Thermal Design Based on Surface Temperature Mapping

Erik C. W. de Jong, *Student Member, IEEE*, Jan. A. Ferreira, *Fellow, IEEE*, and Pavol Bauer, *Member, IEEE*

***Abstract*—A method of extracting a conservative thermal model from an existing PCB assembled converter is investigated. This improves upon thermal management by increasing the thermal management contribution of the PCB itself. A thermal calibration loop is proposed in which a given converter is analyzed and data extracted, in order to create a thermal map of the surface temperature from which the component layout and thermal profiles can be estimated. Thermal figures of merit are vital to quantify the thermal adjustments, recorded in this thermal map, which are required during thermal calibration. The thermal figures of merit are also flexible enough to allow for specific optimization objectives such as high power density, or overall reliability. Two graphical means to predict temperature profiles required in the thermal calibration loop have been investigated: a thermal resistor network method with a purely analytical approach, suitable for relatively small systems where the geometry and loss analysis are simple (fewer than ten components), or a more elaborate method using a finite difference method algorithm, implemented in a spreadsheet environment. Both provide flexible means for PCB thermal layout and provide straightforward graphical visualization. A case study illustrates the complete design method.**

***Index Terms*—AC–DC power conversion, design methodology, finite difference methods, optimization methods, thermal variables control.**

I. Introduction

THERMAL modeling has long been an unavoidable task in power converter design [1]. The need for this task, currently performed by means of cumbersome finite element analysis, grows stronger with the increasing demand for high power density and the continued advances made in electromagnetic and passive integration [2]. Therefore, a first-order analytical approach to address thermal modeling and surface temperature profiling is presented. This method is necessary to guide the combined electrical and thermal design in achieving set objectives, such as increased power density or improved system reliability. The method involves extracting thermal information from a converter and then systematically optimising for an objective by using the *surface temperature mapping* method developed here. A case study illustrating improvement of surface temperature uniformity of a power converter is also presented.

Manuscript received April 28, 2005; revised September 1, 2005. Recommended by Associate Editor D. J. Perreault.

The authors are with the Delft University of Technology, Delft, The Netherlands.

Digital Object Identifier 10.1109/LPEL.2005.860625

II. Thermal Design Approach

The design method starts by acquiring as much thermal and loss information from the converter as possible. A *thermal map of the surface temperature distribution* is then constructed by applying the *thermal design rating (TDR)* figure of merit, defined as $TDR = \exp\left[-4\left(T - T_{\rm optimal}/T_{\max} - T_{\rm optimal}\right)^2\right]$ where T, $T_{\max}$ and $T_{\rm optimal}$ are the actual, maximum, and optimal surface temperatures of a component, respectively [3], which guides the rest of the thermal calibration.[1]The construction of such a *thermal map* is addressed in Section II-A. Thereafter the thermal profile modeling and optimization are performed consecutively in Sections II-B and C.

A. Constructing a Thermal Map of the Surface Temperature Distribution

IR thermography and electrical loss analysis enable the calculation of an average surface temperature for each component in a converter. Thermally critical components are rated using thermal management figures of merit. A thermal profile is then obtained which provides graphical insight into the thermal characteristic of the converter. Together these act as the thermal guideline for thermal calibration. For example: Fig. 1 shows a conventional converter, its measured surface temperature[2] and constructed thermal profile. Table I lists the main thermal contributors, their measured surface temperatures, TDR and adjustment temperature required for each component to operate at its *optimal*[3] temperature, labeled the *surface temperature map*. It differs for every objective set by the figure-of-merit system.

B. Thermal Profile Modeling

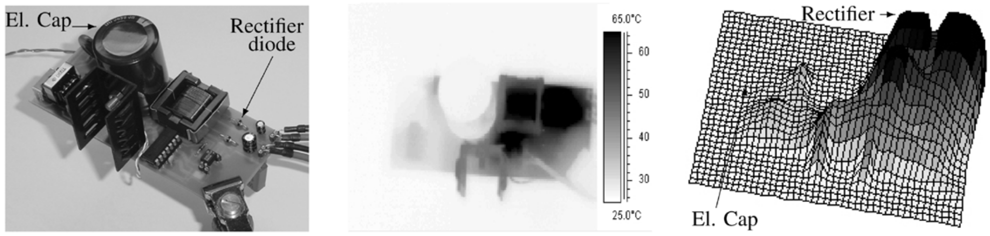
A component position-dependent temperature profile model is required to optimize the layout of the converter toward a set objective, such as, e.g., power density, by creating a uniform temperature distribution along the converter outer surface. Two methods to obtain this, one based on an analytical resistive network model and the other on a finite difference method algorithm [5], [6], are discussed next.

1) Resistive Network Analysis: A generalized thermal resistive network model, incorporating PCB layout and component

[1]Determining these component-specific temperatures remains challenging as they are susceptive to specific optimization criteria.

[2]With IR thermography, avoid inaccurate results due to component emissivities [4] by covering the system in a monochromatic coating as done in [3].

[3]according to the definition of optimal for a set thermal design objective, as discussed in [3]



(a) Conventional converter (b) Surface temperatures (c) Surface temperature profile

Fig. 1. Result of thermal data extraction performed on conventional PCB assembled power converter using IR thermography.

TABLE I
THERMAL MAP OF CONVENTIONAL CONVERTER FOR TWO SEPARATE OBJECTIVES

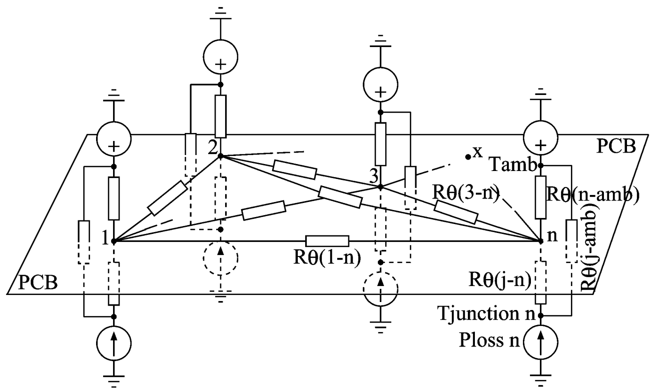
Component	**Filter Capacitor**			**Snubber**		**Coupled**	**Bridge**	**Rectifying D**		**MOSFET**
	Input	**+12V**	**+5V**	**C**	**R**	**Inductor**	**rectifier**	**+12V**	**+5V**	**switch**
Average Surface Temp.[$^{\circ}C$]	27.5	60.0	68.8	112.0	112.0	72.0	38.0	103.0	114.0	50.0
Design objective: Power Density										
$\boldsymbol{TDR}$[%]	0.27	71.47	99.53	0.32	99.00	98.82	2.4×10^{-4}	88.47	96.07	1.2×10^{-2}
Adjustment Temp. $\Delta T[^{\circ}C]$	**+42.5**	**+10.0**	**+1.2**	**-42.0**	**-2.0**	**+3.0**	**+72.0**	**+7.0**	**-4.0**	**+60.0**
Design objective: Reliability										
$\boldsymbol{TDR}$[%]	51.20	87.62	62.67	0.62	37.78	81.42	37.78	57.26	33.90	64.12
Adjustment Temp. $\Delta T[^{\circ}C]$	**+22.5**	**-10.0**	**-18.8**	**-62.0**	**-37.0**	**-17.0**	**+37.0**	**-28.0**	**-39.0**	**+25.0**

loss characteristics, is shown in Fig. 2(a). It consists of thermal resistors representing the thermal pathways present in a converter, focussing primarily on the thermal transportation role of the PCB. A conservative estimate is made by considering only thermal conduction to, from and through the PCB, and thermal convection from component to ambient in a naturally cooled environment. Each node on the PCB represents an average surface temperature of a single component (corresponds to entry in thermal map). The thermal resistor network comprises the sum of all the resistors at and between each of the component nodes, namely between the point of dissipation (junction) and the surface component node x, $R_{\theta(j-x)}$; between the surface component node and the ambient, $R_{\theta(x-amb)}$; between the surface component node and all its neighboring surface component nodes $y = 1, 2, \ldots n$ on the PCB, $R_{\theta(x-y)}$; as well as directly between the point of dissipation to the ambient (through the component packaging, bypassing the PCB), $R_{\theta(j-amb)}$. The inter-node thermal resistances are calculated using the relation for 1-D conductive heat transport, $R_\theta = l/\lambda A$, with l and A the appropriate geometrical dimensions when considering the thermal pathway, and λ the thermal conduction coefficient of the appropriate thermal conducting material. Two situations are distinguished as shown in Fig. 2:

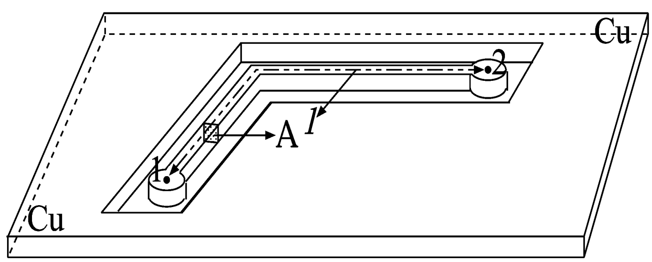
- Nodes *are* electronically connected by means of a good thermal conductor (copper track). Thermal conduction is assumed to take place only inside this conductor. The copper track cross-sectional area, A, and the track length, l, are used in combination with the thermal conductivity of copper, see Fig. 2(b); and
- nodes are *not* electronically connected. Thermal conduction is assumed to take place only in the isolation layer. The equivalent PCB tangential, cross-sectional area, A, and inter-node distance, l, are used in combination with the thermal conductivity of the isolation, typically FR4, see Fig. 2(c).

The node-to-ambient thermal resistances are calculated using the relation for convective heat transport, $R_\theta = 1/h_c A_s$, where h_c is the convective transfer coefficient and A_s the convective surface of the respective component. A loss analysis [7] performed on the electrical circuit reveals the dissipation of each component, modeled as a current source *Ploss* at each node.

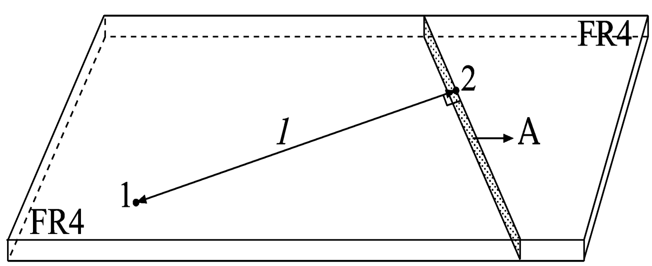
2) Finite Difference Method: A two-dimensional (2-D) component geometry and PCB layout can be modeled by applying a fixed mesh structure to the converter and conveying it into any spreadsheet application by first applying a set dimension to each spreadsheet cell and then associating a single spreadsheet cell with each meshed cell on the converter. The outline of all the spreadsheet cells belonging to a single component in the converter can then be marked, either by outlines or colored cells, as shown in Fig. 3(a), for the converter shown in Fig. 1(a). A finite difference method (FDM) algorithm is



(a) General thermal resistor network model



(b) Nodes on the PCB are electrically connected



(c) Nodes on the PCB are *not* electrically connected

Fig. 2. General thermal resistor network model with legend to calculate inter-node thermal resistance values.

then applied to all the spreadsheet cells modeling the converter. Each corresponding spreadsheet cell is programmed to start with an initial temperature value (obtained from a surface temperature measurement) and by iteration calculate the change in temperature due to its neighboring cells and internal component dissipation (obtained from loss analysis), using the discrete form function for thermal conduction:

$$T_x = \frac{\sum_{i=1}^{n} \frac{T_i}{R_{\theta(i-x)}} + Q_x}{\sum_{i=1}^{n} \frac{1}{R_{\theta(i-x)}}}$$

where Q_x is the Δ Energy in cell $x[W]$, n is the $=$ Number of neighboring cells: four for 2–D or six for three-dimensional (3-D), and $R_{\theta(i-x)}$ is the Thermal resistance between cells i and $x[K/W]$. Two- and 3-D analysis are possible by proper choice of n. The latter requires multiple spreadsheet layers to model different cross sections of the converter. A surface plot of the spreadsheet cells representing the converter directly incorporates the geometric layout of the PCB and reveals the thermal profile in the third dimension, shown in Fig. 3(b).

C. Thermal Calibration

The thermal map, constructed from the thermal data extraction and figure-of-merit criteria in Section II-A, together with the interactive thermal profile model, acquired from any of the two methods described in Section II-B, guides the thermal calibration of the PCB layout [8]. Component positions are then varied intuitively[4]and the thermal profile recalculated, until all components exhibit their optimal surface temperature. The initial thermal profile provides isotherms on the PCB layout which guide component placement at first; iteration then leads to an optimal PCB layout for the set objective.

D. Synthesis and Evaluation

After a satisfactory thermal PCB layout has been achieved, the converter is constructed and, by means of electrical loss measurement and IR thermography, the result can be evaluated. The evaluation should then be based on a comparison between the thermal management figures of merit for the initial and improved converter designs.

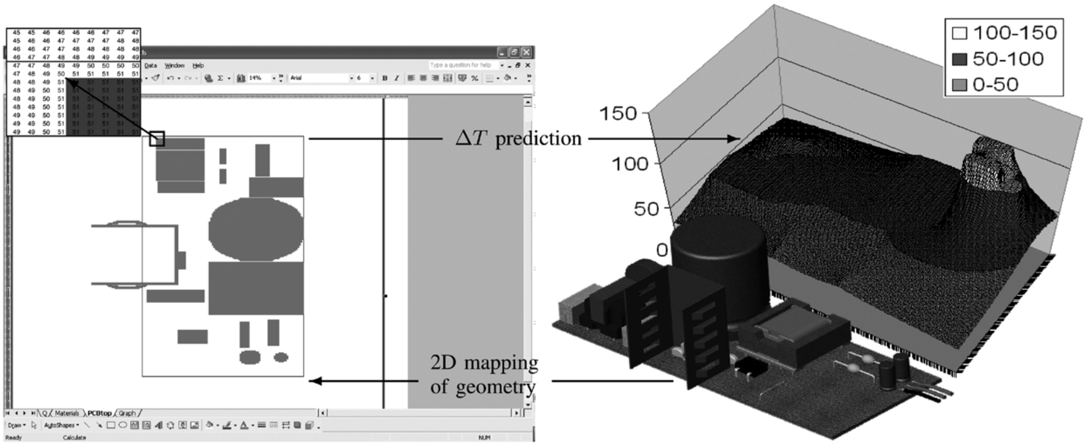
III. Case Study: FDM Method

A case study illustrating the proposed thermal design method, applied to a Flyback converter, is summarized in Fig. 4. Proceeding clockwise from the bottom left. Thermography of the conventional converter under full load. Thermal steady-state conditions reveal the surface temperatures of the ten main thermal contributors as well as the thermal map. The associated thermal profile is then used to improve the 2-D FDM model constructed from the PCB and component geometries. Thermal calibration [9], with the objective set to obtain a high power density by establishing a uniform temperature distribution on the outer surfaces of the converter, leads to a PCB layout, modeled in FDM, as shown in the top right hand corner of Fig. 4 with the associated solid model and predicted thermal profile. Notice the absence of a heatsink for the MOSFET switch. Flexible PCB technology [2] allows folding the converter to allow heat sharing amongst components and to use the enhanced thermal conduction capability of the PCB as a convective surface. The improved converter, with a much greater uniform temperature distribution, results. It is shown complete with measured surface temperature and thermal profile. The thermal performance evaluation based on thermal figures of merit is listed in Table II, completing the thermal calibration loop.

IV. Conclusion

Thermal model extraction for conservative, first-order, thermal design where PCB technology as well as component geometry can be exploited toward a predefined objective has been investigated. A systematic approach, using previously derived thermal management figures of merit, guides the design and thermal calibration process. Two graphical means to predict temperature profiles have been investigated: a thermal resistor

[4]A concise algorithmic description of the layout position falls outside the scope of this publication.



(a) Representation of conventional converter implemented in a spreadsheet to predict its 2D thermal profile
(b) Conventional converter layout along FDM predicted 2D thermal profile of the PCB top surface

Fig. 3. FDM implementation of a temperature profile model.

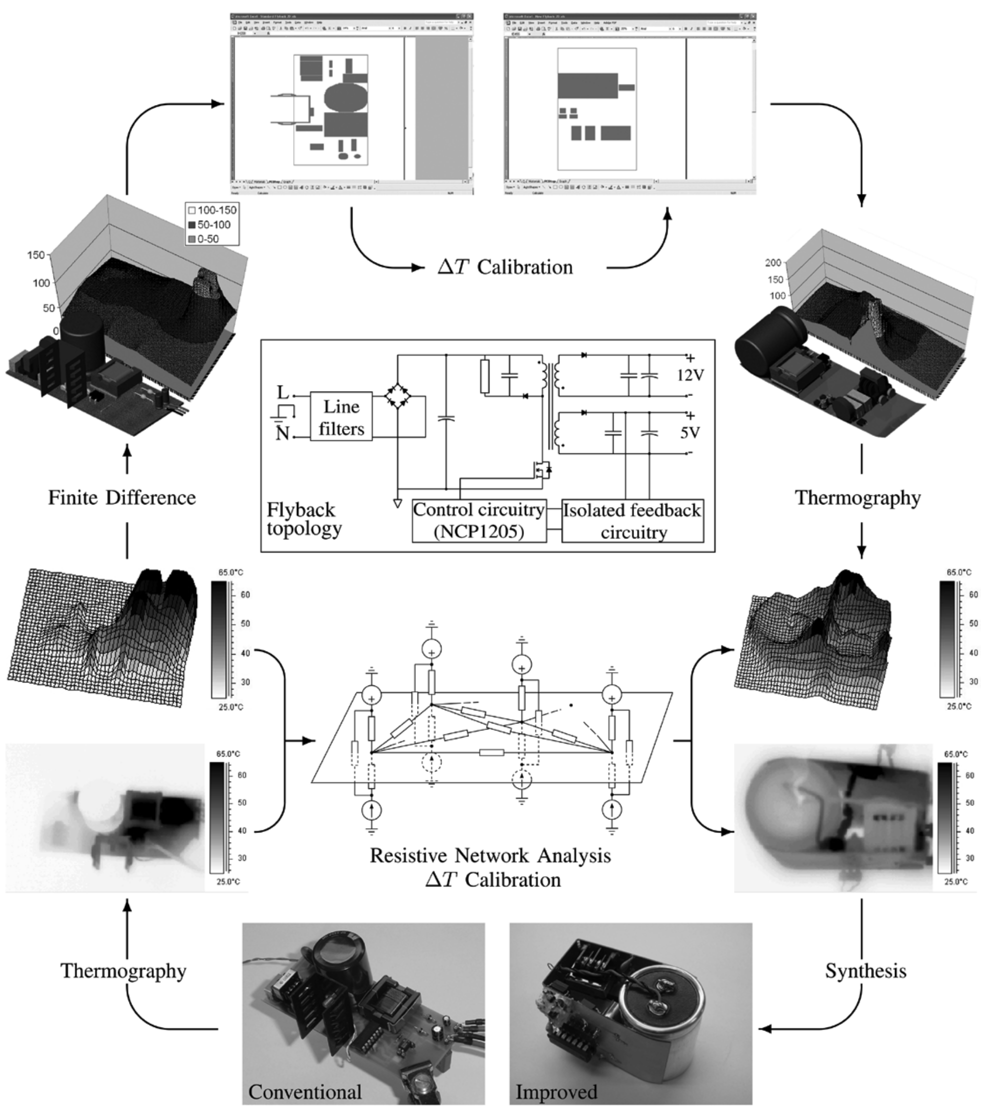


Fig. 4. Overview of model extraction method to improve the thermal management of PCB assembled power converters.

TABLE II
THERMAL PERFORMANCE OF IMPROVED CONVERTER

Component	**Filter Capacitor**			**Snubber**		**Coupled**	**Bridge**	**Rectifying D**		**MOSFET**
	Input	**+12V**	**+5V**	**C**	**R**	**inductor**	**rectifier**	**+12V**	**+5V**	**switch**
Surface Temp. [$^\circ C$]	40.3	53.0	53.8	60.3	70.6	51.4	49.0	80.4	80.0	76.8
Design objectives, TDR[%]										
Power density	5.6	38.9	42.4	73.5	2.0	47.8	0.00091	11.18	10.54	6.3
Reliability	88.3	98.8	98.1	86.9	98.6	99.1	64.8	98.2	97.9	99.7

network method with a pure analytical approach, suitable for relatively small systems where the geometry and loss analysis are simple (up to a few components), or a more elaborate method using a finite difference method algorithm, implemented in a spreadsheet environment. Both provide flexible means for PCB thermal layout and provide straightforward graphical visualization.

REFERENCES

[1] A. Walker and D. Williams, "Thermal design considerations in the design and application of DC-DC converters," in *Applied Power Electronics Conf. and Exposition*, vol. 2, Mar. 1996, pp. 990–996.

[2] E. de Jong, J. Ferreira, and P. Bauer, "Improving the thermal management of AC-DC converters using integration technologies," in *IEEE Industry Applications Conf.*, vol. 4, Oct. 2004, pp. 2315–2322.

[3] ——, "Evaluating thermal management efficiency in converters," in *Power Electronic Specialist Conf.*, Jun. 2004, pp. 4881–4887.

[4] (2003) Surface Temperature Measurement. Luxtron Corporation, Santa Clara, CA. [Online]. Available: www.luxtron.com

[5] R. Babus'Haq, H. George, P. O'Callaghan, and B. Constant, "Thermal management of electronics: problems and analytical techniques," *Comput. Aided Eng. J.*, vol. 7, no. 1, pp. 23–26, Feb. 1990.

[6] D. Jamieson, A. Mansell, J. Staniforth, and D. Tebb, "Application of finite difference techniques for the thermal modeling of power electronic switching devices," in *Power Electronics and Variable-Speed Drives Conf.*, Oct. 1994, pp. 313–318.

[7] R. Erickson and D. Maksimović, *Fundamentals of Power Electronics*, 2nd ed. Dordrecht, The Netherlands: Kluwer, 2001.

[8] J. Lohan, P. Tiilikka, P. Rodgers, C.-M. Fager, and J. Rantala, "Experimental and numerical investigation into the influence of printed circuit board construction on component operating temperature in natural convection," *IEEE Trans. Compon. Packag. Technol.*, vol. 23, no. 3, pp. 578–586, Sep. 2000.

[9] E. de Jong, J. Ferreira, and P. Bauer, "Thermal model extraction as means to thermal management improvement in PCB assembled power converters," in *Power Conversion Intelligent Motion (PCIM) Conf.*, Jun. 2005, pp. 240–245.