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A COMPACT ISOLATED POWER SUPPLY FOR MV SIC MOSFET GATE DRIVER

Petar Marković, Nikola Lepojević, Nikola Popov, Slobodan Vukosavić
University of Belgrade, School of Electrical Engineering

Abstract: *In this paper, we present a design of a compact gate driver power supply, suitable for usage in middle voltage power converters containing SiC Mosfet as a switching element. The power supply is based on using the planar PCB transformer that utilizes isolation capabilities of the PCB material. The demand for high isolation capability leads to significant values of the transformer's leakage inductances, producing unwanted reactive power and secondary voltage attenuation. Design method for overcoming of those drawbacks is presented, by adding some capacitive and inductive components. Selecting the optimal set of parameters of the planar transformer, according to output power and voltage ratings, is also presented. Considerations related to the possibilities of regulating the output voltage are discussed.*

Key Words: ***Planar Transformer/Isolated Supply/Gate Driver/SiC Mosfet***

1. INTRODUCTION

Implementation of power converters in energy distribution, traction and renewable energy sources requires devices with increased power and voltage ratings, lower semiconductor losses, higher switching frequencies and higher operating temperatures. The modern silicon carbide (SiC) switches have unique capabilities, which make these superior in comparison to its silicon counterparts. SiC Mosfets are used in a broad range of power conversion applications, such are boost converter within photovoltaic inverter [1], bidirectional DC-DC converter in HEV battery management [2], three-phase inverter [3].

Beside its numerous advantages, SiC Mosfet still has lower current and voltage ratings than IGBT. Blocking voltage of available SiC Mosfets used in middle voltage applications is rated up to 1.7kV. Only a few companies have developed SiC devices with high power rating. For example, company Cree offer very attractive SiC high power half-bridge modules, CAS300M17BM2 1700V/225A and CAS300M12BM2 1200V/385A [4].

In order to fully utilize the advantages, the SiC Mosfets need to be driven by higher voltage than IGBTs. For Cree's SiC modules, recommended gate driver power supply is +20V/-5V [5]. Positive supply voltage may be as low as 18V, resulting in increased ON-resistance, thus increasing conduction losses. The use of a negative gate voltage decreases turn-off energy losses [6].

On market only a few gate drivers especially designed for SiC Mosfets [7] are available. Numerous SiC converter applications use appropriate IGBT/Mosfet gate drivers, which are suitable to drive SiC switches. The gate drivers must be able to provide a negative voltage, and current output sink/source enough high in order to minimize switching times and energy losses.

Middle-voltage SiC Mosfet switches require appropriate power supply for gate driver circuits. Required power rating of the gate driver power supply primarily depends on the switch device's gate charge. Gate charge of the Cree's high power SiC modules is 1uC approximately [5], and it is used in this paper as referent value of the gate charge. Important fact is that the switching frequency affects power rating of the supply. According to [7], typical switching frequency value for the Cree's high power modules is $f_{SW} = 100\text{kHz}$. Therefore, the average power that the gate driver has to deliver to a SiC Mosfet can be calculated as follows

$$P_{GD,avg} = Q_g \cdot f_{SW} \cdot (V_{GS,on} - V_{GS,off}) \approx 2.5\text{W}. \qquad (1)$$

Beside appropriate voltage and power ratings, the power supply must have high isolation capabilities. The isolation voltage rating must be higher than 3kV for the Cree's 1.7 kV SiC switch. A compact power supply can be utilized using the planar transformer for isolation, since PCB materials offer high isolation capabilities. Block scheme of the presented compact power supply is shown in Fig. 1.

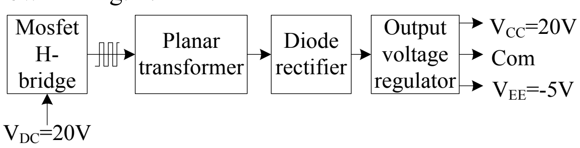

Fig. 1. *Block scheme of the proposed isolated power supply*

The supply is intended to be powered by a DC voltage source. An H-bridge drives the planar transformer with a square-wave voltage signal. Planar transformer's block contains passive elements which compensate transformer's leakage inductances. The diode rectifier and regulator blocks produce the specified voltage sources for suppling gate driver.

Fig. 2. presents typical connection diagram of the power supply, gate driver and the SiC Mosfet.

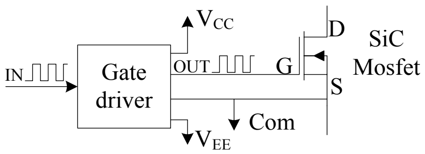

Fig. 2. *Connection of the power supply, gate driver and SiC Mosfet*

Design of the PCB planar transformer is explained in the Section 2. Operating principles of the suggested topology are described in the Section 3. Section 4 proposes procedure for determining optimal parameters values of additional passive elements, added in order to compensate leakage inductances. Also, the transformer with optimal set of parameters is determined. Criteria are the supply's performances under rated output load. Methods for the regulation of the output voltage are discussed in the Section 5.

2. DESIGN OF THE PLANAR TRANSFORMER

Coreless planar PCB transformers can be effectively used in signal and energy transfer applications. The advantages, such as low space requirements, low cost and ease of the manufacturing justify their use. High leakage inductances are present and may be undesirable. The problems associated with low coupling factor can be easily overcome by implementing resonant techniques [8].

Primary and secondary windings are spiral-shaped and printed on the opposite sides of the board. Isolation capability of the planar PCB transformer is provided by high dielectric strength of the used PCB material. FR4 designates the material that is widely used for production of the printed circuit boards. Dielectric strength of FR4 is as high as 20MV/m=20kV/mm.

PCB thickness can be as high as 2.4mm in standard or even 3.2mm in advanced production. In the presented design, distance of 2 mm is taken. Higher distance leads to higher isolation voltage, but also to lower coupling factor.

In order to create space-saving design, distance between adjacent rings in the spiral shape windings has to be as small as possible. In the standard PCB design, the minimal distance equals 0.1mm. Copper line thickness is chosen to be 105μm. Line width is set to 0.1mm, as well.

In order to keep creepage and clearance distances between primary and secondary side as high as possible, standard cores for planar PCB transformer are inadequate. There are two possible solutions regarding the use of the core. The first solution is pure coreless design, as proposed in [8]. The other solution lies in covering the both primary and secondary windings by ferrite plates, in order to minimize presence of the magnetic field outside the transformer and improve magnetic coupling. The advantages of the pure coreless design are absence of core losses and any limitations concerning magnetic core (operating frequency, DC current in windings, etc...). Usage of planar transformer leads to generating significant amount of electromagnetic noise around the transformer. Two copper rings, as electromagnetic shields, for prevention of lateral spreading of the magnetic field, are used. In the design with ferrite plates, 'I' type core is used, with dimensions 43x4x28mm, and of ferrite material designated as N87.

2.1. FEMM model of the planar transformer

Optimal design of the planar transformer by analytic way could be very challenging. Finite element software was used in order to minimize the impact of analytic approach. The *Finite Element Method Magnetics* (FEMM 4.2) software package is used to design and calculate parameters of the planar transformer. The planar transformer's model is defined as an axisymmetric problem, at operating frequency equal to 400 kHz. Current (100mA) is present only in the upper winding.

Fig. 3. and 4. show the distribution of the magnetic filed in coreless design and in design with ferrite plates covering windings, respectively.

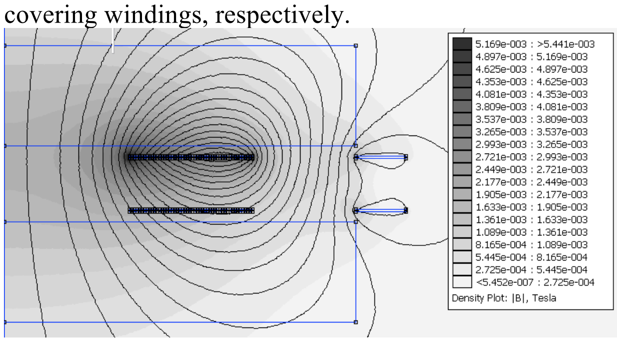

Fig. 3. *Coreless planar transformer, the half of the cross-section*

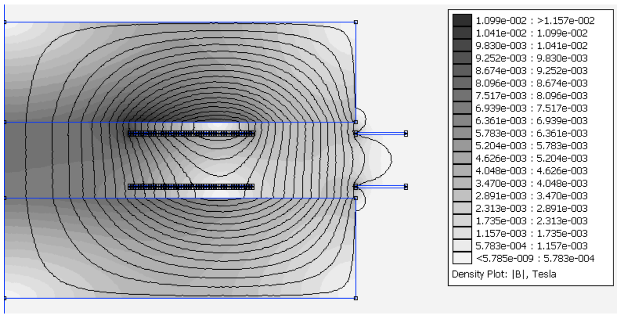

Fig. 4. *Planar transformer with ferrite covering plates*

Results of series of simulations are given in Table 1 and 2. Set of the planar transformer parameters are given, for several different windings turn numbers, N. The inner diameter of the windings is 10 mm.

Table 1. *Transformer's parameters, coreless design*

N	L_s[μH]	R[Ω]	L_m[μH]	L_l[μH]	k
10	1.93	0.65	0.793	1.14	0.41
15	4.10	1.07	1.92	2.18	0.47
20	7.06	1.57	3.60	3.46	0.51
25	10.8	2.15	5.82	4.98	0.54
30	15.1	2.86	8.49	6.61	0.56
35	19.9	3.73	11.4	8.5	0.57

Table 2. *Transformer's parameters, ferrite design*

N	L_s[μH]	R[Ω]	L_m[μH]	L_l[μH]	k
10	4.27	0.688	2.81	1.46	0.66
15	9.75	1.19	6.95	2.8	0.71
20	17.6	1.84	13.2	4.4	0.75

25	27.6	2.70	21.4	6.2	0.78
30	39.3	3.85	31.1	8.2	0.79
35	51.6	5.40	41.2	10.4	0.80

The results in the tables are estimated quantities: L_s – self-inductance of the windings, L_m – mutual inductance, R – windings resistance, L_l – leakage inductance of the windings, k – coupling coefficient. According to the supply's power and voltage ratings, the optimal transformer design is determined, as explained in the Section 4.3.

3. TOPOLOGY OF THE DRIVER-TRANSFORMER-RECTIFIER CIRCUIT

The proposed topology of the isolated power supply with planar PCB transformer is shown in the Fig. 5.

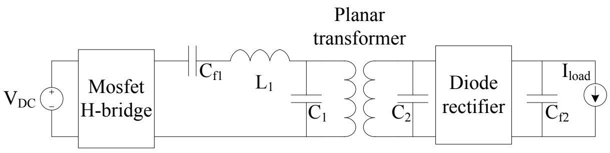

Fig. 5. *The simplified scheme of the proposed isolated power supply*

Mosfet H-bridge is supplied by a DC voltage. It generates a square-wave voltage, with duty cycle equal to 50%. Capacitor C_{f1} eliminates DC current from primary winding. In order to stabilize output voltage, it is added capacitor C_{f2}. Capacitors C_1, C_2 as well as inductor $L_{1,}$ are added to the design in order to eliminate negative influence of the leakage inductances, such as output voltage attenuation and reactive power generation Capacitor C_2 connected in parallel with the secondary winding forms resonant circuit, as proposed in [8] and [9]. As a consequence, voltage gain greater than unity, can be easily achieved choosing appropriate values of C_2 capacitance and square-wave frequency.

The ideal square-wave voltage contains only components of odd harmonic frequencies. The fundamental frequency is equal to the switching frequency $f_{H,SW}$ of the H-bridge. Frequency response of the transformer's circuit at the $f_{H,SW}$ frequency can be adjusted with the capacitor $C_{2,}$ as previously explained. The next significant component is the harmonic at $3{\cdot}f_{H,SW}$ frequency. Therefore, by placing one more capacitor (C_1) in the parallel with the primary winding, new resonant frequency appears. It gives ability for tuning the desired frequency response at both harmonic frequencies. The goal is to minimize primary current by obtaining zero reactive power at both $f_{H,SW}$ and $3{\cdot}f_{H,SW}$ frequencies.

The inductor L1 placed in series with primary winding of the transformer has a goal to filter current of the square-wave voltage source and to provide as low as possible switching current. Thus, adequate choice of inductor L1, for the rated high frequency of the H-bridge, could limit switching losses in the H=bridge.

4. DETERMINING THE OPTIMAL PARAMETERS OF THE TRANSFORMER AND ADDITIONAL PASSIVE ELEMENTS

This section is focused on describing procedure for finding the optimal planar PCB transformer among all those given in the Tables 1 and 2.

At first, procedure for finding the optimal values of C_1 and C_2 capacitances for an arbitrary planar transformer is described. The next design step is determining the optimal value of the L_1 inductance. Finally, we chose the planar transformer which best fits the desired voltage and power ratings of the supply.

4.1. Determining the optimal values of C_1 and C_2

The switching frequency $f_{H,SW}$ of the H-bridge must be chosen. Since the optimal frequency range of the N87 ferrite lies between 25kHz and 500kHz [10]. In this design the switching frequency equals 400 kHz.

Optimal values of capacitance C1 and C2 are determined by performing computer simulations in Matlab and Orcad Pspice softwares. At first, a Matlab program analyzes input impedance of the transformer's circuit, with added capacitors. The goal is to find an area in (C1,C2) plane where the impedance has nearly zero phase angle at both frequencies 400kHz and 1.2MHz. Results are shown in Fig. 6.

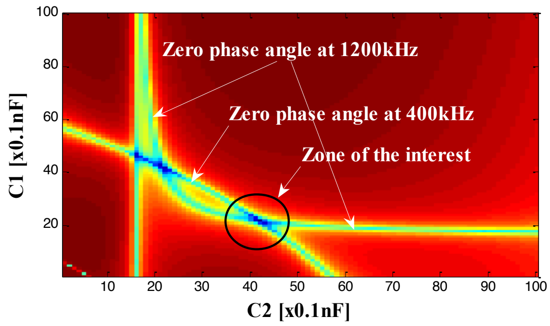

Fig. 6. *Zones with the impedance phase angle close to zero*

This example is given for the planar transformer covered by ferrite plates and N=25 turns in the windings. Roughly estimated capacitances are C_1=2.2nF and C_1=4.2nF.

Parametric AC sweep (in frequency domain) analysis is performed in Pspice for more precise determining of the C1 and C2.

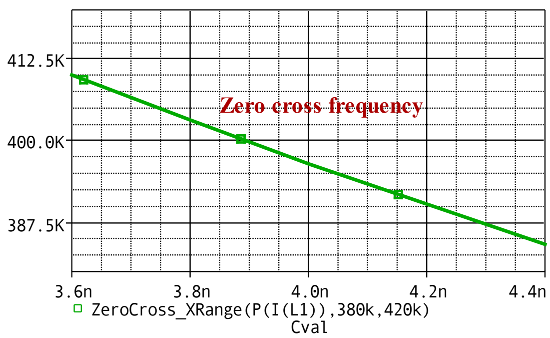

Fig. 7. *Dependence of the zero-crossing frequency of the current's phase response vs. the C_2 capacitance*

Fig. 7. shows dependence of the zero-crossing frequency of the primary current phase response vs. the capacitor C_2 values, around previously roughly estimated value. From the Fig. 7. can be concluded that optimal value of capacitor C2 is 3.9nF in terms of achieving the zero reactive power at 400 kHz.

The above procedure is repeated for all parameters of the planar transformer from the Table 1 and Table 2. Results are shown in the Table 3 that contains optimal values of additional capacitances.

Table 3. *Additional passive parts values*

	coreless			ferrite		
N	C1[nF]	C2[nF]	L1[H]	C1[nF]	C2[nF]	L1[H]
10	11	90	4	8.1	32	8
15	5.7	36	5	4.3	13	10
20	3.5	20	6	2.9	6.8	11
25	2.4	13	7	2.2	3.9	12
30	1.8	9.6	8	1.8	2.2	10
35	1.4	7.2	9	1.5	1.6	10

4.2. Determining the optimal value of L_1

For determining the optimal value of the inductance L_1, Pspice parametric time domain analysis is performed. Fig. 8. shows the Pspice schematic diagram of the isolated supply, with unregulated output. Square wave voltage is generated by a pulse generator. Capacitances C1 and C2 are adjusted on values given in the Table 3. Diodes in the rectifier are 40V/1A fast switching Schottky diodes.

The amplitude of the square wave voltage is set to be 20V. It is explained in Section 3 that the voltage is going to be amplified due to utilized resonance technique. Therefore, the output unregulated voltage may be expected around 25V which is sufficient for generation of +20/-5V regulated voltage. The load current sink is set to be 100mA, in order to match maximal power ratings, which could be calculated from (1).

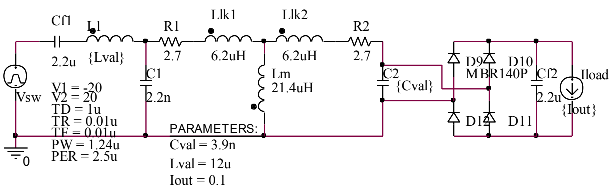

Fig. 8. *The PSPICE schematic for transient parametric analysis of the isolated supply*

Dependences of the most significant values (output unregulated voltage, input RMS current, H-bridge commutation current) on the L_1 parameter are given in the Fig. 9. and Fig. 10. The highest voltage coincides with the lowest RMS and switching primary current values, thus the optimal value of the inductance is L_1=12μH.

This example is given for the ferrite transformer with N=25 turns in the windings. The procedure is conducted for all transformers from the Table 1. and Table 2. The optimal values of additional inductances are given in Table 3.

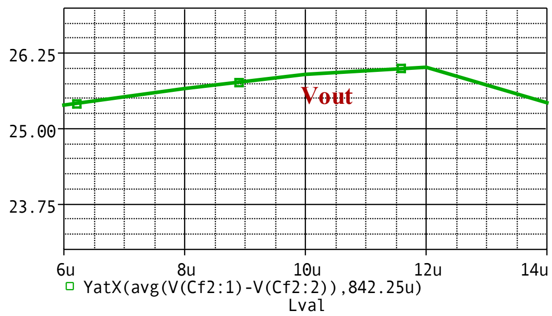

Fig. 9. *Dependence of the output voltage under nominal load vs. the L_1 inductance*

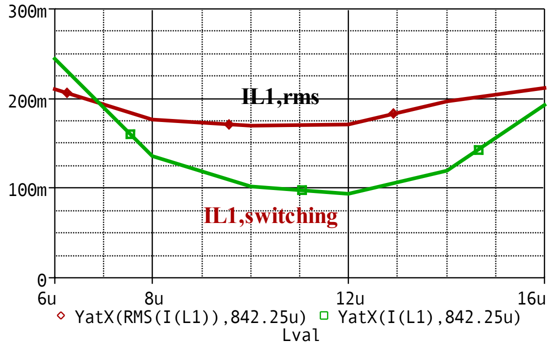

Fig. 10. *Dependence of the primary current rms and switching value vs. the L_1 inductance*

4.3. Selection the optimal planar transformer

The final task of the proposed procedure is to choose one planar transformer, together with its corresponding optimal set of additional elements, which has the best performances under the required voltage and power ratings of the proposed power supply. Figures 11-13. give a comparative view of the most significant supply's characteristics over the range of different planar transformer designs.

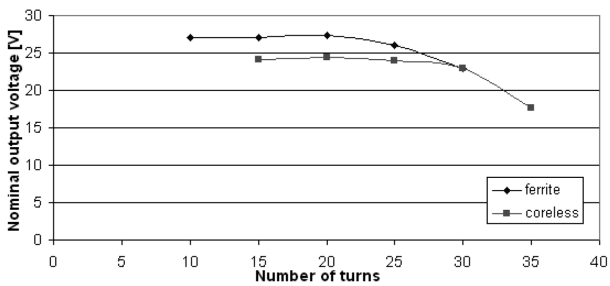

Fig. 11. *Output voltage under nominal load*

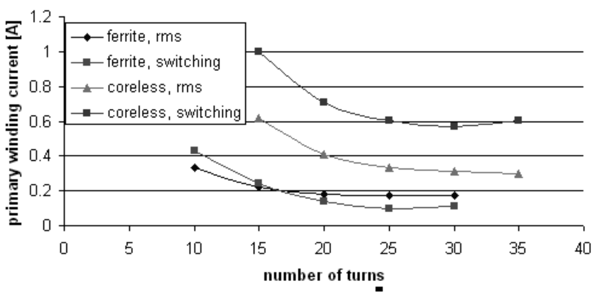

Fig. 12. *Primary winding current under nominal load*

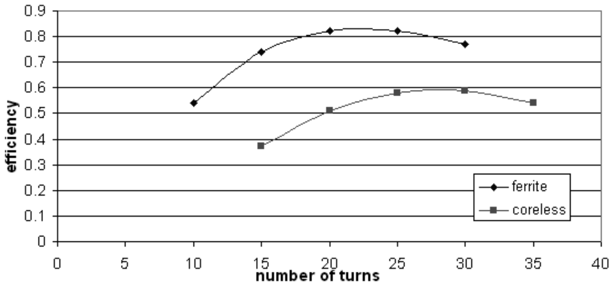

Fig.13. *Efficiency of the supply under nominal load*

The planar transformer covered by ferrite plates and N=25 turns in the windings has the best performance according to the proposed power and voltage ratings of the isolated power supply. It has the best efficiency at the rated load and the lowest RMS and switching values of the primary winding current. The next choice would be the ferrite transformer with N=20 turns. It has a bit higher values of the primary current, but also a little higher output voltage. The transformers without covering ferrite plates have very poor performance characteristics according to all presented criteria.

5. REGULATION OF THE OUTPUT VOLTAGE

Driving the gate of the SiC switch demands supplying the driver with several stabilized voltage levels. Typically, drivers are supplied with non-isolated +5 V so it would not be difficult to provide it. On the other hand, for the purpose of switching on and off, it is necessary to provide two isolated voltages, usually for SiC, +20 V and – 5 V, but it can vary. Several ways for providing isolated voltages are possible. On Fig. 14. is shown linear-voltage-regulator (LVR) based circuit for suppling the gate driver.

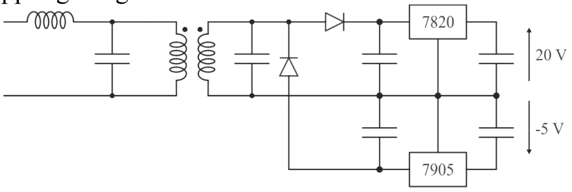

Fig. 14. *Gate driver isolated power supply based on linear voltage regulators*

This circuit topology provides necessary voltage levels by using positive voltage regulator 7820, which is rarely used in conventional application. Negative voltage is obtained by using the negative voltage regulator 7905. Since the switching frequency is around 400 kHz, diode in rectifier must be fast in order to prevent distortion of voltage.

Another way for generating the gate driver power supply is to use SMPS to provide desirable voltages. On the Fig. 15. another circuit topology where SMPS is used.

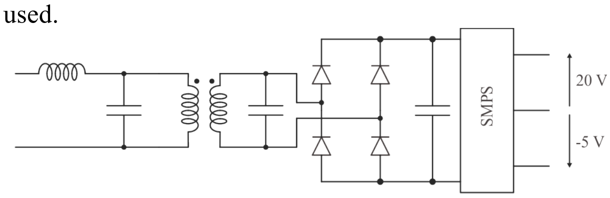

Fig. 15. *Gate driver isolated power supply based on SMPS*

This topology could be much complicated for realization than LVR based supply. Using the compact integrated circuit with built-in switcher could be unreasonable because switcher with output of + 20 V is very rare. On the other hand, realization of SMPS with using simple switcher integrated circuit, could imply much more components than topology presented in Fig. 14. Advantages of using the SMPS over the LVR based supply are better efficiency and zero DC current component in secondary winding.

6. CONCLUSION

In this paper, one concept of using the planar PCB transformer in realization of the gate driver power supply is presented. It is intended for the middle voltage SiC Mosfet gate drivers. Despite high leakage inductances of the proposed planar transformer, it is possible to achieve voltage gain around 1.3 and high efficiency, over 80%, under the nominal output load. Procedure for determining optimal planar transformer design is given.

The planar transformers with the windings covered by the ferrite plates have the clear advantages over the coreless PCB transformers. The long distance between transformer's windings leads to high values of the leakage inductance. Covering the planar transformer with the ferrite plates improves magnetic coupling and thus overall characteristics, while preventing distribution of the magnetic field out the transformer. On the other hand, further efforts have to be made in calculating and modeling core and shield losses and determining the influence on the overall efficiency of the isolated power supply. Compact power supply, compared to conventional, could be less expensive and also less demanding. For future research, physical realization of the planar transformer is required.

7. REFERENCES

[1] O. Mostaghimi, N. Wright, and A. Horsfall, "Design and performance evaluation of SiC based DC–DC converters for PV applications," in Proc. IEEE Energy Convers. Congr. Expo., Sep. 2012, pp. 3956–3963.

[2] D. Han, J. Noppakunkajorn, B. "Sarlioglu, Comprehensive Efficiency, Weight, and Volume Comparison of SiC- and Si-Based Bidirectional DC–DC Converters for Hybrid Electric Vehicles" IEEE Transactions on Vehicular Technology, Vol. 63, No. 7, September 2014.

[3] D. Han, J. Noppakunkajorn, B. Sarlioglu, "Analysis of a SiC three-phase voltage source inverter under various current and power factor operations", IECON 2013 - 39th Annual Conference of the IEEE, 10-13 Nov. 2013, pp. 447 – 452.

[4] Cree. CAS300M17BM2 / CAS300M17BM21200, SiC half-bridge module datasheets. (2013). Online Available: http://www.cree.com/.

[5] B. Callanan, "Application considerations for silicon carbide MOSFETs", Application Note, Cree, Inc., Durham, NC, USA, Jan. 2011.

[6] L. Abbatelli, C. Brusca, G. Catalisano, "How to fine tune your SiC MOSFET gate driver to minimize

losses”, Application Note, STMicroelectronics, Apr. 2015.
[7] Cree. PT62SCMD12 SIC MOSFET driver, Datasheet R08, September 2014.
[8] S. C. Tang, S. Y. Hui, and H. S. Chung. "Coreless planar printed-circuit-board (PCB) transformers - a fundamental concept for signal and energy transfer" IEEE Transactions on Power Electronics, Vol.15, No.5 (2000), pp. 931-941.
[9] S. C. Tang, S. Y. Hui, and H. S. Chung. “Optimal operation of coreless PCB transformer-isolated gate drive circuits with wide switching frequency range,” IEEE Trans. Power Electron., vol. 14, pp. 506–514, May 1999.
[10] SIFERRIT material N87, Data Sheet, EPCOS AG, 2006.