Thermal simulation of a 7kW interleaved module for fast automotive charger

Laura Anoldo

Dept.Scienze Matematiche e
Informatiche, Scienze Fisiche e Scienze
della Terra, University of Messina &
STMicroelectronics
Catania, Italy
laura.anoldo@unime.it

Giuseppe Gabriele Piccione

Dept.Scienze Matematiche e
Informatiche, Scienze Fisiche e Scienze
della Terra, University of Messina,
Messina, Italy
giusepppegabriele.piccione@unime.it

Giuseppe Mauromicale

STMicroelectronics & DIEEI,
University of Catania
Catania, Italy
giuseppe.mauromicale@st.com

Alessandro Sitta

STMicroelectronics
Catania, Italy
alessandro.sitta@st.com

Enza Fazio

Dept.Scienze Matematiche e
Informatiche, Scienze Fisiche e Scienze
della Terra, University of Messina.
Messina, Italy
enfazio@unime.it

Michele Calabretta

STMicroelectronics
Catania, Italy
michele.calabretta@st.com

Antonio Lionetto

STMicroelectronics
Catania, Italy
antonio.lionetto@st.com

Angelo Messina

STMicroelectronics
Catania, Italy
Angelo.messina@st.com

Mario Di Guardo

STMicroelectronics
Catania, Italy
mario.diguardo@st.com

Salvatore Patanè

Dept.Scienze Matematiche e
Informatiche, Scienze Fisiche e Scienze
della Terra, University of Messina.
Messina, Italy
salvatore.patane@unime.it

Abstract— Si- and SiC-based fast on-board chargers require very special thermal strategies, to ensure high reliability in order to assess long life in harsh environments, such as the automotive one. Indeed, the power losses in the switches may lead to a severe temperature rise in the enclosed cabinet, causing a reduce lifetime of the system. In this paper, we propose a scalable fast charger for automotive applications able to manage a 7 kW power flow. A thermal simulation based on COMSOL Multiphysics is performed in this work. The study allows us to get a realistic evaluation of the higher temperatures reached by the active Si and SiC devices of the converter during the normal operation, at the steady state and at the maximum allowed power.

Keywords— DC/DC converter, LLC, PFC, OBC, fast charger, automotive, thermal simulation.

I. INTRODUCTION

Spreading of electric vehicles (EVs), due to environmental reasons, is being more and more pronounced in the last years. In automotive framework, especially for plug-in full and hybrid vehicles, power electronics is of paramount importance, both regarding power converters and power semiconductor devices contained inside them, in traction, charging, and auxiliary architectures inside the car [1] - [3].

This rapid spreading is also due to new power semiconductor technologies: wide band-gap materials such as silicon carbide (SiC) and gallium nitride (GaN), either from device and topology points of views, can enhance higher

efficiency and power density [4], [5]. Additionally, there are also innovative silicon (Si)-based devices useful for automotive applications, both high voltage and low voltage ones. For example, resonant converters usually contain Si MOSFETs [6].

In plug-in EVs, battery's reliability and charging are two of the key topics, both for EV itself and for the integrated grid infrastructure necessary to satisfy the needs of all vehicles, when they will be massively diffused. In this regard, integration with smart grid, distributed generation including renewable energy sources such as photovoltaic, and wind and storage systems, will be on the main challenge [7]. The charging can be done both on board and off-board. Moreover, also the so-called "on-board integrated chargers", that consider existing motors or converters inside the EV, are under development, but nowadays they seem still not enough technologically robust in comparison with other solutions [8].

New technologies for batteries, in particular the lithium-ion based ones, are favoring the development of new solutions. Although many types of batteries exist nowadays, and they need other improvements, currently the type recalled above is the most widely used in EVs [1].

On board chargers (OBCs) can be either unidirectional or bidirectional: in the last case, also a power exchange from vehicle to grid would be possible [9]. There exist various modulation strategies and control modes for OBCs, the main aim is to boost converter's efficiency.

With reference to the off-board solutions, there exist DC fast charging stations: in this case, the converter to charge the

batteries is off-board, placed in the stations [10]. There exist various AC and DC charging modes [1], [11]. Wireless power transfer, based on induction law, is another charging mode, currently under development [12]. It would reduce the time to charge battery and increase the system's safety and reliability; however, today this opportunity is yet in a more infant stage, in comparison to wired modes. Related to this power transfer mode, it has been proposed the vehicle-to-vehicle recharging, when two vehicles can exchange power, one from the other, during a trip [13].

Fast charging can be obtained also with AC-based OBC topologies. The considered architectures can be either single-phase or three-phase. Among the possible converter types, there are: conventional, interleaved, or phase shifted semi-bridgeless boosts, but also bridgeless interleaved topologies, as well as in resonant version [11]. A comprehensive overview of the possible topologies for off-, on-board, and integrated chargers, employing Si, SiC, or GaN devices, can be found in [14] and [15]. Usually, a filter is placed in the system, before the power factor corrector (PFC) stage, in order to mitigate the electromagnetic interference. Considering a system with AC input, then there is AC/DC converter. The converter considered in this work, briefly described hereafter, has a voltage amplitude equal to 85-265 V, while the voltage frequency is in the range: 45-65 Hz.

The OBC first stage is a PFC interleaved totem pole, made up with SiC power semiconductor devices in the power stage. The high-voltage SiC devices are placed in surface-mounted package. Switching frequency is set to 70 kHz. Synchronous rectification is employed to improve the power efficiency, enabled according to load conditions. The other stage, downstream from the PFC, is the DC-DC converter. Usually, it is an LLC converter with a resonant tank, when on the primary side power semiconductor devices are employed. In this work, the placed devices are silicon ones in MDmesh technology. The LLC is an interleaved full-bridge, with a variable switching frequency, in the range 80 – 310 kHz. The DC voltage amplitude is in the range of 250 - 450 V for a 375 V-rated main battery. Furthermore, battery management system is usually placed, in order to assess the correct operations of the system. At the end, the traction inverter feeds the electrical motor, commonly a Permanent Magnet Synchronous one [1]. The global power delivered by the system simulated in this paper is equal to 7 kW.

Thermal management of power devices, in this kind of high-performance converters, is strictly related to the device's lifetime [2]. In fact, the device's junction temperature must stay below a certain limit, to ensure that reliability targets can be satisfied, thereby preventing premature failures [16]-[18]. In this paper, a thermal simulation of OBC is performed, with the aim of assessing the temperature values in a normal operation condition, by studying the heat propagation in the converter structure.

The rest of the paper is organized as follow: in section II we outline the main components to design the scalable solution proposed, able to perform 7 kW per module. In section III, we describe the parameters and the model used to simulate the thermal behavior at the steady state of the system to evaluate the maximum temperature reached during the normal working. In section IV, we give some conclusions.

II. MODULAR SOLUTION DESCRIPTION

In this section, we give a description of the OBC structure already outlined in the Introduction. The 7 kW AC/DC power converter module exploits novel SiC devices and allows to be parallelized in an interleaved stacked solution able to reach up to 21 kW, and to be configured for mono- and three-phase inputs, as depicted in Fig.1.

Fig. 1. Single and three phase configurations

The proposed solution is designed with the aim to provide an AC/DC power converter solution able to be integrated into the OBC in an electric vehicle, as well as in a DC wall-box. The last possibility would be seen as novel solution to reduce drastically the recharging time in comparison to the traditional AC wall-boxes.

The 7 kW AC/DC power module consists of the following blocks, that are showed in Fig.2:

- EMI Filter/front end rectifier;
- SiC-based interleaved Totem pole Power Factor Correction stage to ensure the optimal interfacing with the mains [19] ;

DC/DC converter based on interleaved Full Bridge (FB)-LLC [20] .

Figure 2: block diagram of the DC / DC converter

The scope is to exploit interleaved solutions adopted for the SiC PFC stage (totem pole) and for the high voltage side of the DC/DC converter (FB LLC) to obtain the configuration flexibility to provide the required power size (up to 21 kW stacking up three modules) and the interfacing to the AC mains by means of 7 kW module, used standalone or in parallel, in order to match mono phase (1 Phase+ N) and 3-phase (3 Phases + N) assembly mode.

Fig.3. Top view of the OBC

In Fig. 3 and Fig. 4, the top and exploded views of the OBC are reported, respectively.

III. THERMAL SIMULATION SETUP AND RESULTS

In order to get information about the behavior and the reliability of the system during its normal operative conditions, we perform thermal simulations to predict the temperature reached inside the devices with the aim to define a suitable thermal margin during operation and to build a proper lifetime reliability model.

Fig.4.Exploded view of the OBC

The simulations are performed using COMSOL Multiphysics, a cross-platform finite element method (FEM) analysis software that allows the treatment of conventional physics-based user interfaces and coupled systems of partial differential equations (PDEs). The reliability must be evaluated at the global system level, but in this simulation we focus our attention to the thermal behavior of the PFC and DC/DC converters, that represent without any doubt one of the most critical parts of the assembly. Indeed, by this module it largely descends the efficiency and the lifetime of the whole system.

Fig.5 shows the studied automotive on-board charger, in which the simulated parts are highlighted. Fig.6 reports a schematic diagram of the interleaved tottem pole and of the DC-DC converter (LLC), that represent the power conversion heart of the system.

Fig.5. Picture of the on-board charger. The red ellipses highlight the parts we focused for the thermal simulation (LLC and PFC)

To improve the OBC thermal performances, a complex multilayered mechanical structure has been designed. It consists of an aluminum baseplate (420x200x7 mm), to be connected to the external cooling system. Right up, a 150 thin layer of thermal grease improves the thermal conductivity. An insulated metal substrate (IMS) (203x139x1.5 mm), which integrates on top a copper layer, hosts all the active components (diodes, thyristors, and transistors) that are the

only heat sources taken into account in our simulation. Their internal structure has been simplified and consists of an active part, that is the SiC or Si die represented by a 4x4 mm square layer, with a thickness of 180 μ m. The active part is placed onto a copper slug 1.5 mm thick. The entire structure is encapsulated in a third block, which is the resin.

Fig. 6. Schematic diagram of the power converters

Schematic diagrams of the layers and of the power devices are shown in Fig.7 (a) and (b), respectively. We use the “heat transfer in solid” physics in COMSOL to perform the simulation, solving the associated PDEs, as the static temperature distribution is the target of our study. The only thermal boundary condition used is the Al baseplate temperature, that has been fixed at 60° C. This approximation is acceptable if we consider a liquid-based cooling system, since in this case the baseplate temperature would be approximately considered constant during the converter normal operation.

Fig.7. (a) Details of the layers used to simulate the structure; (b) The model used to simulate the system (on the left) and a power device structure (on the right)

All the dies of the active components work as heat sources in our simulation. The evaluation of the power dissipated by the active component is a challenging task, and developing a detailed model to evaluate the losses is far from the aim of this work. Nevertheless, in the following we analyze the losses of the different parts of the converters on which we focused our attention, to be used in our thermal model. It is noted that the thermal conductivity of some materials is set to be temperature dependent, according to [21]. Silicon and copper show considerably lower thermal conductivity at higher temperatures, so these materials are more sensitive to boundary conditions. For simplicity, it is assumed that the devices are adiabatic with respect to the top and lateral surfaces, and therefore, all the generated heat is dissipated through the cooling system. The analysis of the power losses

does not take into account the two diodes STBR3012G2Y, as these components work only at the startup and become inactive during the normal operation as they are blocked when the voltage in boost converter exceeds the bus one, hence no relevant power is dissipated. The four SCTH35N65G2V-7AG are automotive-grade silicon carbide Power MOSFETs, housed in an H2PAK-7 package: they represent the core of the interleaved totem pole and their low turn-on resistance (55 mΩ) reduces the conduction losses.

The power loss consists of three contributions: the switching, the conduction, and the driver losses. In [22], some formulas are reported for the boost PFC converter topology, that is different from our totem pole PFC.

Indeed, in our case a MOSFET replaces the diode, which works as a rectifier for one half period. Hence, the conduction losses P_{cond} must be re-written splitting the two contributions:

$$P_{cond} = I_{DS(RMS)}^2 \cdot (R_{DS(on)} \cdot \alpha) + I_{RMS_rect}^2 \cdot (R_{DS(on)} \cdot \alpha) \quad (1)$$

where $R_{DS(on)}$ is the drain-source resistance, α is a corrective factor, and the drain RMS currents of the MOSFET $I_{DS(RMS)}$ and of the rectifier I_{RMS_rect} can be expressed as:

$$I_{RMS} = \frac{P_{OUT}}{2 \cdot V_{IN}} \cdot \sqrt{1 - \frac{8 \cdot \sqrt{2} \cdot V_{IN}}{3 \cdot \pi \cdot V_{OUT}}} \quad (2)$$

$$I_{RMS_rect} = \frac{P_{OUT}}{2 \cdot V_{IN}} \cdot \sqrt{\frac{8 \cdot \sqrt{2} \cdot V_{IN}}{3 \cdot \pi \cdot V_{OUT}}} \quad (3)$$

where P_{OUT} is the output power, and V_{IN} and V_{OUT} are the RMS values of input and output voltages, respectively.

In the same way, it is necessary to slightly modify the equations related to the switching and body diode losses, in order to adapt the model with respect to the simulated topology:

$$P_{SW} = V_{DS} \cdot \frac{f_{sw}}{2} \cdot t_{rise} \cdot (I_{DS(min)} + I_{QRR}) \quad (4)$$

$$P_{body_diode} = 2V_{FD} \cdot f_{sw} \cdot t_{dead_time} \cdot I_{Lavg} \quad (5)$$

where V_{DS} is the drain-to-source voltage, f_{sw} is the switching frequency, I_{QRR} is related to the reverse recovery, t_{rise} and t_{dead_time} are, respectively, the rise and the dead time periods, V_{FD} is diode forward voltage, and I_{Lavg} is the average current on the inductor.

Neglecting the driver contribution, which can be considered largely negligible, considering only one leg, and assuming $P_{OUT} = 3680$ W, $V_{IN} = 240$ V, $V_{OUT} = 400$ V, the calculated P_{MOSFET} is about 14 W.

The power losses values for each Silicon Controlled Rectifier (SCR) are calculated using the formula as follows:

$$P_{dSCR} = \frac{V_{TO} I_{LINE(RMS)} \sqrt{2}}{\pi} + R_d \frac{I_{LINE(RMS)}^2}{2} \quad (6)$$

where $I_{LINE} = 32$ A, the threshold voltage $V_{TO} = 1.65$ V, the dynamic resistance in on state $R_d = 0.014$ Ω; the power dissipated by the two TN3050H-12GY-TR will be $P_{dSCR} = 26.5$ W.

Concerning the power dissipated by the LLC section [23], which operates in soft-switching, and at zero-voltage switching at turn-on stage, in a first approximation the only relevant power losses concern the conduction ones. This

statement can be reasonable because we are considering the converter operating at full load. In fact, in this case, we are near the resonance frequency, then the current peak and the frequency values are low. As a consequence, the switching losses are low, accordingly. The Power MOSFET RMS current can be expressed, in this case, as:

$$I_{RMS_MOS} = \frac{P_{IN} \cdot \pi}{V_{IN} \cdot 2 \sqrt{2}} \quad (7)$$

And the conduction losses are given by:

$$P_{cond} = I_{RMS}^2 \cdot R_{DS(on)} \cdot \alpha \quad (8)$$

where the parameter α is set to 1.5. The calculated power loss for each STB47N60DM6AG is around 13 W.

The aluminum plate is designed to be connected to an external cooling system. This external component should be able to perform better than an equivalent heat transfer coefficient equal to 10 kW/m² K: for this reason, we set its temperature, at the steady state, equal to 60°C. This value is fully compatible with the application in the automotive environment. One critical point of the simulation consists of the used mesh; the problem arises from the different thickness of the layers that ranges between a few mm and hundreds of m. This is a typical issue of the Finite-Difference Time-Domain (FDTD) simulations: to well describe the thinner layer a very fine mesh is needed, but this results in a too much memory and time demanding procedure. In the considered modeling flow, quadratic hexahedrons are massively used to discretize the geometry in order to achieve mesh with a reasonable quality. Geometry is subdivided using the COMSOL function “Partition objects”, in order to create regular blocks easy to mesh by extruding from top to bottom structured 2D mapped mesh. In this way, the problem concerning the thickness of thin layers is overtaken.

Fig. 8. Thermal simulation results. The obtained maximum thermal jump is 18 °C and is located on the SiC Power MOSFETs

Figure 8 shows the thermal simulation, as expected the higher temperature belongs to the devices that dissipate the higher power (14 W). The maximum temperature increasing is 18°C

The obtained result concerns only the active components of the system and of course, in a next stage, it should be taken into account the thermal contribution of the passive components with special attention to the inductors that are,

with no doubt, another critical point of the system. Nevertheless, the simulation is effective as it allows us to evaluate the maximum temperature reached by the dies when the system is working at its full load. The temperature swing is relatively low and compatible with a simple liquid-based external cooling system, easily installed on a car, which is the target of this converter.

IV. CONCLUSION

In this paper, we have studied the thermal behavior of PFC and LLC stages of an OBC, by means of a FEM simulation. A simplified boundary-dependent thermal model has been used to evaluate the maximum temperature reached by the semiconductor dies. The boundary conditions, which were applied in the model, are the heat source (power losses) and the heatsink (cooling system). The obtained results highlight that, if the baseplate temperature is fixed at 60 °C, the maximum rated temperature reached by the power semiconductor devices at full load is 78 °C, well below 100 °C. The simulated temperature profiles can be used for accurate life-time estimation of the power devices in long-term mission profiles framework. We can conclude that, despite the minimum footprint, the result guarantees excellent reliable continuous operation and scalability and it is fully compatible with the car technology, and suitable to be installed on board. Future works will be deal with the generation of more accurate models of the board and of the devices, as well as the passive components inclusion in the simulation, and the transient system's thermal performances.

ACKNOWLEDGMENT

These results were obtained in the context of the PROGRESSUS project, that has received funding from the ECSEL Joint Undertaking (JU) under grant agreement No. 876868. The JU receives support from the European Union's Horizon 2020 research and innovation programme and Germany, Netherlands, Spain, Italy, Slovakia.

REFERENCES

- [1] X. Sun, Z. Li, X. Wang, and C. Li, "Technology Development of Electric Vehicles: A Review," *Energies*, vol. 13, no. 1, p. 90, Dec. 2019.
- [2] F. Blaabjerg, H. Wang, I. Vernica, B. Liu and P. Davari, "Reliability of Power Electronic Systems for EV/HEV Applications," in *Proceedings of the IEEE*, doi: 10.1109/JPROC.2020.3031041.
- [3] J. L. Afonso, L. A. L. Cardoso, D. Pedrosa, T. J. C. Sousa, L. Machado, M. Tanta, and V. Monteiro, "A Review on Power Electronics Technologies for Electric Mobility," *Energies*, vol. 13, no. 23, p. 6343, Dec. 2020.
- [4] S. Li, S. Lu and C. C. Mi, "Revolution of Electric Vehicle Charging Technologies Accelerated by Wide Bandgap Devices," in *Proceedings of the IEEE*, doi: 10.1109/JPROC.2021.3071977.
- [5] F. Roccaforte, P. Fiorenza, G. Greco, R.L. Nigro, F. Giannazzo, F. Iucolano, M. Saggio, "Emerging trends in wide band gap semiconductors (SiC and GaN) technology for power devices," in *Microelectronic Engineering*, 2018.
- [6] E. S. Glitz and M. Ordóñez, "MOSFET Power Loss Estimation in LLC Resonant Converters: Time Interval Analysis," in *IEEE Transactions on Power Electronics*, vol. 34, no. 12, pp. 11964-11980, Dec. 2019, doi: 10.1109/TPEL.2019.2909903
- [7] H. S. Das, M. M. Rahman, S. Li and C. W. Tan, "Electric Vehicles Standards Charging Infrastructure and Impact on Grid Integration: A technological Review", in *Renewable and Sustainable Energy Reviews*, Elsevier, vol. 120, March 2020, <https://doi.org/10.1016/j.rser.2019.109618>.
- [8] M. Y. Metwly, M. S. Abdel-Majeed, A. S. Abdel-Khalik, R. A. Hamdy, M. S. Hamad and S. Ahmed, "A Review of Integrated On-Board EV Battery Chargers: Advanced Topologies, Recent Developments and Optimal Selection of FSCW Slot/Pole Combination," in *IEEE Access*, vol. 8, pp. 85216-85242, 2020, doi: 10.1109/ACCESS.2020.2992741.
- [9] J. Yuan, L. Dorn-Gomba, A. D. Callegaro, J. Reimers and A. Emadi, "A Review of Bidirectional On-Board Chargers for Electric Vehicles," in *IEEE Access*, vol. 9, pp. 51501-51518, 2021, doi: 10.1109/ACCESS.2021.3069448.
- [10] M. A. H. Rafi and J. Bauman, "A Comprehensive Review of DC Fast Charging Stations with Energy Storage: Architectures, Power Converters, and Analysis," in *IEEE Transactions on Transportation Electrification*, doi: 10.1109/TTE.2020.3015743.
- [11] G. Maumomiale, A. Raciti, S. A. Rizzo, G. Susinni, G. Parise and L. Parise, "E-mobility: Safety, Service Continuity and Penetration of Charging Systems," *2019 AEIT International Conference of Electrical and Electronic Technologies for Automotive (AEIT AUTOMOTIVE)*, 2019, pp. 1-6, doi: 10.23919/EETA.2019.8804496.
- [12] A. Ahmad, M. S. Alam and R. Chabaan, "A Comprehensive Review of Wireless Charging Technologies for Electric Vehicles," in *IEEE Transactions on Transportation Electrification*, vol. 4, no. 1, pp. 38-63, March 2018, doi: 10.1109/TTE.2017.2771619.
- [13] O. N. Nezamuddin, C. L. Nicholas and E. C. d. Santos, "The Problem of Electric Vehicle Charging: State-of-the-Art and an Innovative Solution," in *IEEE Transactions on Intelligent Transportation Systems*, doi: 10.1109/TITS.2020.3048728.
- [14] S. Rivera, S. Kouro, S. Vazquez, S. M. Goetz, R. Lizana and E. Romero-Cadaval, "Electric Vehicle Charging Infrastructure -- From Grid to Battery," in *IEEE Industrial Electronics Magazine*, doi: 10.1109/MIE.2020.3039039.
- [15] A. Khaligh and M. D'Antonio, "Global Trends in High-Power On-Board Chargers for Electric Vehicles," in *IEEE Transactions on Vehicular Technology*, vol. 68, no. 4, pp. 3306-3324, April 2019, doi: 10.1109/TVT.2019.2897050.
- [16] C. Durand, M. Klingler, D. Coutellier and H. Naceur, "Power Cycling Reliability of Power Module: A Survey," in *IEEE Transactions on Device and Materials Reliability*, vol. 16, no. 1, pp. 80-97, March 2016, doi: 10.1109/TDMR.2016.2516044.
- [17] S. Russo *et al.*, "Reliability Assessment of Power MOSFETs Working in Avalanche Mode Based on a Thermal Strain Direct Measurement Approach," in *IEEE Transactions on Industry Applications*, vol. 52, no. 2, pp. 1688-1697, March-April 2016, doi: 10.1109/TIA.2015.2500890.
- [18] K. Gupta *et al.*, "Thermal Management Strategies for a High-Frequency, Bi-Directional, On-Board Electric Vehicle Charger," *2018 17th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITHERM)*, 2018, pp. 935-943, doi: 10.1109/ITHERM.2018.8419580.
- [19] Q. Huang and A. Q. Huang, "Review of GaN totem-pole bridgeless PFC," in *CPSS Transactions on Power Electronics and Applications*, vol. 2, no. 3, pp. 187-196, Sept. 2017, doi: 10.24295/CPSSPEA.2017.00018.
- [20] D. Nardo, A. Scuto, and S. Buonomo, "Evaluation of primary-side MOSFETs losses in resonant LLC converters," *PCIM Europe digital days 2021*.
- [21] J. H. Lienhard, IV, and J. H. Lienhard, V, *A Heat Transfer Textbook*, 3rd ed. Cambridge, MA, USA: Phlogiston Press, 2006.
- [22] STEVAL-IPFC01V1 3 kW three channel interleaved PFC with STNRGPF01 digital controller, AN5235, STMicroelectronics, 2019.
- [23] C. Yang, T. Liang, K. Chen, J. Li and J. Lee, "Loss analysis of half-bridge LLC resonant converter," *2013 1st International Future Energy Electronics Conference (IFEEEC)*, 2013, pp. 155-160, doi: 10.1109/IFEEEC.2013.6687496.