

Thermal Modeling of a Multilayer Integrated LC Filter for Temperature Distribution Calculation

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How to cite this paper: Coulibaly, S., Ambroise, D.K. and Georges, L. (2019) Thermal Modeling of a Multilayer Integrated LC Filter for Temperature Distribution Calculation. *Engineering*, 11, 759-767.

<https://doi.org/10.4236/eng.2019.1111050>

Received: October 1, 2019

Accepted: November 12, 2019

Published: November 15, 2019

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Abstract

Thermal behavior of integrated passive components has become an important issue when designing these components. This paper presents the thermal modeling of a multilayer integrated LC filter used in DC-DC step-down converter for temperature distribution calculation. The approach used for this analysis is based on thermal equivalent circuit. Temperature distribution is obtained from algebraic equation, which is in vector and matrix form. The results of analytical calculation are compared with simulation results from finite element method. These results showed a good correlation.

Keywords

Thermal Modeling, Integrated LC Filter, Temperature Distribution, F. E. M. Simulation

1. Introduction

Thermal design of electronic components and systems is to ensure that the temperature rise caused by the losses remains within acceptable limits. In power electronic converter, temperature causes around 54% of all the converter failure [1]. It is therefore necessary to investigate the structures of the integrated LC passive module thermally to guarantee reliable operation of the integrated power module. Thermal modeling and simulation have become essential parts in process design. These integrated components are essentially magnetic components. Modeling these components provide good study of investigation of the temperature evolution through the integrated component.

However, modeling magnetic components requires knowledge of electromagnetic losses. These losses are due to current flow in the windings (“copper losses”), to the temporal variation of the magnetic field in the magnetic cores (“iron

losses”) and to link (“connection loss”). Due to the complexity of determining these losses, many approaches are used to investigate the temperature evolution inside the integrated component.

In this paper, we propose compact thermal model that can be integrated into mathematical tools to achieve temperature distribution across the integrated LC component. Calculation of temperature distribution is based on the assumption that the temperature line is linear under steady state.

In order to verify the results of the thermal resistance network approach, it is compared to thermal Finite Element Method simulation.

2. Integrated LC Filter Overview

The studied integrated LC filter is shown in **Figure 1** [2] [3]. It consists of a PCB planar inductor sandwiched between two ferrite layers, and a capacitive part made of ferrite multilayer capacitors. The ferrite layers are flexible ferrite sheets used for both inductor magnetic core and capacitor dielectric medium. Inductor and capacitor parts are stacked together in series connection to give the integrated LC component.

3. Thermal Modeling of the Integrated LC Filter

The thermal analysis of an integrated component consists of studying its ability to evacuate heat to the outside. The purpose of such a study is to predict the risks of overheating of the different materials.

If one side of a solid is warmer than the other side, then heat flow goes through the body from the warmer side to the cooler one. Heat flow mechanism through a solid material is illustrated by **Figure 2**. Difference temperature from inside the component to outside consists of heat conduction and heat convection.

The rate of heat loss is given by [4]:

$$Q = \frac{\lambda \cdot A \cdot (T_1 - T_2)}{d} = \frac{T_1 - T_2}{R_{th}} \quad (1)$$

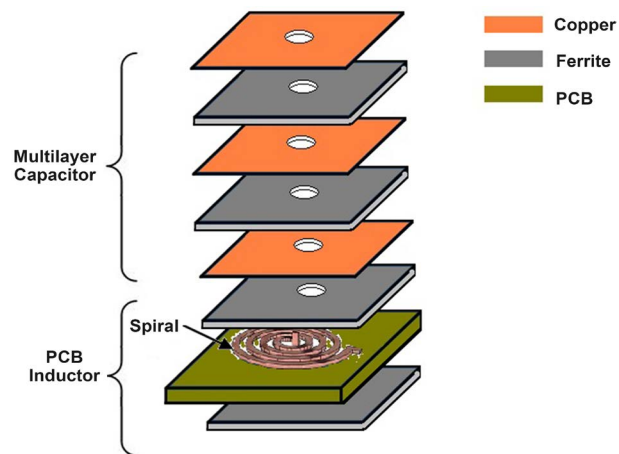


Figure 1. Exploded view of the structure [3].

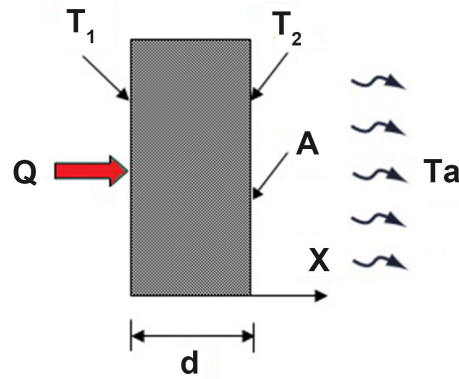


Figure 2. Heat Flow illustration in a solid material.

where:

$R_{th} = \frac{d}{\lambda \cdot A}$ is the thermal resistance of the solid [K/W];

Q = the heat flow [W];

T_1 and T_2 = the temperatures at the ends of the solid material [K];

d = the thickness crossed by the heat source [m];

A = the surface of the heat source [m²];

λ = the thermal conductivity of the material [W/(m·K)].

On the outside surface of the solid material, heat transfer is mainly heat convection which is conducted between air and the surface. It can be obtained based on the Newton's law of cooling [4]:

$$Q = h \cdot A \cdot (T_f - T_a) = \frac{T_f - T_a}{R_{th}} \quad (2)$$

where:

Q = rate of heat flow (W);

$R_{th} = \frac{1}{h \cdot A}$ is the thermal resistance for convection (K/W);

h = convective heat transfer coefficient (W/m²K);

A = cross sectional area (m²);

T_f = surface temperature (K);

T_a = ambient temperature (K).

The thermal system of **Figure 2** can be converted into an equivalent electrical system as shown in **Figure 3** where voltage plays the same role as temperature (Equation (1)).

R_{th1} is the thermal resistance of the solid for conduction; R_{th2} is the thermal resistance for convection.

Since Q is constant throughout the network, it follows that:

$$Q = \frac{T_1 - T_2}{R_{th1}} = \frac{T_2 - T_a}{R_{th2}} \quad (3)$$

Knowing the heat flow Q , the ambient temperature T_a and the solid material properties, the unknown temperatures T_1 and T_2 can be calculated.

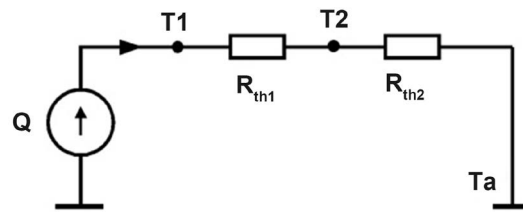


Figure 3. Equivalent thermal model.

This concept of thermal resistance circuit can be easily applied to the multi-layer integrated LC component.

The heat source generated inside the component by the spiral winding copper is drained towards ambient air taking two dissipation paths as shown in Figure 4. In this representation, we considered that capacitor part of the integrated LC filter is made of two layers of ferrite material for demonstration purpose. In practice, number of ferrite layers depends on the value of capacitor.

Knowing the loss in the spiral winding, the thermal model must allow determining the operating temperature in some points of the component along the heat flowing path.

Thermal modeling of an integrated multilayer structure is quite complex. To simplify the modeling of this component, we make a number of assumptions [5]:

- Each layer must satisfy the heat conduction equation.
- Steady state conduction;
- One-dimensional heat flow;
- Constant properties of materials;
- Uniform heat flow in each layer;
- Perfect contact between layers;
- Perfectly flat layers with uniform thickness;
- Component boundaries (top and bottom faces) convect heat to the ambient on both sides.

From the cross section view of the structure shown in Figure 4, the equivalent thermal model of the structure can be represented as interconnection of the thermal resistance of each layer as in electrical circuit (Figure 5).

In this representation, R_{thcu} , R_{thfe} and R_{thFR4} stand for the thermal resistances of copper, ferrite and PCB layers, respectively.

The conduction path 1 consists of seven resistors: $R_{thcu}/2$ (resistance between the center of the conductor and its lower surface), R_{thfe} (resistance due to the ferrite layer) and R_{thcu} (resistance due to the copper layer).

The conduction path 2 consists of two resistors: $R_{thcu}/2$ (resistance between the center of the conductor and its upper surface), R_{thFR4} (resistance due to the epoxy PCB) and R_{thfe} (resistance due to the ferrite layer).

The temperature at the center of the conductive spiral is noted T_{max} and T_{cu} is the temperature at each face of the spiral windings. The temperatures T_1 and T_2 are the temperatures on the outer flat faces in contact with the ambient air. Heat transfer exchange is convection on these faces.

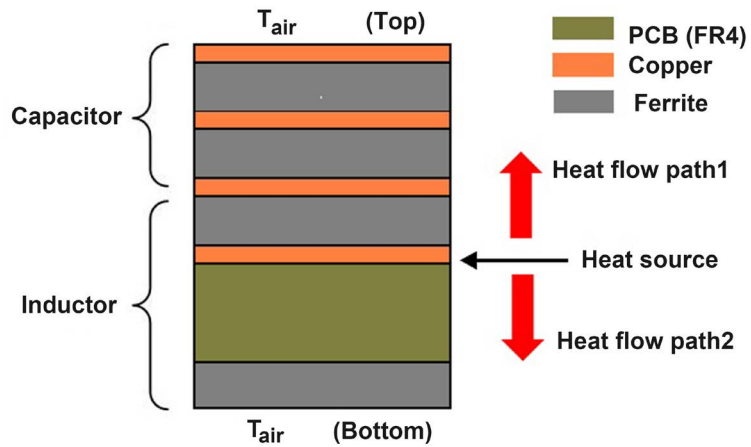


Figure 4. Cross section of the integrated LC component showing heat flow paths from heat source to the outside.

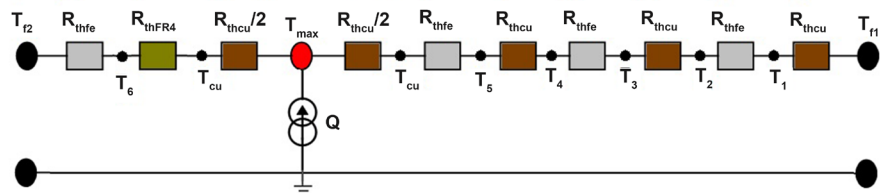


Figure 5. Integrated LC component thermal model.

Because of the high thermal conductivity of the copper and its small thickness (35 μm), the temperature may be considered as uniform inside the spiral winding, and then T_{cu} and T_{max} are equal. We can therefore neglect the thermal resistance $R_{thcu}/2$ on each side of T_{max} . This leads to the reduced model circuit shown in Figure 6.

The heat source Q generated by the copper spiral winding at the node T_{max} is spread into two heat sources Q_1 and Q_2 such that $Q = Q_1 + Q_2$ because of energy conservation.

Finally, the problem is to determine temperatures T_{max} , T_1 , T_2 , T_3 , T_{f1} and T_{f2} from the knowing thermal resistors R_{thfe} , R_{thFR4} , R_{thcu} and the generated heat Q . Temperature T_{air} is fixed by forced or natural convection on both flat faces of the integrated LC component.

Under the above assumptions, temperature distribution can be calculated from the following equations:

$$Q_1 = K_{fe} \cdot (T_{max} - T_2) = K_{fe} \cdot (T_2 - T_1) \tag{4}$$

$$Q_1 = K_{fe} \cdot (T_2 - T_1) = K_{fe} \cdot (T_1 - T_{f1}) \tag{5}$$

$$Q_1 = K_{fe} \cdot (T_1 - T_{f1}) = h \cdot A \cdot (T_{f1} - T_{air}) \tag{6}$$

$$Q_2 = K_{FR4} \cdot (T_{max} - T_3) = K_{fe} \cdot (T_3 - T_{f2}) \tag{7}$$

$$Q_2 = K_{fe} \cdot (T_3 - T_{f2}) = h \cdot A \cdot (T_{f2} - T_{air}) \tag{8}$$

$$Q = K_{FR4} \cdot (T_{max} - T_3) + K_{fe} \cdot (T_{max} - T_2) \tag{9}$$

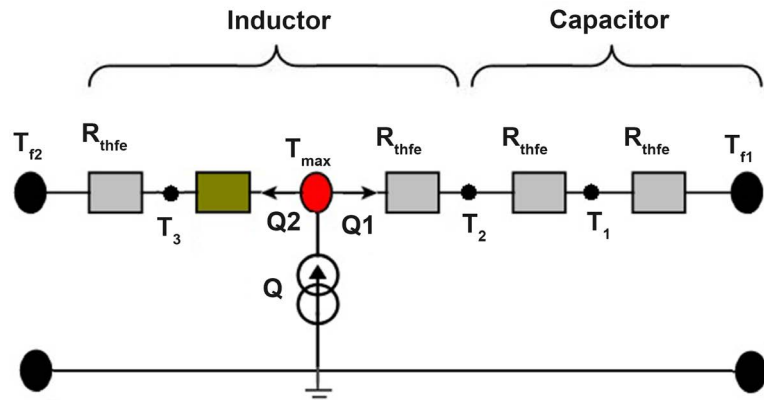


Figure 6. Reduced thermal model of integrated LC component.

where h [W/(m²·K)] is the coefficient of heat transfer by convection, A [m²] the area of the layers of materials, K_{FR4} and K_{fe} are defined as the thermal conductance (inverse of thermal resistance) of PCB and ferrite layers, respectively.

These simultaneous equations can be rearranged by putting unknown parameters (T_{f2} , T_3 , T_{max} , T_2 , T_1 , T_{f1}) on one side and the known ones on the other side. This leads to the matrix equation $[K_{th}] \times [T] = [F]$ represented by Equation (10) where K_{th} is matrix of thermal Conductance, T the unknown temperature vector and F the heat source vector.

$$\begin{bmatrix} 0 & 0 & K_{fe} & -2 \cdot K_{fe} & K_{fe} & 0 \\ 0 & 0 & 0 & K_{fe} & -2 \cdot K_{fe} & K_{fe} \\ 0 & 0 & 0 & 0 & K_{fe} & K_{fe} \\ K_{fe} & K_{fe} & K_{FR4} & 0 & 0 & 0 \\ -(K_{fe} + h \cdot A) & K_{fe} & 0 & 0 & 0 & 0 \\ 0 & -K_{FR4} & K_{FR4} + K_{fe} & -K_{fe} & 0 & 0 \end{bmatrix} \times \begin{bmatrix} T_{f2} \\ T_3 \\ T_{max} \\ T_2 \\ T_1 \\ T_{f1} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ -h \cdot A \cdot T_{air} \\ 0 \\ -h \cdot A \cdot T_{air} \\ 0 \end{bmatrix} \tag{10}$$

The unknown nodal temperatures are given by the following relation:

$$[T] = [K_{th}]^{-1} \cdot [F] \tag{11}$$

The solution can be obtained by using numerical calculation software such as MATLAB.

4. Results and Discussions

To verify the solution of the analytical method, “Heat Flow Problem” module of FEMM software [6] [7] has been used. The values of the properties of the materials used in the design of the integrated LC filter are given in **Table 1**.

Calculated thermal resistance and their corresponding thermal conductance are given in **Table 2**.

These calculations were made by considering the spiral winding copper as a uniform disk with 60 mm for diameter. That gives an exchange area $A = 2.83 \times 10^{-3}$ m².

Table 1. Thermal conductivity λ of different materials.

Material	λ [W/mK]	Thickness (mm)
PCB_FR4	0.3	1.6
Copper	401	0.035
Ferrite	1.5	0.2

Table 2. Values of thermal resistance and corresponding thermal conductance.

Material	Thermal resistance ($^{\circ}\text{C}/\text{W}$)	Thermal conductance ($\text{W}/^{\circ}\text{C}$)
PCB_FR4	$R_{thcu} = 3.08 \times 10^{-5}$	32,394
Copper	$R_{thFR4} = 0.707$	21.206
Ferrite	$R_{thf} = 0.047$	1.413

Since for the design of the integrated LC filter, inductor and capacitor values needed depend on material thicknesses and properties, the calculation of the temperature at each of the six nodes involve three parameters which are:

- Ambient temperature near top and bottom faces;
- Convective heat-transfer coefficient on faces f_1 and f_2 ;
- Generated heat source Q inside the component.

Keeping constant power dissipated inside the component, temperature distribution will depend on convective heat-transfer coefficient (h) and ambient temperature (T_a).

Assuming constant power $Q = 1$ W dissipated inside the component in an environment of temperature $T_a = 30^{\circ}\text{C}$, the effect of convective heat-transfer coefficient on temperature rise inside the integrated LC component will be studied.

For the convective heat-transfer coefficient (h), four different physical situations [8] may be presented:

- $h \rightarrow \infty$, when outer temperature is fixed at the ambient value;
- $h = 100$ W/m²/K, representing forced convection;
- $h = 10$ W/m²/K, representing natural convection;
- $h = 0$, representing adiabatic operation.

Temperature distribution for analytical calculation and FEM through the component for each physical situation of the heat-transfer coefficient is presented in **Table 3**.

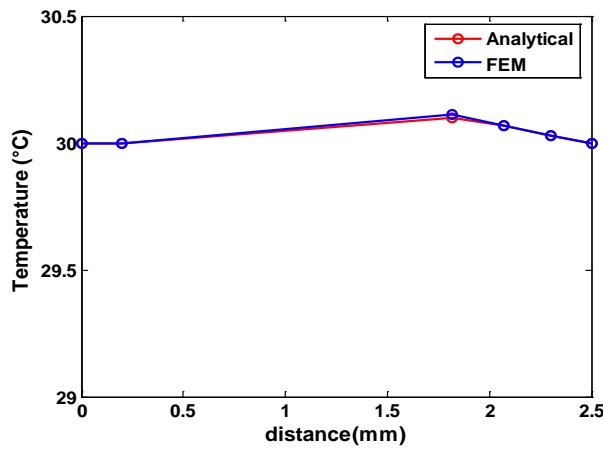
Results of analytical calculation and FEM solution are shown in **Figures 7(a)-(c)**.

Calculation and simulation for $h = 0$ have not been reported, since temperature are unrealistically high for the multilayer integrated LC component.

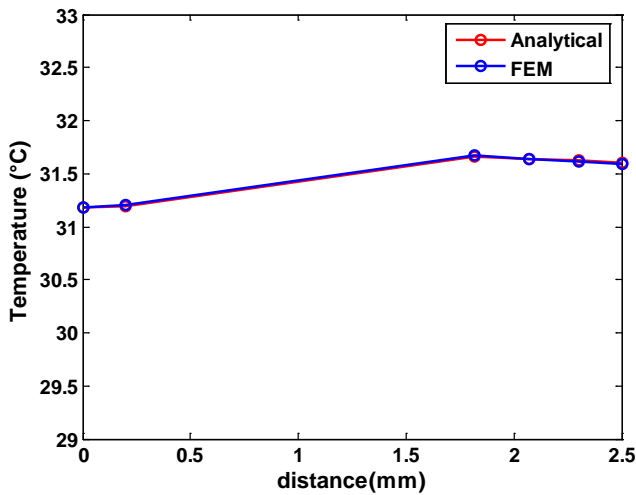
The above table shows that the result obtained from analytical calculation and FEM simulation are very close. The agreement between the FEM solution and the analytical calculation is graphically demonstrated in **Figure 7**. Maximal temperature inside the multilayer integrated component depends on the type of convection on outer surface. Difference temperature between T_{\max} and top outer face is small due to the weak thermal resistance of the ferrite layers.

Table 3. Comparison between Analytical and FEM results of temperature distribution.

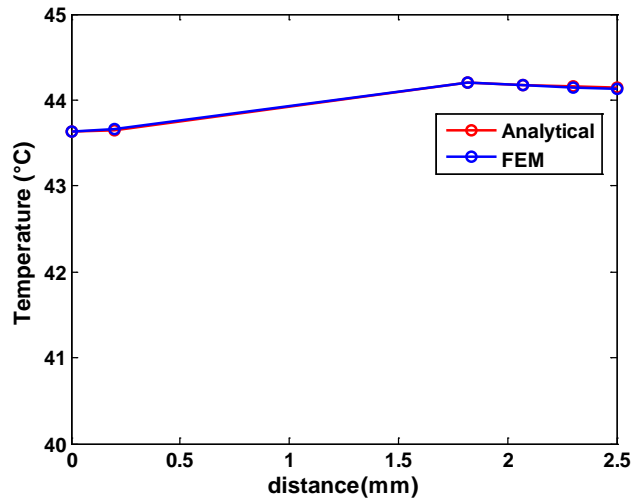
Temperature [°C]	$h \rightarrow \infty$		$h = 100 \text{ W}/(\text{m}^2\text{K})$		$H = 10 \text{ W}/(\text{m}^2\text{K})$		Distance [mm]
	Analytical	FEM	Analytical	FEM	Analytical	FEM	
T_{f2}	30.00	30.00	31.17	31.18	43.63	43.64	0
T_3	30.00	30.00	31.19	31.20	43.65	43.66	0.2
T_{max}	30.10	30.11	31.66	31.67	44.19	44.20	1.82
T_2	30.06	30.07	31.64	31.64	44.18	44.18	2.07
T_1	30.03	30.03	31.62	31.61	44.16	44.15	2.30
T_{f1}	30.00	30.00	31.60	31.59	44.14	44.13	2.54



(a)



(b)



(c)

Figure 7. Comparison between analytical and FEM results of temperature distribution: (a) $h \rightarrow \infty$, (b) $h = 100 \text{ W}/(\text{m}^2\text{K})$, (c) $h = 10 \text{ W}/(\text{m}^2\text{K})$.

From these results, it can be observed that for one-dimensional steady state heat conduction problem with uniform heat generation, thermal resistance approach can be used to investigate the temperature distribution inside the multi-layer integrated LC component.

5. Conclusion

In this paper, temperature distribution in a multilayer integrated LC has been carried out using conduction and convection heat transfer. Temperature distribution in the different material layers has been determined from thermal resistance approach knowing the generated heat source and multilayer material properties. Numerical validation of the results of the established model was done using heat transfer module of the FEMM software. A good correlation between analytical calculation using Matlab software and finite element method simulation tool for the temperature distribution in the integrated LC component has been observed according to the assumptions made.

Acknowledgements

The authors would like to thank Tanoh Aka for his useful discussions.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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