2}}$, the high-frequency transient imbalance current $\Delta i_d$ is mainly limited by $L_m$. In steady-state, $s = 0$, (25) can be simplified to

$$\Delta i_{\max} = \frac{-\Delta R_m + (\Delta L_1 + \Delta L_0)I_s}{I_s}.$$

(26)

Fig. 11. Test rig for parallel SiC MOSFETs. (a) Schematic of test rig, (b) structure of DMC, and (c) equivalent circuit of test rig.

Fig. 12. Transient imbalance current ratio limited by $L_m$. (a) $\gamma$ versus $L_m$ and $f$, (b) mapped $\gamma$ and $L_m$ at $t = 25$ nS, and (c) mapped $\gamma$ and $L_m$ at $t = 10$ nS.
example, in the condition of \( t_i = 25 \text{ ns} \), if the ratio of imbalance current is set as \( \gamma = 5\% \), the minimum \( L_m \) should be 2 \( \mu \text{H} \) to meet the desired \( \gamma \)according to Fig. 12(b). As indicated in Fig. 12(c), to guarantee the same \( \gamma \) in the scenario of faster \( \text{d}i/\text{d}t \), the minimum \( L_m \) should be 7 \( \mu \text{H} \) in the condition of \( t_i = 10 \text{ ns} \).

As mentioned before, it can be found magnetic flux density in the core is the main contributor to limit imbalance current, while leakage magnetic flux density should be minimized to limit parasitic inductance and attenuate switching ringing.

C. Design Guidelines of the Proposed DMC

To optimally design the DMC for imbalance current suppression, some criteria should be fulfilled: high-frequency material, proper winding turns, enough operation magnetic flux density, and optimal winding structure. Some practical design guidelines of DMC are presented step-by-step as follows.

1. Step 1: Selecting Materials of Core and Wire

Targeting at high-frequency application, AlSiFe based metallic powder core is preferred for the DMC to reduce the loss caused by eddy-current and hysteresis effect. Besides, Litz wire is recommended for the windings to reduce the loss caused by skin effect and proximity effect.

2. Step 2: Calculating Winding Turns (n)

Winding turns \( n \) is determined by the expected \( L_m \) which decided by the map between \( \gamma \) and \( L_m \) in Fig. 12. According to (22), the numerical calculation of minimum turns \( n \) can be derived as

\[
n = \left[ \frac{\pi (D_{max} - D_{min}) \gamma}{\mu_n \mu_r (D_{max} - D_{min}) h} \right], \quad (28)
\]

In practice, turns can be chosen as the minimum integer larger than the calculated \( n \) in (28).

3. Step 3: Determining Operation Magnetic Flux Density (\( B_{op} \))

\( B_{op} \) is determined by the maximum imbalance current to be handled, which can be expressed as

\[
B_{op} = \frac{2n \mu_n \mu_r \Delta \phi_{b\text{max}}}{\pi (D_{max} - D_{min}) h}. \quad (29)
\]

\( B_{op} \) is limited by the saturation magnetic flux density of core. To avoid the saturation of DMC, \( B_{op} \) should not larger than the saturation magnetic flux density \( B_{sat} \) of the core material, \( B_{op} \leq B_{sat} \), and it can be derived that

\[
\epsilon = (B_{sat} - B_{op})/B_{sat}, \quad \epsilon \in [0, 1], \quad (30)
\]

where \( \epsilon \) is a coefficient to quantify the margin of reserved magnetic flux to resist the saturation of DMC in extreme load conditions.

4. Step 4: Optimizing Winding Pattern

To avoid turn-off over-voltage caused by DMC, leakage inductance \( L_o \) of the DMC should be minimized. Besides, the EPC may activate switching ringing, and it should be minimized. These issues can be achieved by using an optimal winding pattern.

Sectional and bifilar windings are the commonly used windings, as shown in Fig. 13. Compared with the sectional winding, currents in bifilar winding flow in opposite directions. Therefore, the magnetic field created by one winding is equal and opposite to that created by the other. Thus, leakage magnetic flux density and leakage inductance of the DMC can be reduced by using bifilar winding. Besides, bifilar winding performs lower EPC because the distance between successive turns is greater than sectional winding.

![Fig. 13. Comparison of electromagnetic fields in DMC by using (a) sectional winding and (b) bifilar winding.](image)

The electromagnetic fields of the DMC with specific winding patterns at \( I_L = 30 \text{ A} \) are virtualized by using finite element analysis (FEA) tool Maxwell, as depicted in Fig. 13. Compared with sectional winding, the magnetic flux density \( (B_0) \) of DMC by using bifilar winding is remarkably reduced as desired. Besides, the electric flux density \( (D_0) \) of DMC by using bifilar winding is much smaller than that by using sectional winding. As a result, thanks to the minimized leakage inductance and EPC, bifilar winding is recommended for the DMC to reduce turn-off over-voltage and switching ringing.

5. Design Case of the DMC

It should be noted, like all magnetic components, trial and error method may be used to design the DMC. To better understand the DMC, a design example is provided:

Step 1: Choosing AlSiFe core CS229125 (\( \mu_r = 125 \), \( B_{sat} = 1.05 \text{T} \)), \( D_{max} = 23 \text{ mm} \), \( D_{min} = 14 \text{ mm} \), \( h = 7.62 \text{ mm} \) and Litz wire (100 strands and cross-area 0.78 mm²) as DMC materials.

Step 2: As illustrated in IV.B, based on the trade-off between current-sharing performance and volume, \( \gamma \) is set as 5\%, and \( L_m \) is selected as 9 \( \mu \text{H} \) according to Fig. 12. Winding turns are derived as \( n = 10 \) according to (28).

Step 3: To handle \( \Delta \phi_{b\text{max}} = 20 \text{ A} \), according to (29), \( B_{op} \) is calculated as 0.54 \text{T}, which is much smaller than \( B_{sat} \). Margin coefficient \( \epsilon \) approximates to 50\%. Thus, sufficient margin is reserved to avoid saturation of DMC in extreme load conditions.

Step 4: Bifilar winding is implemented to reduce \( L_o \) and EPC as small as possible.

V. EXPERIMENTAL VALIDATIONS

To confirm the performance of the proposed DMC-based suppression method, an inductor-clamped double-pulse test (DPT) platform is set up, as shown in Fig. 14(a). Parallel SiC MOSFETs C2M0080120D are employed as DUTs. Facilities utilized in the test rig are listed in TABLE III. A TI TMS320F28335 DSP control board is used to generate the gate pulses. DMC prototypes with different windings patterns are made as shown in Fig. 14(b). Overall test conditions are selected as \( V_{dc} = 600 \text{ V} \), \( I_L = 20 \text{ A} \), \( R_G = 20 \Omega \), \( V_G = 20/-5 \text{ V} \), and \( L = 560 \mu \text{H} \).
As mentioned in Section IV, due to the leakage inductance and EPC, performances of the DMC highly depend on the winding pattern. Commonly used sectional and bifilar windings are fabricated and evaluated, as illustrated in Fig. 15. By using sectional winding of DMC, due to the non-optimized leakage-inductance and EPC, the resonant frequency of drain current and drain-source voltage approximates 10 MHz, which is much smaller than that by using bifilar winding (nearly 20 MHz). Thanks to the minimized parasitics, bifilar winding can effectively reduce the ringing during turn-on and -off. Besides, compared with sectional winding, the peak value of imbalance current ratio $\gamma$ is reduced from 40% to 7% by using bifilar winding. It is proved the bifilar winding can achieve better current-sharing performance and reduce switching ringing, compared with the sectional winding.

Different test conditions are further compared, including without solution, with series resistors, and with DMC. Experimental results are depicted in Fig. 16.

In condition of no current-sharing solution, Fig. 16(a) illustrates the measured on-off trajectories of parallel SiC MOSFETs. As mentioned in Section III, the maximum imbalance current occurs at the end of turn-on or -off processes. With the help of series resistors $1 \Omega$ inserted in the parallel branches, Fig. 16(b) demonstrates that the static imbalance current can be suppressed. However, because the utilized series resistors cannot affect the on-off trajectories of SiC MOSFETs, the transient imbalance current remains. By implementing the DMC with bifilar winding, both the transient and static imbalance currents are greatly suppressed, as indicated in Fig. 16(c).

### TABLE IV. COMPARISON OF EXPERIMENTS IN DIFFERENT CASES

<table>
<thead>
<tr>
<th>Condition</th>
<th>Device</th>
<th>$E_{on}$</th>
<th>$i_{\text{max}}$</th>
<th>$t_{r}$</th>
<th>$t_{f}$</th>
<th>$E_{off}$</th>
<th>$i_{\text{max}}$</th>
<th>$t_{r}$</th>
<th>$t_{f}$</th>
<th>$V_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turn-on</td>
<td>DUT1</td>
<td>14.4</td>
<td>36.4</td>
<td>86.8</td>
<td>502</td>
<td>13.6</td>
<td>45.6</td>
<td>378</td>
<td>12.4</td>
<td>59.6</td>
</tr>
<tr>
<td>Turn-off</td>
<td>DUT1</td>
<td>638</td>
<td>36.4</td>
<td>58.4</td>
<td>760</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turn-on</td>
<td>DUT2</td>
<td>14.8</td>
<td>36.4</td>
<td>90.4</td>
<td>470</td>
<td>13.2</td>
<td>36.4</td>
<td>367</td>
<td>12.8</td>
<td>55.2</td>
</tr>
<tr>
<td>Turn-off</td>
<td>DUT2</td>
<td>442</td>
<td>36.4</td>
<td>55.2</td>
<td>760</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Fig. 17 further demonstrates the comparative experiments in conditions of different load currents. As seen, with series resistors, the transient imbalance current cannot be suppressed. The imbalance current increases with the load current, especially in the turn-on process. In contrast, with the DMC, the
turn-on and turn-off trajectories of the parallel SiC MOSFETs are consistent.

![Fig. 17. Experimental results at different load currents. (a) With series resistors and (b) with the proposed DMC.](image)

The trajectories of $v_{ds}$ and $i_d$ during turn-on and turn-off processes are demonstrated in Fig. 18. It can be found that, compared with the inserted series resistors, the imbalance current between parallel SiC MOSFETs can be effectively suppressed by the DMC.

![Fig. 18. Measured on-off trajectories of SiC MOSFETs at different load currents. (a) With series resistors and (b) with the proposed DMC.](image)

To confirm the capability of proposed DMC, comparative experiments by using different gate resistances between 2.5 Ω and 51 Ω are achieved, as depicted in Fig. 19. Small gate resistance can elevate the switching speed and $di/dt$ of SiC MOSFET. In Fig. 19(a), without suppression solution, decreasing gate resistance will increase imbalance current, as analyzed in Section III. Both static and dynamic imbalance currents can be well suppressed by the proposed DMC, as displayed in Fig. 19(b).

![Fig. 19. Experimental results at different gate resistances. (a) Without solution and (b) with the proposed DMC.](image)

Considering the influence of junction temperature difference $\Delta T_j$ of parallel SiC MOSFETs between 0°C and 25°C, experiment results are presented as shown in Fig. 20 in the condition of $R_s = 5$ Ω. In the test bench, one device is soaked in ambient temperature environment and the other one is heated by hotplate. Without suppression solution, the temperature difference mainly affects the turn-off processes. The peak value of transient imbalance current increases with the temperature difference. Because the on-resistance $R_{\text{on}}$ is not sensitive to temperature, the static imbalance current is nearly affected by the temperature. It can be seen the current-sharing performance of DMC-based suppression is very robust to the temperature difference.

![Fig. 20. Experimental results at different junction temperature differences. (a) Without solution and (b) with the proposed DMC.](image)

According to the experiments in Fig. 16 to Fig. 20, a full comparison of studied solutions for imbalance current suppression is conducted as listed in TABLE V. The inserted series resistors cannot suppress the transient imbalance current, while the incorporated DMC can effectively suppress the transient and static imbalance current. The possible turn-off over-voltage and switching ringing, caused by the leakage-inductance and EPC of the DMC, can be overcome by using the optimized bifilar winding. The series resistors will result in remarkable power loss and reduce the efficiency of converters. Due to the excellent current-sharing capability of the DMC, the current rating of parallel SiC MOSFET, limited by imbalance current, can be expanded. The volume, size, and cost of the DMC are slightly larger than the resistor. However, considering the perfect current-sharing capability, the proposed DMC is a more cost-effective solution in general.

![TABLE V COMPARISON OF SERIES RESISTOR AND DMC](image)

A. Extension of Proposed Suppression Approach

Scalability of methods for imbalance current suppression is very important. To extend the proposed method and adapt the scenario with more than two parallel devices, two geometries of DUTs and chokes are indicated in Fig. 21. Theoretically, the maximum number of parallel SiC devices can be infinite.

Concerning geometry 1 in Fig. 21(a), taking $N$-parallel SiC devices into account, primary windings of chokes are inserted into parallel branches. Secondary windings of chokes are series one-by-one. Primary windings flow through load current, while the secondary windings just carry imbalance current.
Concerning geometry 2 in Fig. 21(b), each SiC MOSFET branch contains two windings in series, and the device couples with two neighbor devices. Both primary and secondary windings of each DMC flow through load current.

![Fig. 21. Extension of proposed DMC-based suppression method to multiple parallel SiC MOSFETs. (a) Geometry 1 and (b) geometry 2.](image)

It should be noted, the DMC also can be inserted into the source terminals of parallel devices, which is another alternatively effective way to implement the DMC.

### B. Comparison With Existing Suppression Approaches

To further confirm the performance of the proposed DMC, based on existing methods for imbalance current suppression of parallel SiC MOSFETs, a comprehensive comparison is provided in Fig. 22 from viewpoints of electrical, safety, and economic indices. It can be seen that the proposed DMC approach is a low cost, fast dynamic, easy integration method for imbalance current suppression.

![Fig. 22. Comparison of imbalance current suppression methods with respect to (a) electric indices, (b) safety indices, and (c) economic indices.](image)

### VII. Conclusion

To suppress the imbalance current of parallel SiC MOSFETs, a DMC concept is proposed in this paper. In-depth mathematical mechanisms of the imbalance current are modeled. It is observed that the imbalance current covers the normal operating frequency of SiC MOSFET, and it should be carefully addressed for the high-frequency application. The imbalance current is jointly influenced by inconsistent chips, asymmetrical layouts, and unequal junction temperatures, and it is hard to be overcome by changing the SiC MOSFET itself. Auxiliary DMC is utilized to suppress the imbalance current. Its effectiveness is confirmed by proposed operation principles, theoretical analyses, and design guidelines. Besides, it is recommended that bifilar winding is the best choice for the DMC in the proposed method to minimize the leakage inductance and EPC. Finally, the forced current-sharing capability of the proposed DMC based suppression method is ensured by extensive experiments, which also demonstrates the effectiveness of the proposed DMC method. Moreover, considering electrical, safe, and economic indices, comparative analyses for studied current-sharing approaches are presented, which demonstrates the merits of the proposed DMC, including low cost, fast dynamic, easy integration, etc. Concerning some abnormal conditions like cross-talk, short-circuit, avalanche, etc., the interactions mechanisms between DMC and SiC MOSFET should be further addressed in the near future.

### REFERENCES


This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TIE.2019.2901655, IEEE Transactions on Industrial Electronics

Xin Zhang (M'15) received the Ph.D. degree in Automatic Control and Systems Engineering from the University of Sheffield, U.K., in 2016 and the Ph.D. degree in Electronic and Electrical Engineering from Nanjing University of Aeronautics & Astronautics, China, in 2014. Currently, he is an Assistant Professor at the School of Electrical and Electronic Engineering of Nanyang Technological University. He serves as the AE of IEEE TIE/JESTPE and IET Power electronics. He is also the TPC member in IEEE IA/PELS Singapore joint Chapter. Dr Xin Zhang has received the highly-prestigious Chinese National Award for Outstanding Students Abroad in 2016. He is generally interested in power electronics, power system, and advanced control theory, together with their applications in various sectors.

Zhe Zhang (M'11–SM'16) received the B.Sc. and M.Sc. degrees in power electronics from Yanshan University, Qinhuangdao, China, in 2002 and 2005, respectively, and the Ph.D. degree from the Technical University of Denmark, Kgs. Lyngby, Denmark, in 2010. He is currently an Associate Professor in the Department of Electrical Engineering, at the Technical University of Denmark (DTU). Since Jan. 2018, he has been Head of Studies in charge of Electrical Engineering MSc Programme, which is one of the largest MSc programme at DTU. From 2005 to 2007, he was an Assistant Professor at Yanshan University. From June 2010 to August 2010, he was with the University of California, Irvine, CA, USA, as a visiting scholar. He was an Assistant Professor at the Technical University of Denmark during 2011 and 2014. He has authored or co-authored more than 130 transactions and international conference papers and filed 8 patent applications. He has supervised over 10 PhD students since 2013. Dr. Zhang’s current research interests include applications of wide bandgap devices, high frequency dc-dc converters, multiple-input dc-dc converters, soft-switching power converters and multi-level dc-ac inverters for renewable energy systems (RES), hybrid electric vehicles (HEV) and uninterruptable power supplies (UPS); piezoelectric-actuator and piezoelectric-transformer based power conversion systems. Dr. Zhang has received several awards and honors including Best Paper Award in IEEE ECCE, Best Paper Award in IEEE IGBSG, Best Teacher of the Semester, Chinese Government Award for Outstanding Students Abroad, etc. He is also a guest associate editor in IEEE Transactions on Industrial Electronics.

Zheng Zeng (S’14–M’15) received the B.Sc. degree in electrical engineering from Wuhan University, Wuhan, China, in 2009, and the Ph.D. degree in electrical engineering from Zhejiang University, Hangzhou, China, in 2014. He joined School of Electrical Engineering, Chongqing University, Chongqing, China, in July 2014, where he was promoted to associate professor in August 2017. From July 2018 to July 2019, he was a research fellow with School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore. His research interests include grid-connected inverter for renewable energy integration and customized package for wideband gap power devices.