Peltier Cells Cooling System for Switch Mode Power Supply

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Abstract

The results are presented of an experimental investigation in a liquid cooled Switch-Mode Power Supply (SMPS). The target is a quantitative analysis of the performance of a cooling system designed to dissipate the heat generated by the active and passive electronic components of this SMPS, in order to limit its maximum operational temperature. The active components are cooled with a liquid cold-plate. The passive components are cooled with an air flow. The temperature of this airflow is controlled with Peltier cells coupled to the cold-plate. Measurements are made of temperature and of electric efficiency of the SMPS. The cooling system is placed in an experimental tool where it is possible to measure and control the cooling liquid flow. A detailed analysis of the thermal behaviour of this cooling system is given. Finally, the practical significance of the problem is discussed.

1 Introduction

Nowadays, in power supply electronics when high efficiency, small size and low weight are required, switching regulators are used as replacements for traditional (linear) regulators [1]. A Switch-Mode Power Supply (SMPS) is an electronic unit incorporating a switching regulator to convert electrical power efficiently. Unlike more conventional power supplies, a SMPS minimizes the wasted energy and ideally dissipates no power. This higher efficiency in power conversion is an important advantage of SMPSs, commonly coupled to smaller size and lower weight than a linear supply, due to smaller size and lower weight of the transformer.

High electric efficiency and reduced cooling requirements are thence the main characteristics of a SMPS [2-3]. However, as usual in power electronics, compactness means larger power; for larger power the heat release is large again and thus efficient cooling systems are needed to avoid overheating. The main effects of an excessive temperature increase in a SMPS can be referred to a shorten expected life of the capacitors, a degradation in the insulation of the windings in the inductors, an increase of core losses in the inductors, a shorter life of the MOSFETs [4]. Furthermore, for a safe and effective behaviour of the transformer, an acceptable temperature rise must be guaranteed [5]. Due to limitations of size, the transformer often is the most overheated component of an SMPS.

As an efficient cooling system, liquid cooling can become an interesting solution, also because it allows a significant size reduction of the equipment in line with the requirements of electronics design [6, 7].

Actually liquid cooling is obtained with cold-plates, consisting of a plate, usually in aluminium, on which are fixed some electronic components and within which one or more hydraulic circuits are obtained for their cooling with water flowing in forced circulation [8]. While it is easy to collocate the active components on a cold plate, the large passive components of a SMPS, like condensers, transformers and coils, need to be placed on a printed circuit board (PCB). It is difficult with a cold plate to maintain both PCB and passive components at the design temperature, because they are originally developed for air cooling.

In a previous paper we presented [9] the results of a thermal analysis in a liquid cooled SMPS for digital TV power amplifiers. Since this SMPS was characterized by high power and high compactness, thereby making the standard cooling techniques difficult to be used, a new cooling system was developed, using at the same time water and air as the cooling media. In particular, the active components (MOSFETs) were cooled with a liquid cold-plate, and the passive components (condensers, transformers, coils) with an air flow. This was cooled in a large finned surface, in turn cooled with the cold-plate. Finally, the water was cooled with a low cost external heat exchanger.

Unfortunately, this solution is limited by the ambient air temperature, fixing the lower bound to the temperature distributions. When the ambient air temperature is high it can result the need to distribute the air on the passive components at a lower temperature. To obtain this result a new configuration was developed, where the air flow is still cooled in a large finned surface, the latter being cooled with the cold-plate through a set of Peltier cells. The utilization of Peltier cells in power electronics is not a new; a large review of these applications is given by Zhao and Tan [10]. However, our proposal [11] is outside of the traditional schemes of application of the Peltier cells, because we do not use them to directly cool the power components, but to integrate liquid and air cooling.

In the present paper we present the results of an experimental investigation of the performance offered by this new cooling system specifically designed to dissipate the heat generated by the active and passive electronic components in a SMPS, in order to understand how to limit its maximum operational temperature.

2 Experiment

In [6] the experimental set-up is described in full details. For this reason here just a short description of its main characteristics is given. On the opposite, a detailed description of the new test section is reported.

2.1 Experimental set-up

The experimental set-up consists of a hydraulic testing circuit where we can insert a test section, in this case the cold plate holding the SMPS to be tested. The operating conditions of the SMPS were simulated with a dummy load connected to the output. To identify the components that are thermally stressed, twenty-five thermocouples were placed in the most significant points of the apparatus. To qualify the performance, both the thermal power exchanged with the cooling water and the electric power dissipated in the dummy load, consumed from the electricity network and absorbed by the thermoelectric modules, were measured. The data acquisition of temperature, flow rate and electrical parameters was carried out with a multimeter Agilent HP34970A. This multimeter was connected to a notebook by means of a GPIB-USB interface. The data acquisition was carried out by means of a software developed in Labview environment.

2.2 Test section

The SMPS (3 kW, +25 ÷ 50 V) accommodates a mix of surface mount and traditional technology components to reduce the space occupied as far as possible. The SMPS is protected in temperature and current. It was originally designed for air cooling. Nevertheless, just a limited number of modifications was necessary to place the SMPS on a cold-plate. The modifications were particularly simple, because the active components (MOSFETs) were originally placed on the finned vertical sides of the SMPS. We dismounted the fins and placed the MOSFETs in direct connection with the cold-plate. A top view of the cold plate with its PCB is shown in Figure 1.

The cold plate is used as the base of a closed enclosure where a flow of air is maintained by a pair of fans. Sides and cover of the enclosure are in transparent polycarbonate. The forced flow is used to cool by forced convection the passive components placed on the PCB. They are characterized by a significant volume occupation and cannot be directly cooled on the cold plate. Among the passive components, the ones that mostly contribute to heat release are: a transformer, three coils and two large electrolytic capacitors.

The cold plate (“press-fit” type) is the same used in [9], consisting of an aluminium plate (thickness 10 mm) where a cooling circuit is manufactured with a copper pipe (external diameter 6 mm) pressed in a channel machined on the surface of the plate. The pipe runs longitudinally along the sides of the plate. Inlet and outlet are on the same side (Figure 1). On the opposite side, the pipe is bent to form a coil (Figure 2). Over the coil an aluminium finned heat sink is placed (base 151 × 157 mm). The fins (31) are 30 mm high, 135 mm long, 1 mm thick and are separated by a 3 mm throat.

Between the finned heat sink and the cold-plate 12 Peltier cells are inserted to cool the flow of air. The cells were chosen with a rectangular shape (50 x 25 mm), so as to follow the development of the pipe and overlay as much as possible the pipe itself, with a limited protrusion over the plate, as shown in Figure 2. A thin thermal interface is placed between Peltier cells, heat sink and cold plate. The main characteristics of the commercial Bismuth Telluride-based Peltier cells (Kryotherm TB-195-1.0-0.8) are: I_{max} = 5.8 A, V_{max} = 24.1 V, Q_{max} = 86 W. In the thermoelectric cooler (TEC) the Peltier cells are arranged in four groups of three in series; the four chains are then in parallel. The current in each cell is thence one forth of the total.

In front of the finned heat sink two fans (external sides 50 × 50 mm) collect the warm air from the passive components of the PCB and push it into the finned cooling surface.

Compared to the test section described in [9], besides the use of the Peltier cells, some further changes were made. The PCB was rotated of 180° for reasons of electrical layout.

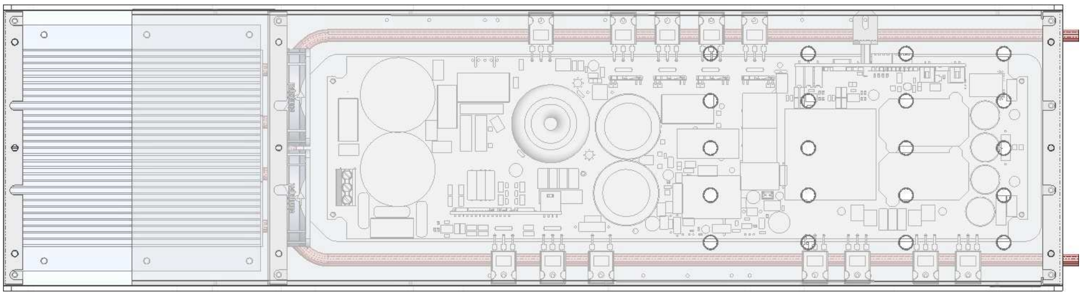

Figure 1: Top view of the cold plate with the PCB and the cooling system.

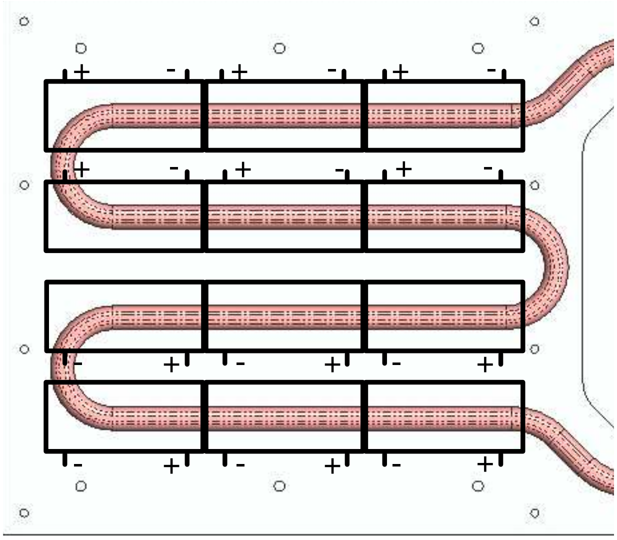

Figure 2: Top view of the Peltier cells distributions on the cooling system of the cold plate.

Furthermore, to better ventilate the thermally stressed components, the perforated wall directing the airflow on the PCB was modified by reducing the number of holes, now concentrated into a smaller area (Figure 1). For these reasons a direct comparison of the temperature data shown here with those reported in [9] is not possible.The passive components (capacitors, inductances and electric transformers) were instrumented with “T type” thermocouples, in order to evaluate the maximum temperature in the SMPS. Two armoured “T type” thermocouples were placed upstream and downstream of the finned heat sink to measure the temperature of the internal air flow. Two armoured “T type” thermocouples were placed upstream and downstream of the cold plate to calculate, together with the complementary data gathered with an ultrasonic flowmeter, the total heat released by the SMPS.

The values of electric power absorbed by the SMPS, by the Peltier cells and dissipated in the dummy load were measured in order to evaluate the power conversion efficiency of the SMPS and the EER (Energy Efficiency Ratio) of the thermoelectric cooler.

The power conversion efficiency is calculated as the ratio of the useful power output to the power absorbed from the electric grid. EER is calculated as the ratio of the cooling power to the power absorbed by the Peltier cells.

Since on the cold plate insist both the thermoelectric cooling system and the active components, a set of preliminary measurements was performed to evaluate separately the cooling power of the MOSFETs and that exchanged with air in the finned heat sink.

3 Results and Discussion

The performance of the thermoelectric cooling system are discussed in terms of efficiency and EER. The efficiency is calculated as the ratio of the useful power output to the power absorbed from the electric grid:

$$\varepsilon = \frac{Q_{DL}}{Q_{SMPS} + Q_{TEC}} \tag{1}$$

where:

Q_{DL} is the power dissipated on the dummy load;
Q_{TEC} is the power needed by the thermoelectric cooler;
Q_{SMPS} is the power absorbed by the grid.

EER is calculated as the ratio of the cooling power to the power absorbed by the Peltier cells:

$$EER = \frac{Q_{air}}{Q_{TEC}} \tag{2}$$

where:

Q_{air} is the power dissipated by the passive components in the airflow.

Since both the thermoelectric cooling system and the active components are cooled by the cold plate, a set of preliminary measurements was performed to evaluate separately the cooling power needed by the MOSFETs and that exchanged with the airflow in the finned heat sink.

General information on the data accuracy were reported in [9]; here only the most relevant information and the uncertainty of some new parameters are reported. The overall accuracy on temperature was estimated to be better than 0.2˚C. The relative overall uncertainty of the power exchanged with the cooling water is always lower than 13 %, whereas for Q_{SMPS}, Q_{DL}, and Q_{TEC} is lower than 1%. The relative overall uncertainty of efficiency and EER is lower than 1% and 2.5%, respectively. The electric measurements are typically more accurate than the thermal ones. The high uncertainty in the measurements of the heat exchanged with the water, is justified in [9].

3.1 Preliminary Results

Both the MOSFETs and the passive components, the latter through the airflow, are cooled by the cold plate. In order to evaluate the performance of the solid state cooling system it is necessary to evaluate separately the different components of the required cooling. For this aim we rearranged the experimental setup for a new set of tests.

The enclosure was opened, the solid state cooling system was made off, in order to be sure that only the MOSFETs placed on the lateral pipes of the cold plate (see Fig. 1) were cooled by the water cooling system. In this new setup the passive components were cooled for natural convection by the surrounding ambient air.

However, in this arrangement the transformer attained, also for low values of Q_{DL}, the maximum temperature allowed by the safety protection of the SMPS and the equipment was turned off. For this reason two small fans (SEPA model MFB30G-12, external dimension 30 x 30 mm) were placed directly on the transformer in order to cool the only passive element that can hardly be cooled for natural convection.

On the MOSFETs, to avoid the forced convection cooling due to the airflow of the two small fans, two confinements walls were placed vertically beside the PCB. Also the openings of the main fans were closed to avoid the effect of the forced air flow on the fins. In this way we were able to measure through the water, the heat exchanged by the MOSFETs for different working conditions. The results are shown in Fig. 3, together with the total thermal dissipation and that due to the passive components to air. A correlation was then obtained to directly calculate the cooling power of the passive components (Q_{air}) as a function of the power absorbed by the SMPS (Q_{SMPS}). This distribution is well interpolated by a second order polynomial.

In Table 1 the distribution of temperature in the "sensible" point of the SMPS (it means on the passive components) is shown. The position of the thermocouples is shown in Figure 4. In these preliminary tests, the only passive component directly ventilated is the transformer. In this tests, except for very low values of power dissipated on the dummy load (0.5 and 1 kW), one of the coils (TC 1) is the most overheated component; the overtemperature increases with the power of the SMPS (Q_{SMPS}).

However, since an overheating protection is placed on the transformer, in Fig. 5 the maximum temperature on the transformer is shown for different air flow rates, attained with different supply voltage of the small cooling fans. The natural convection (0 V) was enough to maintain the transformer at a temperature lower than the security limit only up to a power dissipated on the dummy load of 1 kW; in this case the limited ventilation of the small fans is still enough to limit the temperature on the transformer at acceptable values. The benefits of a good cooling of the SMPS are evident: the power dissipated by the active MOSFETs decreases with the ventilation. The efficiency is constant, with differences lower than the experimental uncertainty.

3.2 Final Results

The cooling system has been tested for different working conditions which are consistent with the manufacturer's operational conditions. The investigation was directed to obtain useful information on the temperature distribution in the thermally stressed components of the device and to establish the optimum working conditions of the cooling system.

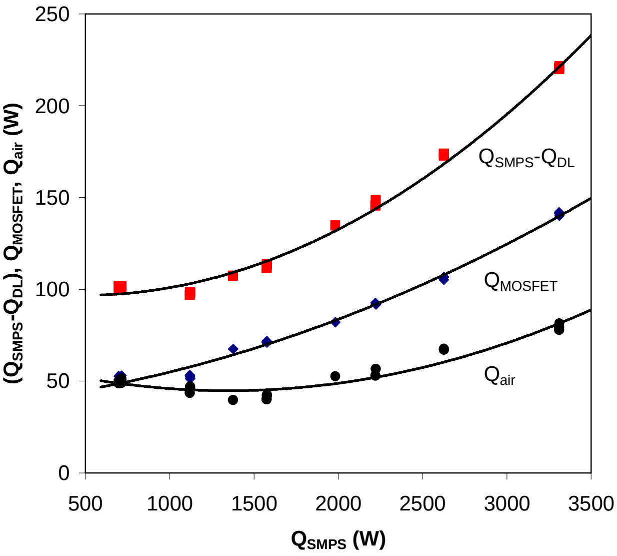

Figure 3: Distribution of heat dissipation between active (MOSFET) and passive (air) components.

Table 1 – Temperature distribution on the passive components of the SMPS.

Temperature (°C)	Q_{DL} (kW)					
	0.5	1.0	1.5	2.0	2.5	3.0
TC 1 induct.	47.0	51.4	55.7	63.2	68.4	83.4
TC 2 transf.	47.7	51.4	55.3	62.5	67.7	82.3
TC 3 cond.	41.5	42.1	43.1	42.9	44.1	46.4
TC 4 induct	47.5	49.6	51.1	55.1	56.5	64.1
TC 5 transf.	38.6	41.2	43.6	48.0	51.0	59.6
TC 6 transf	36.9	40.5	44.1	50.9	55.7	68.6
TC 7 induct	35.7	38.9	40.9	43.8	46.2	54.2
T_{amb}	27.6	28.1	28.3	27.9	27.3	29.0

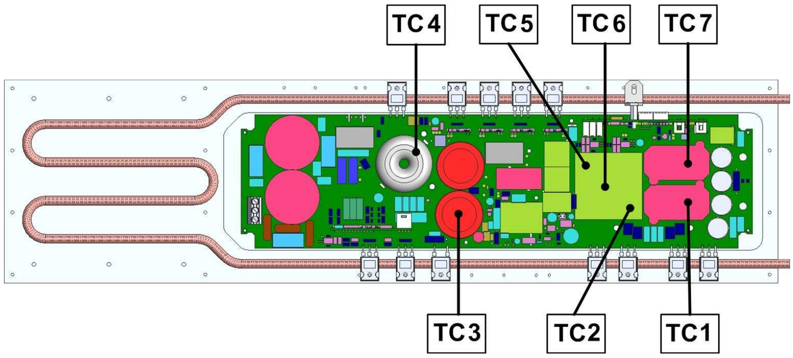

Figure 4: Position of the thermocouples on the passive components of the PCB.

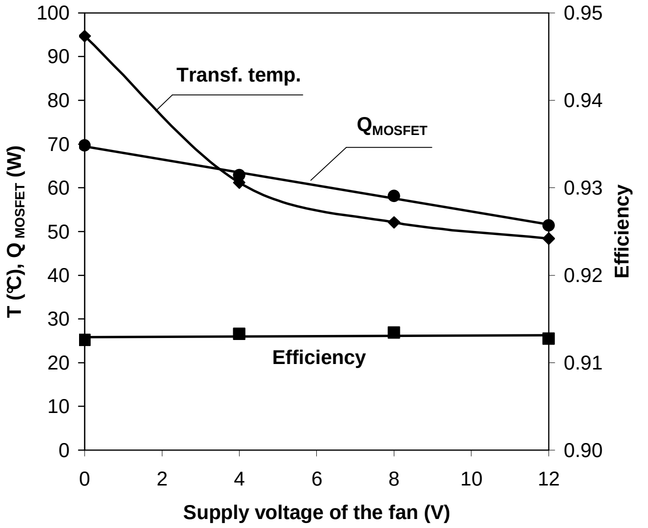

Figure 5: Main parameters of the SMPS for different air flows (Q_{DL} = 1 kW)

In the whole set of final tests the voltage of the SMPS is maintained regulated at 45 V, corresponding to its design condition. The experiments were executed in the late spring, in a room with a quite constant ambient temperature.

In Figure 6 the distributions are shown of efficiency of the SMPS and EER of the thermoelectric cooler for three data sets characterized by different values of the power dissipated in the dummy load (Q_{DL}). The data are shown as a function of the current absorbed by the TEC. These distributions can be well interpolated by power functions. EER decreases for increasing values of current, and thence of the power absorbed by the Peltier cells. Also efficiency decreases for increasing values of current. Both parameters show lower values for lower values of power absorbed by the SMPS.

These parameters are not particularly decisive in the design of the cooling system because if it is trivial that high efficiency and high EER are desired, it is also evident that they seem to be at the best when the cooling system is off. For this reason further parameters need to be analyzed in order to individuate the best performances of the system.

In Figure 7 the distributions are shown of the maximum temperature on the passive components (in this SMPS this is the temperature on the surface of the transformer) for three data sets characterized by different values of the power absorbed in the grid by the SMPS. The data are shown as a function of the current absorbed by the Peltier cells.

These distributions can be well interpolated by second order polynomials. Higher values of temperature on the transformer are reached for low and high currents in the Peltier cells. A minimum of temperature is well evident for a current of 6.0 – 6.5 A, depending on the power. This minimum of the maximum temperature is a good candidate for the optimum design condition of the TEC.

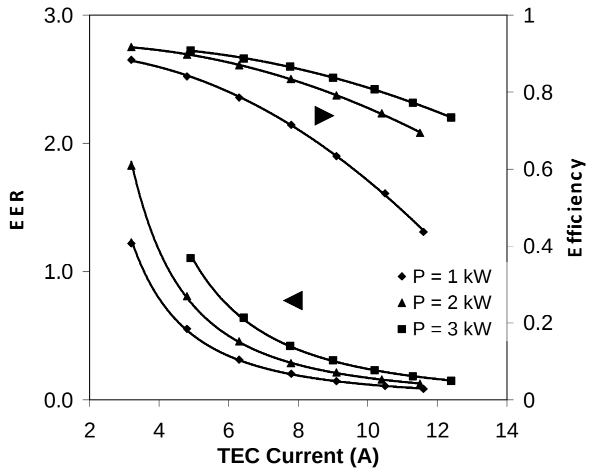

Figure 6: Efficiency of the SMPS and EER of the cooling system.

In Figure 7 the distributions are also shown of the temperature difference between the water in the inlet of the cold plate and the air leaving the finned heat sink. These distributions are useful to characterize the cooling effect of the TEC. Also these distributions can be well interpolated by second order polynomials. A maximum of ΔT is well evident for a current of 9.0 – 9.5 A, depending on the power.

The different points of optimum of the two temperature distributions shown in Figure 7 are due to the power absorbed by the Peltier cells and discharged in the cold plate. While the cooling power needed by the SMPS is constant for constant power conditions, the power absorbed by the TEC increases in order to produce higher ΔT.

The maximum cooling effect on the airflow occurs for values of efficiency and EER lower than in the case of minimum of the maximum temperature. For this reason the TEC current able to guarantee the minimum of the maximum temperature can be chosen as the proper design condition. This values of TEC current can also be slightly reduced so as to obtain higher values of efficiency and EER with acceptable values of maximum temperature.

In Table 2 the distribution of temperature on the most significant passive components is shown. The data refer to the conditions of optimum for the temperature of the transformer, as shown in Figure 7 (it means good efficiency and acceptable EER). A comparison with the data of Table 1, where only the transformer is cooled, shows that the proposed ventilation system is efficient for the cooling of the SMPS. Also for higher values of temperature of the cooling air, the temperature on the passive components is lower; this effect is generalized over the entire equipment.

4 Concluding Remarks

Electronic equipments are often placed inside enclosures to protect them from environmental influences such as temperature, moisture and contaminants. In addition to this, in our proposal an enclosure becomes the way to cool those

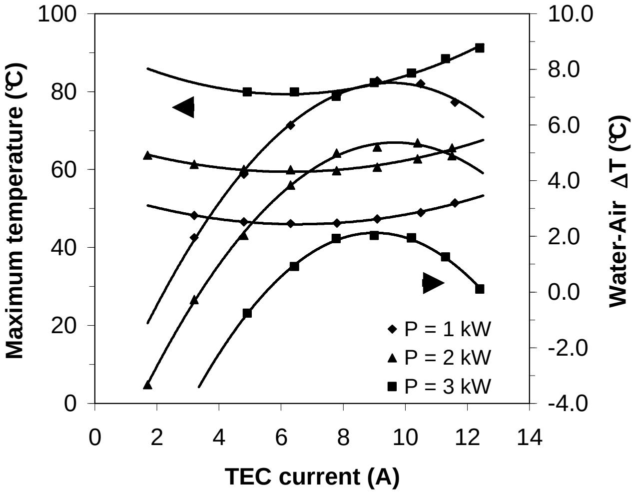

Figure 7: Maximum temperature in the passive components and temperature difference between water and internal air.

electronic components difficult to be cooled with a cold plate, like electrolytic capacitors and magnetic components. A detailed analysis of the thermal behaviour of this cooling system specifically designed is given and the practical significance of the problem is discussed. The efficacy of the cooling system is demonstrated; the trends of efficiency and temperature are evidenced. A strong dependency of the thermal power dissipated by the SMPS on the electric operating conditions is clearly evident.

Based on these data it is possible to suggest some lines of development of this cooling system.

The utilization of a TEC can be a proper solution if the ambient air temperature is high, because it is able to create an environment at a proper temperature. However, for a complete exploitation of the TEC an accurate design of the system on the base of the parameters affecting its performance is required. Differently, the risk of a dissipation of power without a corresponding cooling effect exists.

Furthermore, as already suggested in [9], the internal air circulation can be modified to obtain a more efficient flow on the critical components. This can be obtained with different fans and/or with a different distribution of air over the passive components. Due to the limited available spaces, our system of “fans and fins” is not particularly efficient. This system can be redesigned for a better distribution of air between the fins.

Table 2 – Temperature distribution on the passive components of the SMPS for different powers.

Temperature (°C)	Q_{DL} (kW)		
	1.0	2.0	3.0
TC 1 induct.	32.0	38.1	46.4
TC 2 transf.	46.1	59.7	78.8
TC 3 cond.	36.7	42.9	50.8
TC 4 induct	35.8	41.5	48.7
TC 5 transf.	34.3	42.5	53.7
TC 6 transf.	32.9	43.6	58.0
TC 7 induct	31.8	38.0	46.7
$T_{cooling\ air}$	27.1	30.7	34.4
T_{amb}	27.7	27.2	26.7

Acknowledgements

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Nomenclature

I	electrical current	A
Q	thermal and electrical power	W
T	temperature	°C
V	electrical voltage	V

Greek letters

ε	Power conversion efficiency	Eq. (1)

Subscripts

air	airflow
amb	ambient air
DL	Dummy Load
SMPS	Switch Mode Power Supply
TEC	Thermoelectric Cooler

Abbreviations

EER	Energy Efficiency Ratio	Eq. (2)
TEC	Thermoelectric Cooler	

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