Peer Review of the PhD Thesis

Analytical Models for IGBT Junction Temperature Estimation

issued by
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The focus of the dissertation thesis covers one of the most challenging issues during the converter development process. The understanding of the thermic field inside of the power semiconductor elements is crucial to creating and operating the semiconductor power converters in the optimal mode. The semiconductor chip and its surrounding elements are suffering from the most critical thermal stress in the converter operation. It means the knowledge about the temperature distribution there is necessary offline during the device dimensioning to reach good performance targets. The calculation using a model is the only way to get the temperature values in the development phase before some physical prototype exists. The knowledge about chip temperature values distribution online during converter operation is necessary to perform condition monitoring. The values online can be obtained by measurement.
The direct measurement of the critical temperature levels is usually not possible due to physical limitations like surface size, and the small thermal constant of the semiconductor chips. The next issues to employ a direct measurement are the high voltage and current levels inclusive fast transients resulting in many EMC and safety challenges. The indirect temperature measurement methods are usually implemented to acquire the temperature values in converter applications. The reference temperature is physically measured in the place, where it is easy to perform. The chip temperatures are computed using some mathematical model.
In both cases, online and offline is the accurate thermal model a key factor in the archive a good result.

The motivation and benefits of using an accurate thermal model are explained in the introductory chapters of the thesis. The author writes mainly about the necessity of the exact knowledge of the chip temperature to be able to calculate the gap between the actual load and the critical operation point.
There is one more motivation, which could be mentioned by the thesis as well. The thermal stress of the semiconductors and their connection to the surrounding is the key factor in the wear process. This wear defines besides the power capacitor wear the lifetime of the semiconductor power converters. The effects are well-known power cycling and temperature cycling and must be considered in the application with cyclic load, for example, traction.

The state-of-the-art implementation of the thermal modeling, using linear Cauer and/or Forster network is introduced and described in the thesis inclusive of its limits. This is used in almost all semiconductor power converters because the linear models are suitable for forced cooling applications. The exact calculation of the natural convection heatsink requires nonlinear modeling, but this special case is not a focus of this thesis, and the common naturally cooled converters usually implement a simplified linearized thermal model.

The advantages of cauer and Forster network thermal modeling are described in chapter 2.2.2. The information mentioned in this chapter, that the cauer network model can be converter into the Forster one should be more explained. Direct conversion is generally not possible, the notes in the Forster model represent not the physical layers of the semiconductor module structure. One point, which should be accurate after conversion, should be selected before the conversion and the other points would differ. The next issue could be, that the Forster network model matching is

not accurate as well. The matching of semiconductor module parameters defined by the datasheet and heatsink parameters of in-house measurement leads to some tolerances. This fact is usually negligible in the field practice but should be mentioned here in the case of the scientific approach.

The common technique to acquire the junction temperature of the chips is mentioned in chapter 2.2.3 and subchapters. The forward voltage drop depending on the temperature is the most favorite option in this case. This determination is made usually offline on some samples, the measurement of this parameter on the main current path during converter operation is usually useless. There is some research focused on online measuring the static internal gate resistance, but the results of it do not promise good accuracy.

The common technique of parameter determination, the forward voltage dependency is verified by the laboratory experiment with the thermal camera imaging reference. The measurement setup and the experiment details are according to the state of the art in this field.

The measured thermal impedance characteristics, Zth=f(t), are used to calculate the thermal network model parameters. This part shows the key focus of the dissertation because there are a lot of different techniques to obtain the parameters and the structure in general.

Chapter 3 of the dissertation deals with the experimental measurements and shows the real use of the methods, described in chapter 2. The measurement results are plausible, there is nothing to claim. Some details could be mentioned there, for example in chapter 3.3 the calibration curve Tj = f(Vf) seems to be valid for the forward current of 100mA, but this information is not included. Chapter 3.4 describes the Forster network parameter fitting, which is usually the final step of thermal system identification. These parameters are usually used in the application. More detailed information on the fitting technique could be mentioned in this chapter because the state-of-the-art fitting quality could be a benchmark for the newly researched identification technique.

Chapter 4 introduces the core of the dissertation and shows a new approach to calculating the temperatures. The new approach employs a general fitting strategy instead of the models based on the physical properties of the system, like Cauer/Forster networks. The gained results seem to be useful. I can imagine, that this technique of identification can cover the issues like cross impedance between different elements, etc because the new technique employs the full matrices.

The presentation of the method and its description are fair enough to understand the principle. A deep benchmark of this technique to the conventional one is missing in that chapter, or some other in this dissertation. The accuracy check of the technique in all possible operating points is crucial to approve it for the application. Identification with a current of 50A like in this case and a benchmark between new technique vs. Forster network model vs. direct measurement with another operation point could be very interesting. The next very interesting comparison would be a benchmark concerning the necessary computation power of the controller operating online with the two different modelings (Cauer/Forster and the new one) approaches. Such benchmarks were fine may instead of the application description in chapter 6.

Chapter 6 describes the use of online thermal modeling in the converter application and describes more or less the state of the art. The chapter offers a nice view, of what is possible with an advanced online thermal modeling of the semiconductor operating temperature.

The grammar, language, and visual qualities of the thesis are fair and allow one to understand the ideas and results of the thesis.

In general, the dissertation offers an introduction to a novel approach to thermal modeling which seems to be useful and could be finalized for use in the real converter.

Due to this fact I recommend this thesis be accepted into the defense process.

Vladislav Damec, Ostrava/Vienna 26.08.2022

Review of the PhD Thesis "Analytical Models for IGBT Junction Temperature Estimation" by Ing. Humphrey Mokom, Njawah Achiri

The submitted thesis deals with a very topical problem of converter operation under peak loads and frequent thermal transient conditions, which needs their proper thermal management. These conditions are common in inverters used in automotive traction drives often operating under low speed and high torques.

This thesis presents the methods for accurate description of the thermal impedance network of the IGBT module from which the junction temperature can be estimated. Performance reduction strategies to guarantee safe operation and optimum performance under high load operation of converter-fed drives are investigated.

My view is that the aims stated at the beginning of the thesis have been fulfilled.

The work is written in English and has standard extent of 84 pages. Besides Declaration, Abstract, Acknowledgement, Table of Contents, List of Figures, List of Tables, References, the thesis consists of eight chapters.

In the first chapter author's motivation, the state of the art in detail and the objectives of the thesis are presented. In the second chapter different inverter power losses are presented and possible thermal impedance networks discussed and compared. The third chapter is focused on determination of thermal impedance network from direct temperature measurement. First, the experimental setup is presented in detail with many illustrative photos. Then a way of measurement of currents, voltages and temperatures required for determination of thermal impedance is described. The calibration curve and extraction of network parameters is presented. Finally, junction temperature measurement using infrared camera used by the author is explained. The chapter four includes principles of identification of thermal networks using least squares strategy. The key chapter five presents the experimental results obtained using the least squares strategy and also the TSEP (Thermo-Sensitive Electrical Parameters) based on the calibration curve, and comparison of advantages and disadvantages of both the approaches in different temperature regions. The sixth chapter includes the principles of conventional implementations and also some improvements on the derating methods with respect to comfort safe operation of the electric drive system, which are supported by some simulation results in the Matlab/Simulink environment. The last seventh chapter summarizes the major results obtained and suggestions for further research in the field.

Formal arrangement of the thesis

The content of the thesis proves author's very good proficiency in modern trends in the field. The theme of the thesis is complicated and it was elaborated in many previous contributions from several

different aspects considered. Nevertheless, the presented thesis provides sufficiently comprehensive view of already published knowledge. English is good and there is only a minimum number of typing errors in the thesis. I have only three formal remarks detailed in the following.

New scientific knowledge

The work brings about some new scientific knowledge and interesting information, especially those disseminated in the chapters from three and six. The simulation results and experimental verifications, which are based on the original improvements of standard methods, prove the effectiveness of these modifications. The knowledge referred in the thesis can be used in potential industrial applications and can be also applied as starting basis for further academic research. I would personally appreciate also the review presented in the first chapters as a useful contribution of the work, which can provide inspiration for further research in the field.

Regarding my remarks, questions, and proposes that might discuss during the defense of the thesis, I would suggest following ones.

Formal remarks:

1. there in no list of meaning for symbols, variables and the abbreviations used in the thesis, which makes reading of the thesis more difficult, especially for those not specialized to this specific branch of power electronic converters;
2. there is no list of author's publications related to the thesis and others, arranged according to categories of such publications, so it is difficult to evaluate author's full publication activity;
3. I think that the author could more explain and emphasize his own original contribution in key chapters to make a reader's information and orientation easier and clearer in his work;

Questions and proposes to discussion:

4. at the end of your Summary and Conclusion you say "The adaptive derating strategy is an attractive candidate for commercial automotive applications as it is simple, robust, less computational intensive and can easily be implemented on a microcontroller". What further research steps must be performed to recommend and deliver this strategy to converter manufactures for real applications? So, is it possible and/or necessary to continue this research within the framework of university research centers and how?
5. the author provides a broad review of scientific works related to the problems of temperature estimation of semiconductor elements in power electronics converters. Nevertheless, temperature of individual elements and the converter itself can be influenced also by used PWM strategy and some published studies have been focused on this issue, for example [1]. Could the author explain whether is there any relation among the problems solved by him and these aspects related to control and PWM strategies of converters? Could it make any sense

to address a possible relationship between these two aspects of the design and operation of power converters, and if so, what could be the direction and expected benefits of this research?

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[1]Martin Votava, Tomas Glasberger, Vaclav Smidl, Zdenek Peroutka: Improved Model Predictive Control with Extended Horizon for Dual Inverter with Real-Time Minimization of Converter Power Losses, PRECEDE 2017, IEEE.

Conclusion

The theme of the thesis is very modern and the targets set have been achieved. The thesis is the work with some interesting and analyzed results of experiments and simulation. The approach and methodology used are in the agreement with the current state-of-the-art of the field. In the dissertation developed optimal thermal management strategy for an electric traction drive allows reaching maximum possible torque for specific operating conditions and guaranteeing thermal safety of the drive system in the same time. The potential use of the presented and tested methods would bring new options for improving the functionality of power electronics converters and electric traction drives.

Ing. Humphrey Mokom, Njawah Achiri presents in the list of references 1 his contribution in the MDPI journal with IF, 3 publications in journals indexed in WOS database, and 1 other contribution. So, his publication activity is sufficient according its quality but probably low for its quantity.

The thesis fulfils the conditions of independent creative activity, contains the original scientific ideas as well as results published by the author before and thus it complies with § 47, point 4 of the Law No.111/98 Sb. of the Czech Republic.

I recommend the diploma thesis for public defense, and in case of its successful course I agree that the PhD degree be awarded to Mr. Ing. Humphrey Mokom, Njawah Achiri.

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Czech Academy of Sciences

Faculty of Electrical Engineering CTU in Prague

Prague 30. 6. 2022

FAKULTA ELEKTROTECHNICKÁ
ZÁPADOČESKÉ UNIVERZITY
V PLZNI

POSUDEK OPONENTA DISERTAČNÍ PRÁCE

Assessment of the Dissertation

Titul, jméno a příjmení studenta: Title, name, surname of student	Ing. Humphrey Mokom, Njawah Achiri
Doktorský studijní program: Doctoral study programme	Elektrotechnika a informatika
Studijní obor: Study branch	Electronics / Electrical Power Engineering / Electrical Engineering
Téma disertační práce: Topic of the disseration	Analytical Models for IGBT Junction Temperature Estimation
Školitel: Supervisor	Prof. Ing. Zdeněk, Peroutka, Ph.D., Doc. Ing. Vaclav Smidl, Ph.D.
Oponent: Opponent	Doc. Ing. Pavel Vorel, Ph.D.

Zhodnocení významu disertační práce pro obor
Evaluation of the importance of the dissertation for the field

The dissertation is focused on actual problems solved in the field of traction inverters of electric vehicles nowadays. The goal is to enable to achieve the maximum inverter power (i.e. corresponding maximum inverter loss power) dependent on time with respect to thermal transient effects - to operate with the instantaneous chip temperature close to its allowed maximum value – not to have an unnecessary reserve and also not to exceed it. Commonly only the dominant thermal capacity of the heatsink is considered and then the solution is common. But considering also the small thermal capacities of the materials between the sink and chip and also the chip thermal capacity correspondingly to the practical situation, a higher peak loss power can be performed at short time durations. Also the non-linear sink-to-ambient thermal resistance can be considered. Modeling and analytical mathematical description of these problems are proposed.

Vyjádření k postupu řešení problému, použitým metodám a splnění určeného cíle
Evaluation of the the problem-solving process, the methods used and the goal to be met

The above mentioned main ideas of the dissertation are unfortunately not explicitly exactly formulated by the author. Firstly a state-of-the-art description is performed and also the problems of power semiconductor loss evaluation are briefly introduced. Thermal "impedance" dependent on time is defined and an electro-thermal analogy for modeling the thermal transients of a power semiconductor with heatsink is explained. The term "impedance" in the used meaning seems a bit strange from the formal theoretical point of view, maybe transient thermal resistance could be used. Standard Cauer and Foster models are introduced. Further standard chip temperature measurement methods used in the experiments are explained (thermistors, IGBT saturation voltage measurement, thermo-camera). Identification of the Foster model parameters was performed using the measured chip temperature time dependence during the cool-down phase with zero generated heat power. This important process is unfortunately not described transparently. An equation (2.10) is mentioned as the base for the identification of the parameters, but there is no equation (2.10) in the text. The equation (3.3) corresponds to the heating phase with a constant heating power but not the cool-down phase - so neither this could be the equation used for the Foster model parameters identification. The Figure 25 is confused and it does not correspond to the reality. Steady state thermal measurements and following calculation of thermal resistances were performed. Above mentioned three temperature measurement methods were compared. As the emissivity

at the measurement with the thermo-camera cannot be set precisely, this measurement has an off-set error compared to other methods, which is expectable. However author makes a wrong conclusion that the camera results (higher measured temperatures in his case) should be generally used to get higher safety reserve. In fact the camera must not provide the maximum (most pessimistic) values compared to other methods from principle - it depends on the emissivity setting. The rest of the work contains the core of the dissertation (chap. 4, 5 and 6) and its importance will be noticed below. But the ideas of proposed mathematical processes could be explained much more clearly and understandably.

Stanovisko k výsledkům disertační práce a k původnímu konkrétnímu přínosu předkladatele disertační práce
Statement to the results of the dissertation and on the original contribution of the submitter of the dissertation

I can see the main dissertation merit in chap. 4, where an identification method of a thermal ARX model of a power semiconductor module is created. A non-standard least square method is implemented there and a better accuracy compared to standard identification methods of thermal impedance is demonstrated. The originality of these results is also documented by author's contribution in an IF journal. A partial benefit can be seen in chap. 6, where an original derating method is proposed by the author (also for an application with cooling failure). Maybe the introduced derating algorithms could be finished in detail to make them usable for real applications.

Vyjádření k systematice, přehlednosti, formální úpravě a jazykové úrovni disertační práce
Statement to the systematics, clarity, formal adaptation and language level of the dissertation

As mentioned above the description clarity of solved problems could be much better. The quality of some figures is bad (e.g. Figure 17). There are a bit strangely formulated sentences in some places. But on the other hand the language of the thesis is rich and without substantial errors.

Vyjádření k publikacím studenta
Statement to student's publications

It is obvious from the list of references that author published the core of his dissertation sufficiently and in accordance with respected standards for dissertations. Anyway it is important to accent here that these currently standard criterions unfortunately are not relevant to compare technical skills and talent of authors. These qualities cannot be evaluated with any simple algorithm applicable for science officers without deep knowledge and technical skills. No objective criterion applicable for these evaluators can be found.

Celkové zhodnocení a otázky k obhajobě
Total evaluation and questions for defence

Based on the previous evaluation I definitely recommend this dissertation to the defense and I ask the author to answer following questions at the defense:

1. Please, explain the algorithm of identification the parameters of the Foster model from the cool-down phase dependence of the chip temperature on time, including used equations.
2. Please, present and explain a correct version of Figure 25.
3. Please, explain in detail what is the benefit of the method in chap. 4 compared to the Foster model with parameters identified previously. Please try to demonstrate the practical significance of the gained results from chap. 4 with some numbers.
4. Please highlight the overall benefit of Your work considering the fact that the time dependence of the transient thermal resistance can be usually found in the IGBT module datasheet, see e.g. Fig. 23 here: https://www.infineon.com/dgdl/Infineon-IGW60T120-DataSheet-v02_04-

EN.pdf?fileId=db3a304412b407950112b428250e3d74

Doporučuji disertační práci k obhajobě
I recommend the dissertation for the defence

YES

Datum
Date

14.8.2022

Podpis oponenta:
Signature of opponent