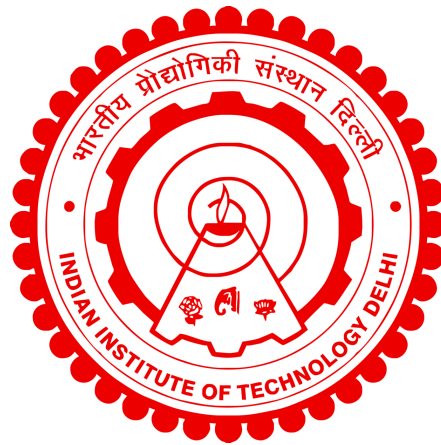


PCB COIL BASED MULTIFUNCTIONAL HIGH BANDWIDTH CURRENT SENSOR FOR SIC MOSFETS

Aamir Rafiq



DEPARTMENT OF ELECTRICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY DELHI

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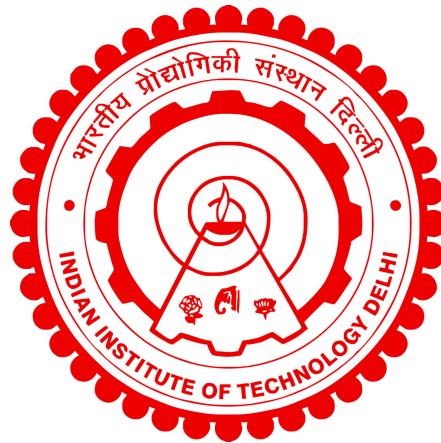
Aamir Rafiq

Department of Electrical Engineering

Submitted

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Certificate

This is to certify that the thesis titled “**PCB Coil Based Multifunctional High Bandwidth Current Sensor for SiC MOSFETs**”, submitted by **Aamir Rafiq** to the Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy** in Electrical Engineering, is a record of the original, bona fide research work carried out by him under my supervision and guidance. The thesis has reached the standards fulfilling the requirements of the regulations related to the award of the degree.

The results contained in this thesis have not been submitted in part or in full to any other University or Institute for the award of any degree or diploma to the best of my knowledge.

Prof. Sumit Pramanick

Department of Electrical Engineering,
Indian Institute of Technology Delhi.

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Abstract

Silicon-carbide (SiC) MOSFETs are poised to become the power semiconductor devices of choice in the medium voltage automotive and renewable power electronics industry due to their high voltage blocking capability, low switching losses, and the ability to operate at high junction temperatures. To be able to operate at high switching speeds with optimal switching performance, the power-loop design needs to be compact. Consequently, sensing device current in such layouts with minimal intrusion in power-loop remains challenging. Current sensing through these devices is pivotal to implement new and effective protection and control techniques for these devices.

Rogowski coil-based current sensors are effective for sensing switching current through SiC MOSFETs owing to their high bandwidth and ease of integration in compact power-loop layouts. Through a Printed Circuit Board (PCB) Rogowski coil design on a two-layer PCB for a TO-247 SiC MOSFET, the thesis first demonstrates the design of PCB coils with the aid of electromagnetic field computation. The design utilizes finite element method (FEM) simulations to determine a suitable position for the PCB coil on the power converter board and simultaneously computes the increase in the power-loop inductance due to any changes in the layout. Therefore, an optimal position and size of the coil can be reached with minimal intrusion inside the power-loop. The design approach delineates the methodology of placing the coil inside compact power-loop layouts, characterizing the electrical model of the coil, and further building the integrated model of the sensor for complete characterization of its bandwidth.

Furthermore, based on the insights gained through the developed design methodology, a single interconnect-based PCB coil design is presented in this thesis for a TO-247-4L SiC MOSFET on a four-layered PCB. The PCB coil is fabricated near a single interconnect trace between the power device and the DC busbar. To ensure minimal intrusion inside the power-loop, the methodology of selecting the minimum trace length for a desired mutual inductance between the coil and the interconnect trace is presented through finite-element analysis. The design links the coil size to the interconnect trace length, therefore, significantly simplifying the coil design process. The PCB coil is further interfaced with an integrator to reproduce the device's current signal and, thereafter, used for implementing an ultrafast short-circuit protection scheme for SiC MOSFETs. Silicon Carbide (SiC) MOSFETs offer significant advantages in terms of improved efficiency and reduced size of power electronic converters. However, they possess lesser short-circuit withstand time

(SCWT) than silicon devices. Experimental results for a SiC MOSFET subjected to a hard switched fault (HSF) and a fault under load (FUL) are presented, and the protection circuit response time under 25 nanoseconds is reported.

Lastly, to demonstrate other applications of the PCB coil-based current sensors for facilitating next-generation power converters, a condition monitoring technique for junction temperature estimation of SiC MOSFETs is presented. The technique measures the turn-on delay time with the aid of the current sensor and uses the temperature depending on the delay on the junction temperature to estimate the junction temperature of the device. Finally, utilizing the designed current sensor, the peak current-mode controller design for a buck converter is presented. Therefore, the PCB coil is demonstrated to be an effective alternative for the Hall effect and magnetic core-based sensors in current control applications with DC/DC converters.

सारांश

सिलिकॉन-कार्बाइड (SiC) MOSFETs अपनी उच्च वोल्टेज अवरोधक क्षमता, कम स्विचिंग हानि और उच्च जंक्शन तापमान पर काम करने की क्षमता के कारण मध्यम वोल्टेज ऑटोमोटिव और नवीकरणीय ऊर्जा इलेक्ट्रॉनिक्स उद्योग में पसंद के पावर सेमीकंडक्टर उपकरण बनने के लिए तैयार हैं। इष्टतम स्विचिंग प्रदर्शन के साथ उच्च स्विचिंग गति पर काम करने में सक्षम होने के लिए, पावर-लूप डिज़ाइन को कॉम्पैक्ट होना आवश्यक है। नतीजतन, पावर-लूप में न्यूनतम घुसपैठ के साथ ऐसे लेआउट में डिवाइस करंट को सेंस करना चुनौतीपूर्ण रहता है। इन उपकरणों के माध्यम से वर्तमान संवेदन इन उपकरणों के लिए नई और प्रभावी सुरक्षा और नियंत्रण तकनीकों को लागू करने के लिए महत्वपूर्ण है।

रोगोव्स्की कॉइल-आधारित वर्तमान सेंसर अपने उच्च बैंडविड्थ और कॉम्पैक्ट पावर-लूप लेआउट में एकीकरण में आसानी के कारण SiC MOSFETs के माध्यम से स्विचिंग करंट को सेंस करने के लिए प्रभावी हैं। TO-247 SiC MOSFET के लिए दो-परत पीसीबी पर एक मुद्रित सर्किट बोर्ड (पीसीबी) रोगोव्स्की कॉइल डिज़ाइन के माध्यम से, थीसिस पहले विद्युत चुम्बकीय क्षेत्र गणना की सहायता से पीसीबी कॉइल्स के डिज़ाइन को प्रदर्शित करती है। डिज़ाइन पावर कनवर्टर बोर्ड पर पीसीबी कॉइल के लिए उपयुक्त स्थिति निर्धारित करने के लिए परिमित तत्व विधि (एफईएम) सिमुलेशन का उपयोग करता है और साथ ही लेआउट में किसी भी बदलाव के कारण पावर-लूप इंडक्शन में वृद्धि की गणना करता है। इसलिए, पावर-लूप के अंदर न्यूनतम घुसपैठ के साथ कॉइल की इष्टतम स्थिति और आकार तक पहुंचा जा सकता है। डिज़ाइन दृष्टिकोण कॉइल को कॉम्पैक्ट पावर-लूप लेआउट के अंदर रखने, कॉइल के विद्युत मॉडल को चिह्नित करने और इसके बैंडविड्थ के पूर्ण लक्षण वर्णन के लिए सेंसर के एकीकृत मॉडल का निर्माण करने की पद्धति को चित्रित करता है।

इसके अलावा, विकसित डिज़ाइन पद्धति के माध्यम से प्राप्त अंतर्दृष्टि के आधार पर, इस थीसिस में चार-परत पीसीबी पर TO-247-4L SiC MOSFET के लिए एक एकल इंटरकनेक्ट-आधारित पीसीबी कॉइल डिज़ाइन प्रस्तुत किया गया है। पीसीबी कॉइल को पावर डिवाइस और डीसी बसबार के बीच सिंगल इंटरकनेक्ट ट्रेस के पास निर्मित किया गया है। पावर-लूप के अंदर न्यूनतम घुसपैठ सुनिश्चित करने के लिए, कॉइल और इंटरकनेक्ट ट्रेस के बीच वांछित पारस्परिक प्रेरण के लिए न्यूनतम ट्रेस लंबाई का चयन करने की पद्धति परिमित-तत्व विश्लेषण के माध्यम से प्रस्तुत की जाती है। डिज़ाइन कॉइल आकार को इंटरकनेक्ट ट्रेस लंबाई से जोड़ता है, इसलिए, कॉइल डिज़ाइन प्रक्रिया को काफी सरल बनाता है। पीसीबी कॉइल को डिवाइस के वर्तमान सिग्नल को पुनः उत्पन्न करने के लिए एक इंटीग्रेटर के साथ जोड़ा जाता है और उसके बाद, SiC MOSFETs के लिए एक अल्ट्राफास्ट शॉर्ट-सर्किट सुरक्षा योजना को लागू करने के लिए उपयोग किया जाता है। सिलिकॉन कार्बाइड (SiC) MOSFETs बेहतर दक्षता और पावर इलेक्ट्रॉनिक कन्वर्टर्स के कम आकार के मामले में महत्वपूर्ण लाभ प्रदान करते हैं। हालाँकि, उनमें सिलिकॉन उपकरणों की तुलना में कम शॉर्ट-सर्किट झेलने का समय (एससीडब्ल्यूटी) होता है। एक हार्ड स्विचड फॉल्ट (HSF) और एक फॉल्ट अंडर लोड (FUL) के अधीन SiC MOSFET के लिए प्रायोगिक परिणाम प्रस्तुत किए गए हैं, और \$25\$ नैनोसेकंड के तहत सुरक्षा सर्किट प्रतिक्रिया समय की सूचना दी गई है।

अंत में, अगली पीढ़ी के पावर कन्वर्टर्स की सुविधा के लिए पीसीबी कॉइल-आधारित वर्तमान सेंसर के अन्य अनुप्रयोगों को प्रदर्शित करने के लिए, SiC MOSFETs के जंक्शन तापमान अनुमान के लिए एक स्थिति निगरानी तकनीक प्रस्तुत की गई है। तकनीक वर्तमान सेंसर की सहायता से टर्न-ऑन विलंब समय को मापती है और डिवाइस के जंक्शन तापमान का अनुमान लगाने के लिए जंक्शन तापमान पर देरी के आधार पर तापमान का उपयोग करती है। अंत में, डिज़ाइन किए गए वर्तमान सेंसर का उपयोग करके, हिरन कनवर्टर के लिए शिखर वर्तमान-मोड नियंत्रक डिज़ाइन प्रस्तुत किया गया है। इसलिए, पीसीबी कॉइल को डीसी/डीसी कनवर्टर्स के साथ वर्तमान नियंत्रण अनुप्रयोगों में हॉल प्रभाव और चुंबकीय कोर-आधारित सेंसर के लिए एक प्रभावी विकल्प के रूप में प्रदर्शित किया गया है।

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Abbreviations

DPT	D ouble P ulse T est
SiC	S ilicon C arbide
GaN	G allium N itride
WBG	W ide B andgap
HBW	H igh B andwidth
PCB	P rinted C ircuit B oard
FEM	F inite E lement M ethod
RSCS	R ogowski S witch C urrent S ensor
Op-Amp	O perational A mplifier
CT	C urrent T ransformer
GMR	G iant M agneto R esistance
GMI	G iant M agneto I mpedance
SCWT	S hort C ircuit W ithstand T ime
HSF	H ard S witched F ault
FUL	F ault U nder L oad
PCMC	P eak C urrent M ode C ontrol
EMI	E lectro M agnetic I nterference
TSEP	T emperature S ensitive E lectrical P arameters
OCP	O ver C urrent P rotection