

Halbleitertechnik

Ajay Poonjal Pai

**Impact of Silicon Carbide based Power
Modules on Mission Profile Efficiency
of Automotive Traction Inverters**

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**Impact of Silicon Carbide based Power Modules on Mission Profile
Efficiency of Automotive Traction Inverters**

**Der Einfluss von Leistungsmodulen auf Siliciumcarbiddbasis auf die
Effizienz von Traktionswechselrichtern für Kraftfahrzeuge im
Einsatzprofilbetrieb**

Der Technischen Fakultät
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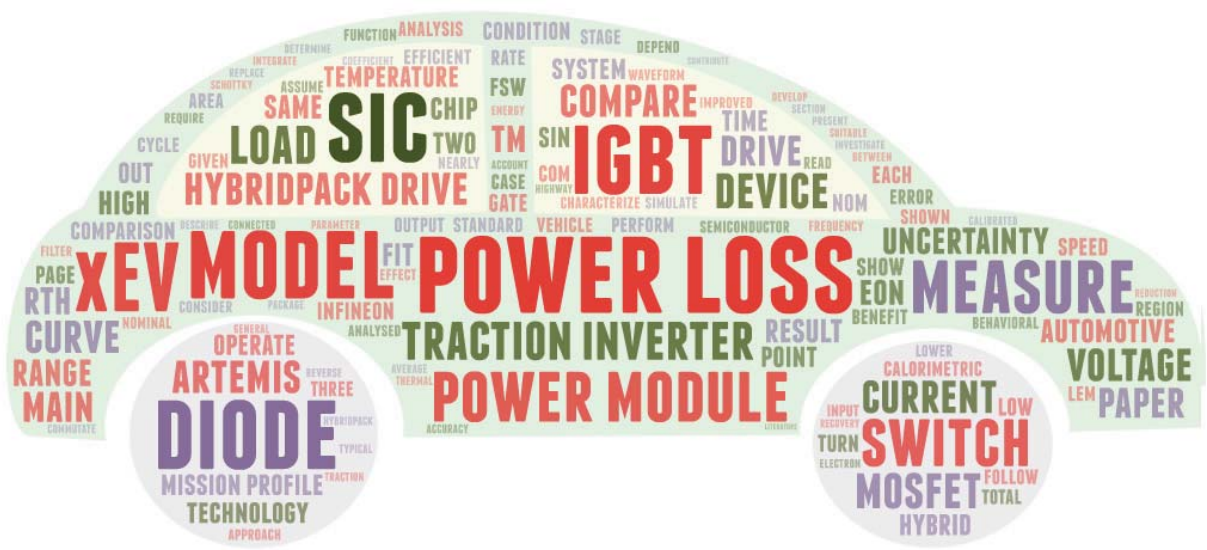
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कर्मण्येवाधिकारस्ते मा फलेषु कदाचन ।
मा कर्मफलहेतुर्भूर्मा ते सङ्गोऽस्त्वकर्मणि ॥

“To work you have the right, but not to the fruits thereof.”

-Bhagavadgita, Chapter 2, Verse 47



A Representative Word-Cloud of the Contents of the Thesis

Dedication

To my Parents, my brother Akshay and wife Sowmya for their unconditional love and support.

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Zusammenfassung

Die meisten Länder arbeiten daran, ihren CO₂-Fußabdruck und ihre Abhängigkeit von fossilen Brennstoffen zu reduzieren. Infolgedessen rücken batteriebetriebene Fahrzeuge und die Erhöhung ihrer Reichweite immer mehr in den Fokus. Daher versuchen die Automobilhersteller, ihre Systeme so effizient wie möglich zu gestalten und jedes einzelne Joule Energie in nützliche mechanische Leistung zu verwandeln. Ein wesentlicher Beitrag zu den Energieverlusten in elektrifizierten Fahrzeugen kommt von den Leistungshalbleitern im Traktionswechselrichter. Jedoch wird von einer Optimierung mit Widebandgap-Halbleitern wie etwa Siliziumcarbid (SiC) eine deutliche Effizienzsteigerung erwartet.

Diese Arbeit untersucht die Effizienzvorteile des Ersatzes von Silizium (Si)-Leistungsmodulen von Traktionswechselrichter Anwendungen im Automobilbereich durch SiC-basierte Leistungsmodule. Die Auswertung erfolgt für Einsatzprofile wie das Worldwide Harmonized Light Vehicles Test Procedure (WLTP), New European Drive Cycle (NEDC) und Artemis bei verschiedenen Randbedingungen wie Schaltgeschwindigkeit, Betriebsspannung, Strom, Schaltfrequenz und Kühlmitteltemperatur. Die verglichenen Leistungsmodule sind in einem identischen Gehäuse mit geringer Streuinduktivität untergebracht, die für schnelles Schalten optimiert ist. Nur die Chip-Technologien sind unterschiedlich. Auch der Rest des Systems bleibt unverändert. Dies ermöglicht einen direkten Vergleich von Si gegenüber SiC, ohne Raum für Diskrepanzen zu lassen, die durch Unterschiede im Gehäuse entstehen, z. B. Modulstreuinduktivitäten, thermische Unterschiede im Stack oder durch Unterschiede im System, z. B. Unterschiede in den Streuinduktivitäten des DC-Links, in der Charakteristik der Elektromotoren und dem Gate Driver Verhalten. Um diese Untersuchung zu erleichtern, wird ein durch mehrere Polynome beschriebenes, kurvenangepasstes, verhaltensbasiertes Leistungsverlustmodell entwickelt, das für die Durchführung von Analysen von Einsatzprofilen von Traktionswechselrichter Anwendungen optimiert ist. Die Leistungsverluste werden nicht nur in Bezug auf Betriebsströme, Spannung und Temperatur modelliert, wie es bei den meisten existierenden Modellen in der Literatur der Fall ist, sondern auch in Bezug auf Gate-Widerstand und Gate Driver-Spannung, die einen großen Einfluss auf die Leistungsverluste haben. Es modelliert auch in Bezug auf die Chip-Fläche, so dass es für die Berechnung der optimalen Chip-Fläche für eine bestimmte Anwendung geeignet ist. Es wird gezeigt, dass dieses Modell eine höhere Genauigkeit im Vergleich zu linearen Standardmodellen bietet, insbesondere bei geringer Last, was die am häufigsten auftretende Bedingung in einem Traktionswechselrichter für Kraftfahrzeuge ist.

Ein weiterer wichtiger Beitrag dieser Arbeit ist die Entwicklung einer auf Kommutierungsgeschwindigkeit basierten Methodik zur Trennung von Leistungsverlusten auf Systemebene in ihre grundlegenden Ursachen wie Tailströme, Reverse Recovery und so weiter. Diese Methode wird als Tool zur Feinabstimmung und Optimierung der Performance des Leistungsschalters für eine bestimmte Anwendung und ein bestimmtes Einsatzprofil verwendet. Um ein gutes Vertrauen in das vorgeschlagene Leistungsverlust-Berechnungsmodell zu haben, wird es experimentell mit zwei unabhängigen Methoden zur Messung der Verluste bei Wechselrichtern überprüft. Das erste gewählte Verfahren ist das auf einem Leistungsanalysator basierende elektrische Input-Output Verfahren. Es ist das für solche Anwendungen am häufigsten verwendete Verfahren. Die Unsicherheitsquellen werden mit einem spektral-basierten Ansatz analysiert, und es wird gezeigt, dass dieses Verfahren aufgrund der hochfrequenten Welligkeit der Wellenform der Ausgangsspannung von hart geschalteten Wechselrichtern eine hohe Unsicherheit im Bereich von 25% aufweist, insbesondere unter Bedingungen mit geringer Last. Das Verfahren ist aus diesem Grund weniger geeignet, verschiedene Chip-Technologien in solchen Anwendungen zu vergleichen. Daher wird eine kalorimetrische Methode vorgeschlagen, die die Leistungsverluste unabhängig von den elektrischen Transienten misst, was zu einer Unsicherheit unter 5% führt. Schließlich werden die Leistungsverluste der Module für verschiedene Einsatzprofile mit der auf Kommutierungsgeschwindigkeit basierten Methodik untersucht, um zu verstehen, welche Vorteile SiC bringt. Ebenfalls diskutiert werden der Unterschied in den Zielkonflikten für Si und SiC und wie Si-basierte Systeme optimiert werden können, um die Lücke zu SiC zu schließen. Es zeigt sich, dass SiC-basierte Systeme die durchschnittlichen Leistungsverluste der Wechselrichter um bis zu 80% reduzieren können. Diese werden den Weg für effizientere Traktionswechselrichter ebnen.

Abstract

Most countries are working towards reducing their carbon footprint and dependency on fossil fuels. As a result, there is an increasing focus on battery electric vehicles and on increasing their driving range. Therefore, car manufacturers are trying to make their systems as efficient as possible to squeeze every single Joule of energy into useful mechanical output. A significant contribution to the energy losses in electrified vehicles comes from the power semiconductors in the traction inverter. Optimizing them with wide-bandgap semiconductors such as Silicon Carbide (SiC) are expected to bring significant efficiency improvements.

This thesis investigates the efficiency benefits of replacing Silicon (Si) power modules of automotive traction inverter applications with SiC-based power modules. The evaluation is done for mission profiles such as the WLTP, NEDC and Artemis, at different boundary conditions such as switching speed, operating voltage, current, switching frequency and coolant temperature. The compared power modules are in an identical package with state-of-the-art stray inductance optimized for fast switching, and only the chip technologies are varied. The rest of the system is kept the same too. This gives a direct comparison of Si versus SiC without giving scope for any discrepancies arising due to differences in the package, e.g., module stray inductances, thermal stack, or due to differences in the system, e.g., differences in the stray inductances of the dc-link, electric motor characteristics and gate driver behaviour. To facilitate this investigation, a quadratic curve-fitting based behavioural power loss model is developed which is optimized for performing mission profile analysis of traction inverter applications. The power losses are modelled not only in terms of the operating currents, voltage and temperature, like most existing models in literature, but also in terms of gate resistance and gate driver voltage which have a major impact on the power losses. It also models in terms of chip area which makes it suitable for calculating the optimum chip area for a given application. This model is shown to offer higher accuracy compared to standard linear models, especially at light load which is the most commonly occurring condition in an automotive traction inverter.

Another key contribution of this work is the development of a commutation-speed based methodology for segregating system level power losses into their root causes such as tail currents, reverse recovery and so on. This method is used as a tool to fine-tune and optimize the performance of the power switch for a given application and mission profile.

To have a good confidence level in the proposed power loss calculation model, it is verified experimentally with two independent methods of measuring inverter power losses. The first method chosen is the power-analyser based input-output electrical method, which is the most commonly used method for such applications. The sources of uncertainty are analysed using a spectrum-based approach and it is shown that this method suffers from high uncertainty in the range of 25% especially in the light-load condition, owing to the high frequency ripple in the output voltage waveform of hard switched inverters. This makes the method less suitable for comparing different chip technologies in such applications. Therefore, a calorimetric method is proposed, which measures the power losses independent of the electrical transients, resulting in an uncertainty below 5%.

Finally, the power losses of the modules are investigated for different mission profiles using the commutation-speed based methodology, to understand what benefits SiC brings. Also discussed are the difference in trade-offs for Si and SiC, and how Si-devices could be optimized to narrow the gap with SiC. It is shown that SiC devices can bring upto 80% reduction in the inverter average power losses, which could pave the way for more efficient traction inverters.

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