

THERMAL MANAGEMENT OF A PLANAR MAGNETIC MICRO-TRANSFORMER

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ABSTRACT

This paper reports a numerical and experimental study of micro-transformer thermal behavior in a cell-phone charger. A detailed thermal analysis of the charger has been presented. In the end some thermal solutions for spreading the hot spot temperature have been outlined. It is shown that this thermal solution strategy can reduce the touch temperature by 13 C at high line. Based on thermal simulation some heat sinking approaches have been proposed which drastically reduced the transformer temperature.

Key words: Thermal management, planar magnetic transformer, heat spreading, touch temperature, geometric optimization method.

INTRODUCTION

One of the main objectives of a 3D shape optimization in electronic industry is to place components in a system volume in such a manner that the overall system volume becomes as small as possible. To achieve this objective, the issue of placing as small as possible components inside the system has already been identified as a crucial measure for volume optimization [1-6]. Thermal management is defined as a procedure by which the temperature of all components should be maintained at or below the allowable operating temperature, while satisfying electrical, volumetric and safety protocols.

Excessive components temperature is one of the principal causes of power supply failure. This can cause malfunctioning of components or in some cases may lead to complete system failure [2]. In addition, the undesired temperature rise can reduce the life cycle of components drastically. Due to these concerns much attention is directed towards the thermal management of power supplies. The other factor that puts more constraints on the thermal management in electronic industry is the miniaturization. The current trend in portable charger is towards volume reduction strategies. Volume reduction plays an important role in reducing the transport and

packaging cost [3]. However, the volume reduction has an undesirable effect on the surface temperature, commonly known as the touch temperature.

To achieve volume reduction or geometric optimization, a thorough understanding of the components sizes is necessary. The bulky components will dominate the charger volume and will ultimately determine the final shape of power supplies. Transformer is one of the components that occupies significant volume portion inside cell-phone chargers. This paper reports an experimental and numerical study of the thermal performance of a micro-transformer for use in 5 W cell-phone chargers. The transformer is of planar magnetic type and is 19 mm in length, 9 mm in width and 5 mm in height. This kind of transformers is well adapted for low profile design where the usage of heat sink can be easily incorporated. A detailed thermal management of the charger and transformer has been presented. The importance of geometric features of transformer on the thermal behavior of charger is highlighted and emphasized experimentally. Thermal maps of charger have been presented and problem areas are particularly emphasized. The temperature evolution curves for components are obtained experimentally. Some heat transfer enhancing strategies are put forward. In the follow up, the results of micro transformer which uses planar magnetic technology have been compared with wire-wound transformer. The thermal behaviors of these transformers are analyzed and some new figures of merit have been proposed. These figures can be used to achieve better thermal designs and in some cases show in which cases usage of heat sinks are necessary.

In the follow up, some heatsinking strategies are put forward which can reduce the transformer temperature drastically. A thermal solution for spreading the hot spot temperature has been proposed. It is shown that this thermal solution strategy can reduce the touch temperature (case temperature) between 9C to 13 C.

The paper is organized in the following manner: numerical and experimental. In the numerical part the feasibility of the usage of planar transformer inside a

charger is sought. Based on approximate dissipation values the component temperatures were determined. Later in the experimental section, the temperature evolution curves were obtained. Finally, some heatsinking and heat spreading solutions have been proposed which were proven very effective in reducing the temperature.

FEASIBILITY STUDY

In this part of the study, we examine the feasibility of the design. Based on proposed geometric dimensions and proposed shape, we will determine if the proposed design will satisfy the thermal criteria. So, before manufacturing we check the feasibility of the proposed design. Our first approach is the numerical analysis of the proposed design.

Numerical Results

In this section we report numerical results for thermal simulation of a 5 W power supply. Our objective is to determine if the power supply will behave normally under the ambient condition (35 °C) and the temperature of components will not exceed a certain limit. This is very important for life expectancy of the components and its safety. The mass, momentum and energy equations were written in three dimensions and the Boussinesq approximation in the momentum equation has been considered. The working fluid is air and the efficiency of power supply is 0.72. We may write the three dimensional steady state equations as:

$$\begin{aligned}\nabla \cdot \vec{V} &= 0 \\ \vec{V} \cdot \nabla \vec{V} &= -\frac{1}{\rho} \nabla P + \nu \nabla^2 \vec{V} + g\beta(T - T_0)\vec{z} \\ \vec{V} \cdot \nabla T &= \alpha \nabla^2 T\end{aligned}\quad (1)$$

where $\nabla^2(\cdot) = \partial^2(\cdot)/\partial x^2 + \partial^2(\cdot)/\partial y^2 + \partial^2(\cdot)/\partial z^2$. The associated boundary conditions are:

$$\vec{V} = 0 \quad \forall M \in \partial\Omega \quad \text{and} \quad -\lambda \nabla T \cdot \vec{n} = h[T(M \in \partial\Omega) - T_0]$$

Where h is the heat transfer coefficient ($h=10\text{Wm}^{-2}\text{K}^{-1}$) and $T_0 = 35^\circ\text{C}$ the reference temperature. The computational domain and a schematic of the charger are represented in Figure 1.

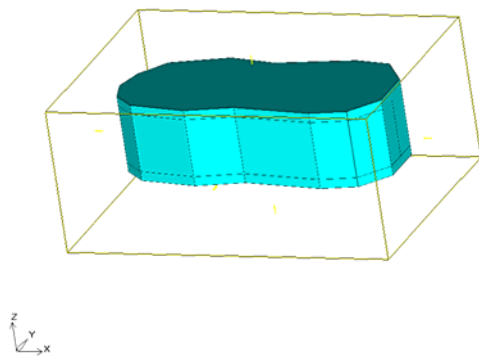


Figure 1. Geometric features of problem

In order to solve this coupled system of equations, we need the power dissipations related to the components; some of these values are estimated and presented in Table 1.

It should be pointed out that transformer is of multi-layer (here we used 16 layers) type PCB plus copper shields. Transformer has been modeled in a detailed manner. Later when it was put in charger we made use of a simplified version.

Components	Function	Power loss (W)	Temperature (°C)
C1	Primary capacitor	0.04	80
C2	Primary capacitor	0.04	80
C6	Primary capacitor	0.04	80
M	Transformer	0.2	103
L	Rectifier	0.1	84
Q2	Transistor	0.12	93

Table 1. Power loss of selected components

Figure 2a illustrates the thermal map of this power supply.

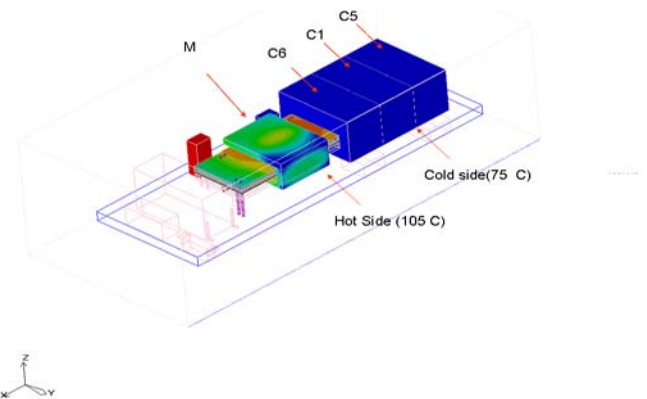


Figure 2. Thermal map of charger

One of the important messages of figure 2 is existence of a cool region around the primary capacitors. We will see later that we may use this as a part of simple heat sinking idea to reduce the temperature of transformer.

Figure 3 represents the touch temperature. As can be observed from the figure the region above the transformer forms the hot spot region.

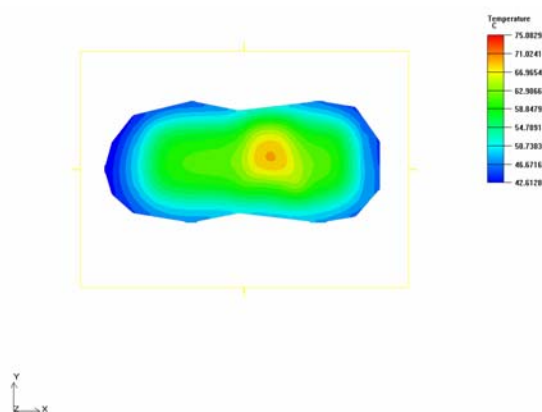


Figure 3. Touch temperature

It should be noted that system of equations (1) has been solved using Icepak computer code. The number of nodes and elements used are 844586 and 823495 respectively. For generating mesh, hexagonal unstructured elements have been used.

PROTOTYPE DESIGN

In this section, we investigate a power supply prototype for this micro-transformer. The focus will be on the thermal behavior.

Experimental Results

The experimental setup consists of a kidney shaped power adapter, with a length of 67mm, height of 13mm and width of approximately 30 mm. The experiments are performed at high line (230V) and low line (110V). For this purpose we used a Chroma programmable AC loader (model 6314). This loader can provide a wide range for the input power. In order to measure the input power, a Chroma digital power mete (model 6314) was used. Finally, for simulating DC load, we used the DC loader Chroma 631.

In order to study the thermal behavior of a cell-phone charger, we made use of K-type thermocouples. These thermocouples are placed on main components in the adaptor through small holes which were bored in the casing of the charger. These holes were then tightly sealed.

In addition we measured the ambient temperature and casing temperature, too. Care has been taken so that the air flow will not disturb the temperature measurement readings. The ambient temperature is 23 C.

Figure 4 illustrates a prototype (visual charger) where planar magnetic transformer has been used.

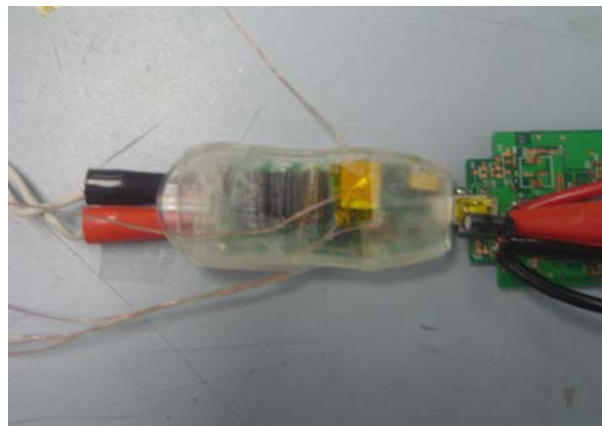


Figure 4: Prototype (visual charger)

We can see the position of some of the thermocouples. The temperature evolution of the components is presented in Figure 5.

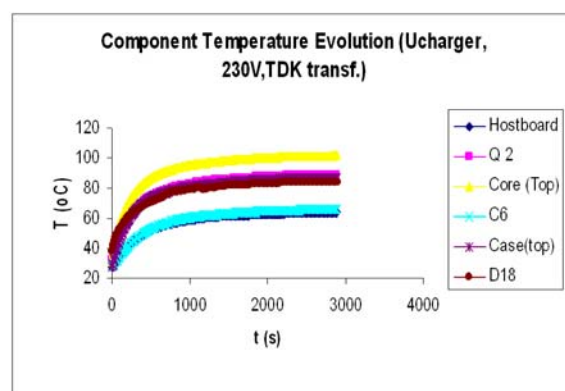


Figure 5: Temperature evolution of the components

As can be seen, the components reach steady state after approximately half an hour.

Here for a comparison purpose, we compared the thermal behavior of planar transformer with a wire-wound one.

Charger With wire- wound transf. Temp. (C)	Host board	Q2	Transf.	C6	Diode	Eff.
	70.5	88.4	95.59	71.1	98.9	0.754

Table.2 : Temperature of components in charger with wire-wound transformer

Table 2 shows the component temperatures of a charger with wire-wound transformer while table 3 shows the thermal behavior of the charger with planar magnetic transformer. As can be seen the performance is comparable.

Charger With planar transf. Temp. (C)	Host board	Q2	Transf.	C6	Diode	Eff.
	70.7	85	100.3	70.9	99.2	0.745

Table.3: Temperature of components in charger with planar magnetic transformer

In Figure 6, efficiency evolutions of the two chargers with different transformers are presented. As can be seen from this figure, charger with planar magnetic transformer more temperature dependant.

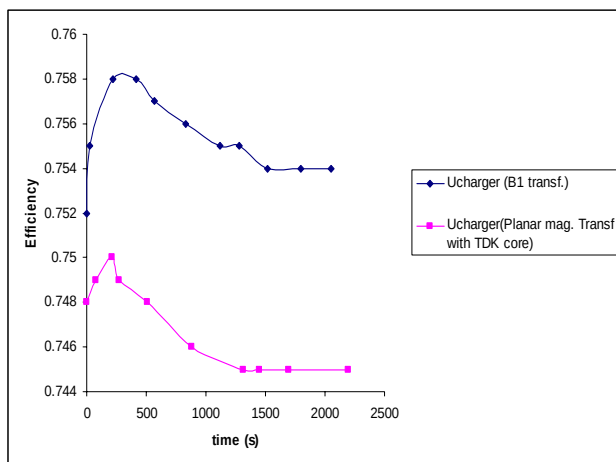


Figure 6: Comparison of efficiency curves between wire-wound transformer and planar magnetic transformer

Thermal Solutions

1. Usage of heatsinks

A quick look at results of the previous section shows that we can use heat sinks to decrease the temperature of the charger, see Figure 7.

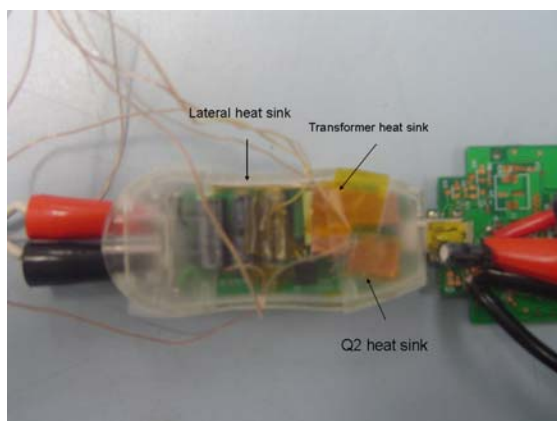


Figure 7: Prototype with heat sink

The temperature evolution curves are presented in Figure 8a. The most interesting feature of this figure is that the curves are very compact which clearly shows the effect of heatsinking. In addition there is a significant reduction in components temperature.

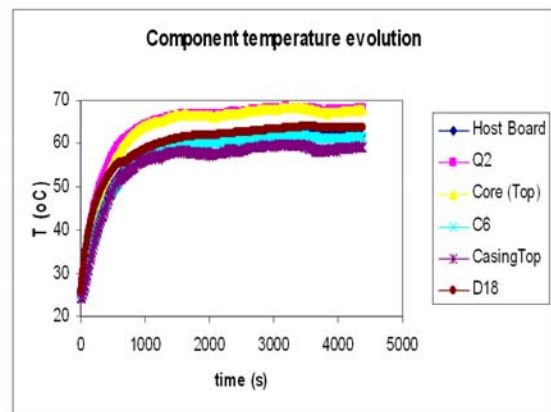


Figure 8a: Components temperature evolution at low line
The steady state temperature of components is presented in table 4:

Charger With heatsink	Host board	Q2	Trans.	C6	Diode	Case
Temp.	62.38	68	67.98	61.7	64	59
(C)						

Table 4: Temperature of components with heatsink (low line 110V)

The experiment is repeated at high line and the results are presented in Figure 8b.

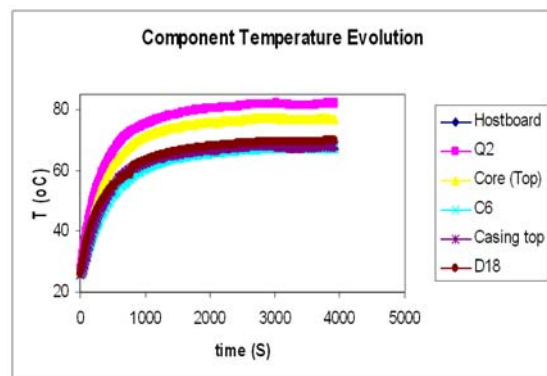


Figure 8b: Temperature evolution of the components in charger with heatsinks (high line 230V).

The steady state temperature of components is illustrated in table 5:

Charger With heatsink	Host board	Q2	Trans.	C6	Diode	Case
Temp.	67.4	81.1	78.8	67.7	67	69.87
(C)						

Table 5: Temperature of components with heatsink (230V)

The results of high line show the same behavior as low line. It is evident that heat sink has drastically reduced the temperature of transformer.

2. The usage of PCB as a heat spreader

Among the goals of the thermal management work, was the desire to obtain a thermal solution that keeps the power supply case temperature (touch temperature) below some specified value at some predetermined ambient temperature.

As can be seen from Table 4 and 5, the temperature of the casing is at the limit (low line) and exceeds the limit under the high line condition. As a way of addressing this issue other temperature reducing strategies were explored.

One such mechanism involves minimizing the standoff height of the transformer. It has been shown elsewhere how the geometric features can enhance heat transfer [7, 8]. The rationale for this empirical approach is to use the host board as a heat spreader.

It was determined that the distance between bottom of the transformer and the PCB board has a direct impact on the temperature of the casing, see Figure 9.

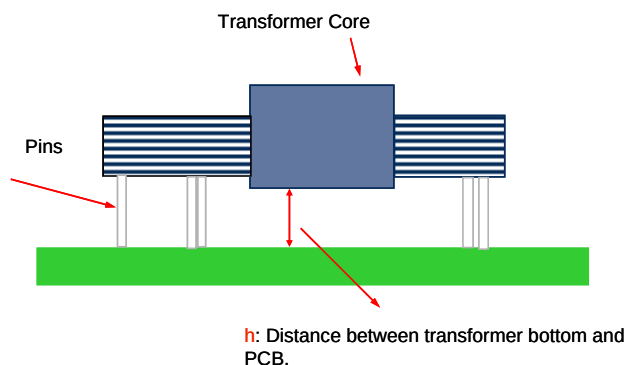


Figure 9: Important geometric features of planar transformer

As can be observed from figure 9, h the distance between the transformer core bottom and the PCB host board is an important parameter. This geometric parameter was used as a variable and its effect on the thermal behavior of the system was determined. The thermal behavior of charger was determined experimentally in two different cases ($h=3\text{mm}$ and $h=0\text{mm}$).

The findings for $h=3\text{mm}$ are presented in Figure 10:

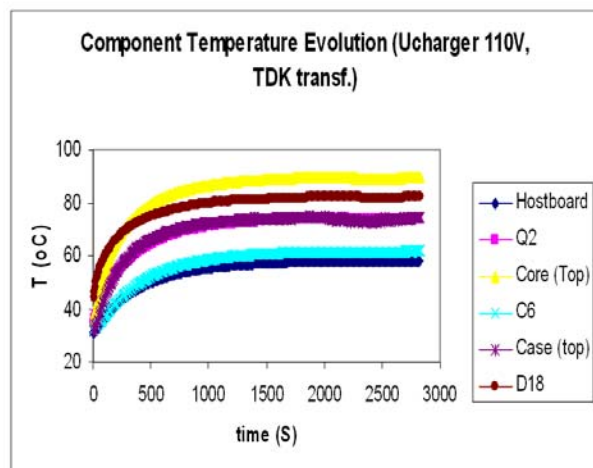


Figure 10: Component temperature evolution at low line (h the distance between transformer bottom and PCB is 3 mm)

The components at steady state temperatures are presented in table 5:

Trans. $h=3\text{mm}$	Host board	Q2	Trans.	C6	Diode	Case
Temp.	68.14	89.52	89.52	61	82	74
(C)						

Table 5: Steady state temperatures of components and casing top at $h=3\text{mm}$ (h is the distance between transformer bottom and PCB) at low line

Temperature evolution of components at low line is presented in Figure 10.

Figure 11 represents the case where transformer core is in direct contact with the host board.

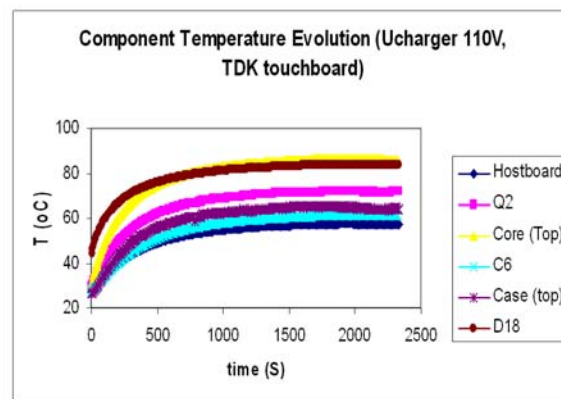


Figure 11: Component temperature evolution at low line (when h , the distance between transformer bottom and PCB is 0 mm; touch board case)

The steady state temperature is presented in table 6:

Trans. $h=0\text{mm}$	Host board	Q2	Transf.	C6	Diode	Case
Temp.	57.59	71.72	85.79	61	83.42	64.13
(C)						

Table 6: Steady state temperature of components and casing top at $h=0\text{mm}$ (h is the distance between transformer bottom and PCB) at low line

As can be seen from temperature results of table 4 and 5, the repositioning of the transformer has decreased the case temperature by ten degrees and decreased the transformer core temperature by five degrees.

These experiments were repeated at high line (230V). Figure 12, shows the temperature evolution at $h=3\text{mm}$ (where h is the distance between transformer bottom and PCB board)

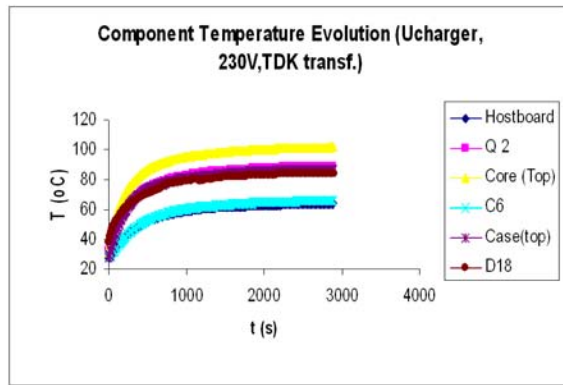


Figure 12: Component temperature evolution at high line (where h, the distance between transformer bottom and PCB is 3 mm)

To better illustrate the repositioning of the transformer, the steady state temperature results are presented in table 7:

Trans. h= 0 mm Temp. (C)	Host board	Q2	Tran.	C6	Diode	Case
	64.18	88.86	101.49	65.87	89.93	86.14

Table 7: Steady state temperature of components and casing top at h = 3 mm (h is the distance between transformer bottom and PCB) at high line

The case where, the transformer touches the PCB is illustrated in Figure 13.

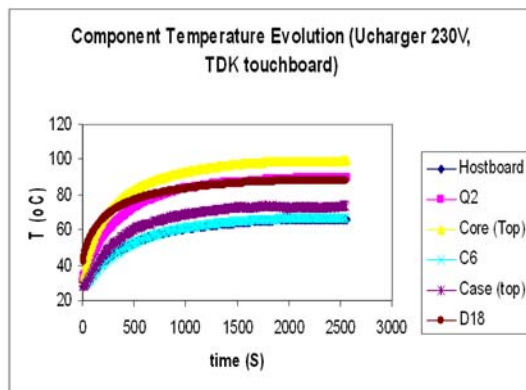


Figure 13: Component temperature evolution at high line (h the distance between the transformer bottom and PCB is 0 mm, touch board case)

The steady state temperature corresponding to this case is represented in table 8.

Trans. h= 0mm Temp. (C)	Host board	Q2	Transf.	C6	Diode	Case
	66.23	89.69	99.19	66.68	88.14	73.74

Table 8: Steady state temperature of components and casing top at h = 0 mm (where h is the distance between the transformer bottom and PCB) at high line

By placing the transformer in direct contact with the hostbord, a 13C reduction in casing temperature at high line is achieved. A potential concern with this method is safety issues, which was not the case in our study.

CONCLUSIONS AND DISCUSSIONS

In this paper a comprehensive thermal analysis of a 5W cell-phone charger has been carried out. The study is numerical as well as experimental. A micro-transformer of 19 mm in length, 9 mm in width and 5mm in height has been fabricated and used. The planar magnetic transformer performance was proved comparable with wire-wound transformer.

Planar magnetic transformers have this capability that they are well adapted for the utilization of the heat sinks. In the studied case, the heat sink can reduce the transformer temperature by 10 C. Furthermore, it was shown visually how we can distinguish a good heatsinking by the compactness of components temperature evolution curves.

In the follow up, it is shown that by using the geometric features of transformer (the distance between transformer core and host board), the casing temperature can be reduced by 13 C.

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