PCB Coil Based Multifunctional High Bandwidth Current Sensor for SiC MOSFETs

INTRODUCTION

Wide Bandgap (WBG) power devices like Silicon Carbide MOSFETs are ushering a new revolution in power electronics due to their high blocking voltage, high switching speed and high operating temperatures [1, 2]. Their excellent material properties make them especially suitable for automotive applications which operate in harsh environments. With the fast pace of penetration of SiC MOSFETs in the power electronic industry, advances in the protection, control and condition monitoring methods for these devices is imperative.

There are several challenges which limit the potential of these devices. Firstly, the low short-circuit withstand time (SCWT) of SiC MOSFETs makes the conventional IGBT protection schemes inadequate for SiC MOSFETs [3, 4]. Secondly, for controlling the power device in a power converter topology, the state-of the art current sensors pose layout challenges when used for SiC MOSFETs. The PCB layout for SiC MOSFETs needs to be compact, owing to the fast switching speed of the power devices. Therefore, sensing current through the devices by placing bulky current sensors in the power-loop is not feasible with SiC MOSFETs. Thirdly, SiC MOSFET technology is still evolving, and therefore, the reliability data on SiC MOSFETs is scarce. Consequently, along with ultrafast protection schemes, real-time junction temperature estimation can be helpful for real-time condition monitoring of the power device.

Therefore, a current sensor is identified as a crucial pivot in overcoming the aforementioned challenges. A compact and low cost current sensor possessing high bandwidth can be used to realize the following objectives:

1. By sensing the device current signal with high bandwidth, it is possible to compare the device current with a fault current reference and turn-off the device safely before damage to the device occurs.

2. The device current signal can be used to implement various current control methods for power converters e.g. peak current mode control (PCMC).

3. Temperature sensitive electrical parameters (TSEPs) like on-state voltage drop ($V_{DS,ON}$), threshold voltage (V_T), turn-on delay time (t_d, on), and di/dt of the device current can

be monitored for junction temperature (T_j) estimation of the SiC MOSFET if the device current signal can be sensed.

From the aforementioned points, it can be observed that the device current can be an excellent indicator for both fault events as well as condition monitoring of the power device. However, designing a low cost current sensor with high bandwidth is challenging. A brief literature review on the state of the art current sensors is given below.

STATE OF ART ON CURRENT SENSORS

HBW current sensing in power converters has been a challenge, and over the years many different types of sensing methods based on several technologies have been reported [5, 6]. Resistive shunt based current sensing has been popular due to its simple implementation and HBW [7]. Low cost surface-mount shunt based current sensing technique using field cancellation has been reported in [8]. However, the shunt resistor incurs losses and doesn't provide galvanic isolation. The resistive shunt also exhibits stray inductance that can be mitigated through co-axial shunts [9], though at a high cost [10].

Current transformer (CT) based sensing techniques offer isolation and HBW, but saturation of magnetic core limits the current rating of these sensors. Moreover, sensing device current requires routing of current through the core center which, therefore, requires longer power-loop traces. This inevitably introduces large stray inductance in the power-loop. To mitigate these issues compact CT based sensors based on co-axial CT and planar CT have been reported [11, 12], but complexity of design and core saturation remain a challenge.

Hall effect based current sensing Integrated Circuits (ICs) have been popular due to their ease of implementation and low cost, but they lack HBW. Recently, Giant Magnetoresistance (GMR) based ICs have been utilized to develop current sensors for power devices with a bandwidth upto 10 MHz [13, 14].

Rogowski coil based current sensors have been utilized in applications where the required sensing bandwidth is higher than that offered by Hall effect and GMR based sensors. Rogowski coil is an air core coil which senses the magnetic field generated by the current under measurement and produces a terminal voltage which is proportional to the derivative of the current [15]. The voltage induced across the coil is then integrated to produce a voltage signal, which is proportional to the current to be measured. A PCB-Rogowski coil design based on Partial Element Equivalent Circuit (PEEC) method is proposed in [16] for press-pack IGBTs. A silicon carbide (SiC) MOSFET module based converter with a PCB-Rogowski coil integrated in the gate driver circuit is demonstrated in [17, 18].

In case of the coil designed for the press-pack IGBT in [16] or the MOSFET module in [17], the large size of the device package ensures that the coil can be placed without any change in the power-loop layout. However, a smaller package like TO-247 does not present such an opportunity of coil placement due to the limited space between device terminals. Alternatively, a field sensing PCB coil can be placed near a trace which routes the device current on the printed circuit board (PCB) layout. The coil placement may, however, require an extension of power-loop traces, and therefore, increase stray inductance in the power-loop. One such approach for placing the coil, for a TO-247 package based SiC MOSFET, is presented in [19].

A current sensing technique for a GaN device, using a PCB coil and an offline integration method, is presented in [20]. A PCB coil, like a Rogowski coil, produces an output voltage which is proportional to the derivative of current to be measured. Even though the PCB coils can be designed to be extremely small, they are asymmetrical unlike Rogowski coils. The PCB coil voltage is then sampled and integrated offline using a computer program to reproduce the current signal. A similar approach using offline integration is presented in [21] for a laminated bus-bar based PCB coil.

OBJECTIVES AND SCOPE OF WORK

Due to their small footprint, PCB pickup coils are, therefore, appropriate current sensing elements for placement inside compact power-loop circuits. However, to design an online current sensor with PCB coils it is important to understand the influence of coil placement on the power-loop stray inductance. The influence of the power-loop design and the PCB pickup coil geometry on the sensitivity of the PCB coil needs to be investigated as well. Since the PCB coils are asymmetrical, the influence of the coil shape and its dimensions on the noise immunity of the current sensor is investigated. After addressing these issues, this work further develops a single interconnect based PCB coil design with an online current sensor signal fed to the gate driver card. The current signal is thereafter utilized for protection and junction temperature estimation of the power device.

The main objectives and scope of this work, are broadly presented as follows.

1. Development of a methodology for designing compact PCB coils based on the process of

electromagnetic field computation.

2. Development of the sensor model which incorporates non-ideal op-amp characteristics for estimating the bandwidth of the PCB coil based current sensor.

3. Development of a single interconnect based PCB coil design on a four-layered PCB based on the developed coil design methodology.

4. Development of an ultrafast protection scheme for SiC MOSFETs based on the PCB coil based current sensor.

5. Development of peak current-mode control scheme for a Buck converter with the PCB coil based current sensor.

6. Development of junction temperature estimation method for SiC MOSFETs with PCB coil based currents sensor using the turn-on delay time as a temperature sensitive electrical parameter (TSEP).

A diagrammatic overview of the work done in the thesis is shown in Fig.1.

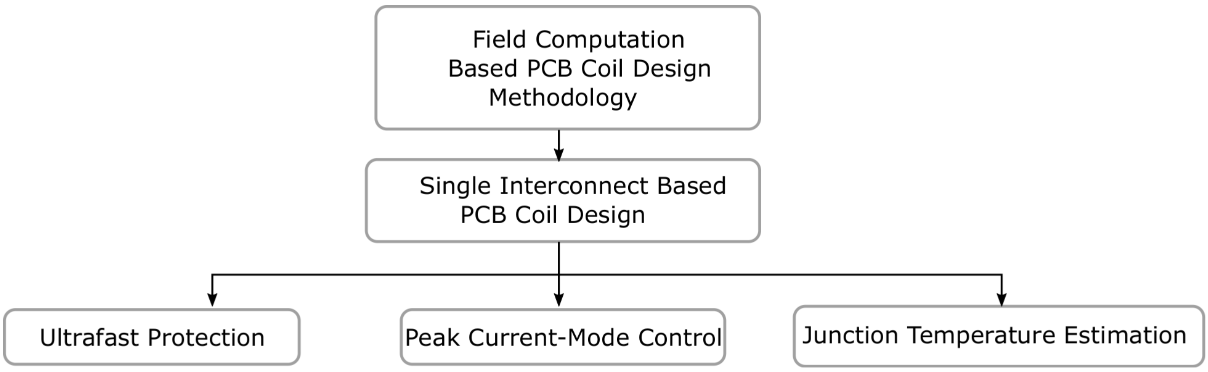

Fig. 1. Diagrammatic overview of work

OUTLINE OF CHAPTERS

A brief outline of chapters in the thesis is given here.

Chapter-I: Introduction The opening chapter of this thesis introduces the concept of PCB coil as a multifunctional solution for protection, control and junction temperature estimation of SiC MOSFETs. This chapter establishes the main objectives of this work and briefly presents the thesis outline.

Chapter-II: Current Sensing Techniques in Power Electronics: State-of-the-art In this chapter, a comprehensive review of the state of the art current sensing technology is documented in detail. Based on the detailed analysis of previously reported work, the chapter concludes with identification of possible research areas.

Chapter-III: Field Computation Aided PCB Coil Design This chapter gives the field computation aided design of PCB coils. The development of models for 3D-FEM electromagnetic simulations of PCBs is discussed. The simulation methodology developed in COMSOL is elaborately discussed. A single interconnect trace based PCB coil design is thereafter presented. The influence of the trace length on the mutual inductance between the PCB coil and the power-loop stray inductance is investigated. Furthermore, design of the PCB coil on a four-layered PCB is discussed for sensing the current through the top and bottom device in a half-bridge circuit. Lastly, noise immunity of the PCB coil developed for the single interconnect trace is discussed.

Chapter-IV: Ultrafast Protection of SiC MOSFETs This chapter presents the ultrafast protection of SiC MOSFETs with a single trace interconnect based PCB coil design. The design of the integrator circuit and the protection circuit, integrated with the gate-driver, is discussed. A sensor model is developed which includes the influence of op-amp non-idealities. The efficacy of the protection scheme for both the fault types , viz. the hard-switched fault (HSF) and the fault under-load (FUL), is demonstrated. The factors influencing the response time of the circuit are explored and the design guidelines for selecting the components of the protection circuit are established.

Chapter-V: Peak Current-Mode Control This chapter deals with the peak current-mode control of a buck converter with a PCB coil based current sensor. The developed PCB coil based current sensor is used to implement the control strategy. Design of the slope compensation network is also discussed. The control to output transfer function of the converter is developed while incorporating the sensor gain.

Chapter-VI: Junction Temperature Estimation of SiC MOSFETs This chapter deals with the junction temperature estimation of SiC MOSFETs with PCB coil based current sensor. The developed PCB coil based current sensor is used to estimate the turn-on delay time of the SiC MOSFET. The turn-on delay time changes as a function of device junction temperature due to variation of the threshold voltage with the junction temperature. This relationship is utilized to sense the junction temperature of the MOSFET by measuring the change in the turn-on delay time.

Chapter-VII: Conclusion The concluding chapter of this thesis briefly highlights key contributions of this work and identifies further scope of work.

LIST OF PUBLICATIONS

1. A. Rafiq, S. K. Pramanick and R. Maheshwari, "Design of PCB Coil Based High Bandwidth Current Sensor With Power-Loop Stray Inductance Characterization," in IEEE Transactions on Industrial Electronics, vol. 68, no. 12, pp. 12791-12801, Dec. 2021.
2. A. Rafiq and S. K. Pramanick, "Ultrafast Protection of Discrete SiC MOSFETs with PCB Coil Based Current Sensors," major revision submitted in IEEE Transactions on Power Electronics.
3. A. Rafiq and S. K. Pramanick. "Design For Enhanced Noise Immunity of PCB Coils used for Sensing Current through Power Devices", accepted in EPE'22 to be held in Hannover Germany from 5th Spetember 2022.
4. A. Rafiq and R. Maheshwari, "Investigation of Trade-Off Between Sensor Bandwidth and Damping Achievable Through a Rogowski Coil Based Current Sensor," 2020 IEEE International Conference on Power Electronics, Smart Grid and Renewable Energy (PESGRE2020), 2020, pp. 1-5, doi: 10.1109/PESGRE45664.2020.9070574.
5. A. Rafiq and S. K. Pramanick, "Junction Temperature Estimation of SiC MOSFETs with PCB Coil Based Current Sensors," article under preparation.

PATENT APPLICATION

Patent application titled, " A system and circuit for achieving peak current-mode control with a PCB Pick-up Coil" is currently under examination at FITT IIT Delhi.

BIBLIOGRAPHY

[1] J. Biela, M. Schweizer, S. Waffler, and J. W. Kolar, "Sic versus si evaluation of potentials for performance improvement of inverter and dc dc converter systems by sic power semiconductors," vol. 58, no. 7, pp. 2872–2882, 2011.

[2] X. She, Huang, Alex Q. Lucía, and B. Ozpineci, "Review of silicon carbide power devices and their applications," *IEEE Transactions on Industrial Electronics*, vol. 64, no. 10, pp. 8193–8205, 2017.

[3] X. Zhang, H. Li, J. A. Brothers, L. Fu, M. Perales, J. Wu, and J. Wang, "A gate drive with power over fiber-based isolated power supply and comprehensive protection functions for 15-kv sic mosfet," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 4, no. 3, pp. 946–955, 2016.

[4] Y. Shi, R. Xie, L. Wang, Y. Shi, and H. Li, "Switching characterization and short-circuit protection of 1200 v sic mosfet t-type module in pv inverter application," vol. 64, no. 11, pp. 9135–9143, 2017.

[5] S. Ziegler, R. C. Woodward, H. H. Iu, and L. J. Borle, "Current sensing techniques: A review," *IEEE Sensors J.*, vol. 9, no. 4, pp. 354–376, 2009.

[6] F. Costa, P. Poulichet, F. Mazaleyrat, and E. Laboure, "The current sensors in power electronics, a review," *EPE Journal*, vol. 11, no. 1, pp. 7–18, 2001. [Online]. Available: https://doi.org/10.1080/09398368.2001.11463473

[7] A. J. L. Joannou, D. C. Pentz, J. D. van Wyk, and A. S. de Beer, "Some considerations for miniaturized measurement shunts in high frequency power electronic converters," in *2014 16th European Conference on Power Electronics and Applications*, Aug 2014, pp. 1–7.

[8] J. Bocker, S. Schoos, and S. Dieckerhoff, "Experimental comparison and 3D FEM based optimization of current measurement methods for GaN switching characterization," in *2018 20th European Conference on Power Electronics and Applications (EPE'18 ECCE Europe)*, Sep. 2018, pp. P.1–P.9.

[9] J. A. Ferreira, W. A. Cronje, and W. A. Relihan, "Integration of high frequency current shunts in power electronic circuits," *IEEE Trans. Power Electron.*, vol. 10, no. 1, pp. 32–37, 1995.

[10] T. Research. SERIES SDN-414. [Online]. Available: https://www.tandmresearch.com/

[11] R. O. C. Lyra, B. J. Cardoso Filho, V. John, and T. A. Lipo, "Coaxial current transformer for test and characterization of high-power semiconductor devices under hard and soft switching," *IEEE Trans. Ind. Appl.*, vol. 36, no. 4, pp. 1181–1188, July 2000.

[12] L. Dalessandro, N. Karrer, and J. W. Kolar, "High-performance planar isolated current sensor for power electronics applications," *IEEE Trans. Power Electron.*, vol. 22, no. 5, pp. 1682–1692, Sep. 2007.

[13] S. J. Nibir and B. Parkhideh, "Magnetoresistor with planar magnetic concentrator as wide-band contactless current sensor for power electronics applications," *IEEE Trans. Ind. Electron.*, vol. 65, no. 3, pp. 2766–2774, March 2018.

[14] S. J. Nibir, M. Biglarbegian, and B. Parkhideh, "A non-invasive DC-10-MHz wideband current sensor for ultra-fast current sensing in high-frequency power electronic converters," *IEEE Trans. Power Electron.*, vol. 34, no. 9, pp. 9095–9104, Sep. 2019.

[15] M. H. Samimi, A. Mahari, M. A. Farahnakian, and H. Mohseni, "The rogowski coil principles and applications: A review," *IEEE Sensors J.*, vol. 15, no. 2, pp. 651–658, 2015.

[16] D. Gerber, T. Guillod, R. Leutwyler, and J. Biela, "Gate unit with improved short-circuit detection and turn-off capability for 4.5-kv press-pack IGBTs operated at 4-ka pulse current," *IEEE Trans. Plasma Sci.*, vol. 41, no. 10, pp. 2641–2648, Oct 2013.

[17] J. Wang, Z. Shen, C. DiMarino, R. Burgos, and D. Boroyevich, "Gate driver design for 1.7kv SiC MOSFET module with rogowski current sensor for shortcircuit protection," in *2016 IEEE Applied Power Electronics Conference and Exposition (APEC)*, March 2016, pp. 516–523.

[18] J. Wang, Z. Shen, R. Burgos, and D. Boroyevich, "Integrated switch current sensor for shortcircuit protection and current control of 1.7-kv SiC MOSFET modules," in *2016 IEEE Energy Conversion Congress and Exposition (ECCE)*, Sep. 2016, pp. 1–7.

[19] Y. Xue, J. Lu, Z. Wang, L. M. Tolbert, B. J. Blalock, and F. Wang, "A compact planar rogowski coil current sensor for active current balancing of parallel-connected silicon carbide MOSFETs," in *2014 IEEE Energy Conversion Congress and Exposition (ECCE)*, Sep. 2014, pp. 4685–4690.

[20] K. Wang, X. Yang, H. Li, L. Wang, and P. Jain, "A high-bandwidth integrated current measurement for detecting switching current of fast GaN devices," *IEEE Trans. Power Electron.*, vol. 33, no. 7, pp. 6199–6210, July 2018.

[21] Y. Kuwabara, K. Wada, J. Guichon, J. Schanen, and J. Roudet, "Implementation and performance of a current sensor for a laminated bus bar," *IEEE Trans. Ind. Appl.*, vol. 54, no. 3, pp. 2579–2587, May 2018.