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A Review of the Computer Based Simulation of Electro-Thermal Design of Power Electronics Devices

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Abstract

Temperature is one of the most important factors that affect the performance of power electronics systems. It is important that thermal management is considered initially at the design stage of the systems. Because of its advantages of being low cost, high accuracy, and adaptable, computer simulation based analysis and design techniques have become important tools for power electronics designers. This paper presents the state of the art design and analysis techniques that are used for power electronics components and systems design. The focus is on the review of the existing computer based simulation of electro-thermal design solution techniques. Methodologies of electro-thermal modelling of power electronics systems such as converters are explored, their advantages and disadvantages of them are discussed and the benefits of computer based simulation over the existing methodologies are highlighted.

1 Introduction

Power Electronics is the application of solid-state electronics devices for the control and conversion of electric power. Power electronics plays a great role as a key driver of modern society, and as an enabling technology it has penetrated almost every sector of life and becomes a crucial part of communication equipment, renewable energy, automobiles, computers, motors, electric vehicles, and many other technologies. An example of power electronics systems is power electronic converter which transforms electric current/voltage from one form to another (e.g. from AC to DC).

The trends in power electronics systems manufacturing are towards producing products that are low in costs, light, compact, and integrated; and they can operate efficiently at high switching frequency and high operational temperatures, and are reliable in harsh application environment [1-3]. Some of the requirements for power electronics systems are contradictory and they pose great challenges to designers and manufacturers. More compact and more powerful systems result in high power dissipation density and therefore potentially high temperature. Electromagnetic interference may also increase in more compact systems. Higher switching frequency allows the use of smaller passive components which helps to reduce the product’s physical size and weight but parasitic inductance/capacitance may create more serious EMC problems. The challenges for designers are multitude and design techniques should be effective in taking all the factors into account.

In power electronics component and system design, reliability has always been an important issue [1-2]. As the volume of power electronics system shrinks, thermal energy dissipation density increases and the temperature may increase as the result. With the increasing temperature, the electronic components performance and reliability may suffer due to variations in the temperature dependent parameters. Therefore, good thermal management in design and operation not only improve the performance of the power electronic components but also reduce the thermally induced failures and thus enhance reliability.

The control of the temperature can be done using adequate cooling systems, active or passive but they add to the weight/size, manufacturing/operational complexity and costs. For instance, forced liquid cooling capacity can be improved by increasing the liquid flow rate but that increases the pressure and power consumption. It would be more economical to optimize the design in the early stage of the product cycle so that the demand for the cooling system is minimised.

Power electronics systems consist of components, interconnects and other packaging parts. Design for better thermal performance requires the understanding of the loss mechanisms of the components as well as the thermal path, and it also involves the understanding of the effects of temperature on the component characteristics as the latter may have significant impact on the losses which are the source of thermal energy [18, 29, 38, 41, and 49]. Only when the losses and temperature dependent behaviour models are known, the temperature can be predicted accurately.

The prediction of the performance of power electronics components/systems includes the analysis of the components or systems’ behaviours in multiphysics domains such as thermal, electric, mechanical, and electromagnetic phenomena. Because of the complex nature of these physical processes, design methods that are based on experiences may be inadequate and this is why computer simulations are now used more and more to analyze and design power electronics systems.
Inevitably, the physical processes in power electronics systems are coupled and changes in one process affect other processes. For example, if the current changes in a component, the temperature will change as the result and this temperature change then affects the electric/mechanical/thermal properties of the component itself as well as other components. In practice, however, analyses are often done in separate domains and for individual component [39-45].

The software packages that can be used to analyse power electronics systems include SPICE, Saber, Plecs, Matlab/Simulink, Caspoc, Simpleror, ANSYS, [6-13] and many others. As an example, the schematic structure of an IGBT power module is given in Fig. 1. The current can be predicted using circuit simulator such as SPICE. Finite Element software ANSYS or others can then be used to predict the electric current density distribution and this result can be used to predict the temperatures in the power module.

![Schematics of the structure of a power module.](image)

**Fig. 1: Schematics of the structure of a power module.**

2 Analysis Methods

Analysis methods are essential in the virtual design of Power Electronics systems. Any improvements of the design must be based on the results of the analyses on performance under given conditions. The methods can be physics based numerical methods [35,37-39,47] that provide detailed solutions, compact models [22,50] that is quick to give approximate solutions, lumped parameter circuit simulations [28-29] that solve electric current, simple analytical models [23-25] and empirical models [16,29] that are based on experimental results. Some authors suggested electro-thermal design of power module based on physically matched device model [37-39] which includes switching loss, power loss and the model requires detailed device modelling and very small simulation time steps and thus requires long computer time and memory. Temperature dependent parameters such as mobility, lifetime and intrinsic carrier concentration can also be modelled [36]. Another approach of design is to use analytical calculation that is based on device data sheet provided by manufacturers. This method is easy to use but it lacks accuracy [40].

Analytical 1-D and 2-D Fourier series solutions of heat equations is proposed to solve transient heat transfer problem in power semiconductor devices [23, 24]. In [24] a method of solving 3D heat transfer equation using Fourier series was also presented. The method was implemented and validated using FLOThERM and Simulink. The drawback of this method is that the temperature of unheated chip decreases even if adjacent chips are heated during fast transient period [24]. When more than one heat source is present, superposition principle can be applied, and the thermal impedance matrix is formed by combining the self-heating thermal impedance and mutual-heating thermal impedance [25].

Finite Element Method (FEM) [29, 32-33, 34, 44], Finite Difference Method (FDM) and Computational Fluid Dynamics (CFD) [5] etc. are numerical methods that are used to solve governing equations for electric, thermal, electromagnetic, and mechanical problems. They are powerful and can provide much more detailed and precise solutions for current density, temperature, electromagnetic field distribution in power electronics systems than, for example, analytical methods, but they are also time consuming and complicated. Szekley and others [50-52] proposed computationally efficient methods that are based on deconvolution and multi-exponential fitting techniques. For quicker analysis, compact (electro-thermal) method [22, 46, and 53] or model order reduction techniques can be used.

For the analysis of current flow and losses, SPICE type circuit simulators are powerful tools. PLECS is one of the circuit simulators that have been used in power electronics design analysis [8]. It simulates semiconductor devices and their thermal losses using ideal models for switching circuits. Analysis tool for magnetic design is also available in the software but it lacks the capability of coupling different domains [8]. CASPOC is also a circuit simulator for modelling power electronics systems. It uses switch models based on loss calculation, and its magnetic design tool provides the flux distribution that is based on geometry parameters of wound components [9]. Transient junction temperature or short-term overload temperature can be determined and EMI filter design is achievable through the use of GeckoCIRCUITS and GeckoMAGNETICS which provide design and modelling capability for inductive power components [10]. Another circuit simulator is SABER, it can deal with thermal, magnetic, and mechanical problems, but it can’t deal with the interactions of different domains, heat generation due to different domain interaction, electrical-thermal, electro-magnetic or EMI effect [11]. In an application of SABER, temperatures at different positions in an IGBT were predicted and the simulation results were compared with experimental results [16]. In another work, the step response was obtained from a transient thermal simulation and the time constant spectrum was then derived using deconvolution method and the RC network elements of a Foster network were calculated. 3D FEM was used to predict the temperature distribution of an SML5020BN device at t=1000s and the transient thermal response of the
SML5020BN device is obtained using Cauer/Foster network and finally the electro-thermal model of the step-up converter was then implemented in the Saber circuit simulator [17]. In order to simulate stationary and transient characteristics [26-30] conventional lumped parameterized RC networks are used widely and the network parameters can be extracted from FEM simulations or experimental data [28, 29].

In most power electronics components or systems, there are more than one heat source. It is therefore necessary to include thermal coupling in order to get accurate results. Numerical methods such as FEM and FDM can be used for the purpose but these methods may require dense discretization mesh for accurate results [14] and are therefore time-consuming in building the model, in running the simulation and in processing the results. A quicker method of thermal modelling is to use a network of equivalent resistors and capacitors to represent the thermal energy flow and thus temperature can be solved by using electric circuit simulators. Parameterization of the circuit elements can be done using measurements or computer simulation. Transient impedance can be derived from heating and cooling curves. The losses in semiconductor device model are entered into Cauer or Foster thermal network and the junction temperature can be determined by solving the network problem depicted in Fig.2 [18].

![Diagram](image)

**Fig. 2: Thermal Modeling of Power MOSFET [18, 49].**

This analysis using equivalent thermal circuit can also be implemented in MATLAB. In [21], IGBT’s voltage and current wave forms were inserted into a power loss evaluation model and the power loss is fed into a FEM thermal model to calculate the temperature which is then used as the input for a power loss evaluation model so that a parameterized RC thermal network can be formed. In [22], compact thermal model was developed for multi-IGBT devices that are mounted on a common heat-sink and the surface temperature of IGBT module with a single or double heat sources (both 100W) is simulated using FLOThERM.

The effective transient thermal impedance curves from manufacturers’ data sheets help to measure the peak junction temperature in devices. The curves are obtained using convolution method which is an analytical method that takes into consideration of the finite dimension of the die. Other authors [33] suggested the use of thermal networks that are based on the discretization of the heat equation using FDM or FEM, and they also developed an analytical model formulation of the heat diffusion problem considering boundary conditions and compared the solution offered by these methods. It turned out that the analytical model was not suitable for 2-D and 3-D thermal phenomena. In Yun and others’ work [34], 3D FEM was used to predict the thermal behaviour of an IGBT module mounted on water cooled heat sink. From the 3D temperature distribution results of the FEM analysis, an RC component network thermal model was developed. The time constants were calculated using Elmore delay which represents the propagation delay of heat flux through each physical geometry layer. This method can be coupled to a circuit simulator to analyse the electro-thermal behaviours of IGBT modules [34]. Luo et al developed a thermal model for a power IGBT module and introduced a parameter extraction method that relies on the transient junction-to-case thermal impedance and the transient case-to-ambient thermal impedance [29]. The accuracy of the approach was verified by comparing its predictions with the results of 3D FEM simulations.

### 3 Electro-Thermal Design of Converters

A power electronics converter converts electric power from one form to another. A converter typically consists of IGBT modules, inductors, capacitors, input and output EMI filters, gate driver circuit, controller and DSP/FPGA devices. An IGBT power module consists of a number of layers of different materials. Each layer can be represented as an RC network which is characterized by thermal resistance and thermal capacitance parameters. There are two types of networks: the Foster network and the Cauer network. A Foster network is constructed using thermal resistance and thermal capacitance parameters from data sheet of the device and the parameters do not have physical meanings. Cauer network is more practical and realistic and have full physical meaning. Every Cauer network has its Foster equivalent. Heat sources are modelled as voltage source in electrical equivalent circuit and heat transfer through different layers such as junction to case, case to sink, sink to ambient is represented by RC networks [40-45, 48].

Look up table based simulation approach has also been used in power electronics analysis. A look-up table contains the current and temperature dependent switching characteristics and conduction loss characteristics of IGBT and diode. From experimental transient thermal curves, IGBT and diode thermal resistance and time constants can be extracted and from these the thermal capacitance can also be calculated [22]. Zhou et al developed a compact thermal model of a three phase IGBT inverter power module (IPM) using Cauer and Foster networks. The thermal impedance parameters were determined from the results of 3D Flotherm simulation and the parameters were inserted into the compact thermal model matrix and the junction temperature...
4 Conclusions

Computer simulation has been widely used in power electronics analysis and design. Both high-fidelity methods such as FEM and faster compact model and analytical methods are all used by researchers to predict the junction temperature of the semiconductor devices. A typical way of combining high-fidelity method as compact model is to use FEM etc. to extract network parameters and then circuit simulators are used to solve the temperature. Great effort has been spent on developing efficient parameter extraction methods but the derived parameters do not have much physical meaning and therefore not transferable from one design to another. This means that for every design-iteration, the analysis process has to be repeated. The methods that have been used can't cope with some design changes efficiently and this is not suitable for design optimization where various designs must be investigated. Another weakness of the current research is in the multi-domain analysis of power electronics systems. Thermal, EMC etc. tend to be investigated independently. For accurate analysis and optimization of power electronics systems an integrated approach requires more attention.

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Literature


