A Power Converter Integration Approach with a Multi-Functional Heat Sink Shaped Inductor

Wenbo Liu, Yan-Fei Liu, *Fellow, IEEE*
Department of Electrical and Computer Engineering
Queen's University,
Kingston, Canada
liu.wenbo@queensu.ca, yanfei.liu@queensu.ca

Laili Wang
Department of Electrical Engineering
Xi'an Jiaotong University.
Xi'an, China
llwang@mail.xjtu.edu.cn

***Abstract*— this paper presents a novel multi-functional component which combines the features of heat sink and magnetic device in the power converters. Inspired by the functional integration concept, the proposed heat sink component is well designed in order to also serve as an inductor. With the modified winding and magnetic circuit design, the inductance can accommodate the requirement of power converter without increasing the DC condition loss. This proposed heat sink-inductor device can significantly save the total volume of power module and improve the thermal performance at the meanwhile. In the studied point of load power module, the total volume is decreased by 40% and the temperature of voltage regulation IC is decreased by 14°C.**

Keywords—integration; heat sink; inductor; thermal analysis; FEA simulation

I. INTRODUCTION

The continuously increasing power density of electrical systems presents a demand for thermal management technologies. For the point of load power (POL) modules with 1~5V output and 6~40A maximum load current, the power density can be 1000~2000 W/in^3. The extreme hot spots are introduced into the electronic devices due to high power density, which is harmful to the whole power system and draws much attentions.

Using air-cool finned aluminum heat sink to dissipate heat is the most commonly used method to improve the thermal performance and meet the temperature requirement. By adding these cooling tools, not only the reliability but the performance of the converter is improved. In the cooling system that are applied to high power applications, heat sinks are usually installed together with fans to guarantee the performance. Natural convection cooled heat sink is also a popular method in plenty of applications. They are more volume-effective and can provide enough cooling performance especially in low or medium power levels. The thermal resistance in these cases are relatively low therefore natural convection method can same much volume of the whole system.

However, the heat sink that introduced into the electronic system is always bulky and difficult to be assembled with the active devices, which is adverse to make further progress in power density and reduce total size. Design of the parallel thermal plate (fins) shown in Fig. 1 are required to maximize their surface area of the heat sink. A number of researches have been proposed on optimizing the structure of heat sinks to improve the efficiency of heat dissipation per volume [1]-[3]. Advanced materials and design of parallel plates (fins) are utilized and the total power system volume is decreased. Modified thermal modeling methods are applied to analyze the proper shape and size for a certain power converter. Thermal resistance network is built to estimate the resistance values of the forced air or natural convection cooling systems. Despite the improved structural design and accurate modeling approach, cooling of the POL applications are not very applicable due to the small size and assembling process. Another solution is provided by the power-supply-in-inductor (PSI^2) technology which explores the inductor to serve as the case of power module. The high thermal conductivity of magnetic material improves the ability of heat spreading so that the inductor can provide a similar but weakened effect of heat sink [4].

To achieve both the objectives of miniaturized system size and desired thermal performance, this digest proposes a multi-functional component consisting of three key features: (1) it is based on a heat sink and integrates an inductor inside, the cooling performance can be monitored; (2) no additional inductor is needed and the power module can get rid of bulky magnetic component, limiting the overall volume of power system; (3) this component can be 3D integrated with the active devices so the assembling is flexible and the footprint will not be increased. The paper is organized as follows: Section II describes the principle of functional integration, a

Fig. 1. Sample of heat sink

heat sink shaped inductor is constructed based on the structure of a common heat sink. The winding and core design are reported. Section III shows the thermal and electro-magnetic simulation with FEA tools, the performances for each modified structure are presented. Section IV builds a prototype of the proposed multi-functional component and presents the experimental verification results. Section V concludes the paper.

II. PRINCIPLE OF 3D PACKAGING STRUCTURE AND FABRICATION PROCESS

The sampled heat sink shown in Fig. 1 is a typical heat sink components with 16 paralleled cooling fins and a base plate. The proposed multifunctional heat sink shaped inductor is built based on this structure. The copper fins are explored as turns of coil and magnetic material and is attached above the top of the active devices (a DC-DC voltage regulation IC in the studied case). To achieve the conversion from a heat sink to an inductor, it is firstly modeled as a concept map with wire 1-16 and its top view is shown in Fig. 2. As a regular heat sink, all the wires (fins) are connected together on the base plate (black block in the figure). The structure of inductor winding must be in the shape of turns and avoid short circuit, therefore direction of half the wires changed in Fig. 3. Current in wire 1, 3, 5, 7, 9, 11, 13, 15 flows out of the surface and the connection with the other turns are changed. In addition, the fins are no longer connected to the base plate: a magnetic core is added aside to the winding to build a closed magnetic circuit. The current is input from wire 1 and output from wire 16, the direction of current in the terminals is 1-2-3-…-15-16. Thus with coil and core established a magnetic device whose winding is exposed to the air with wide and long dimensions is obtained. In consequence, this component can serve as an inductor as well as a heat sink in a point of load power module to manage thermal problem and realize the purpose of system integration.

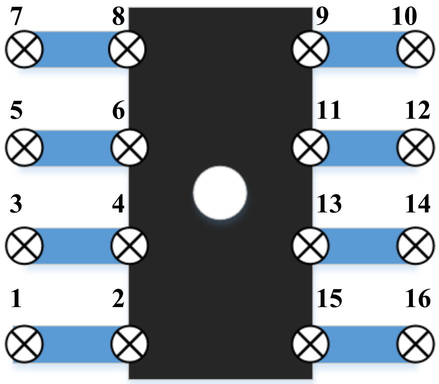

Fig. 2. Top view of the sample heat sink

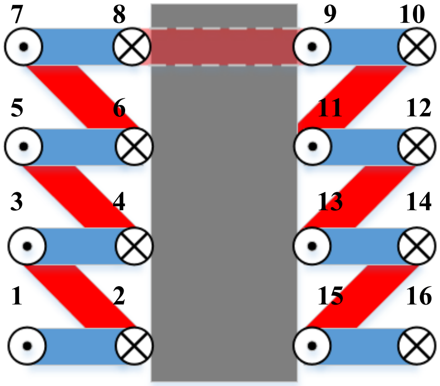

Fig. 3. Top view of the modified parallel fins

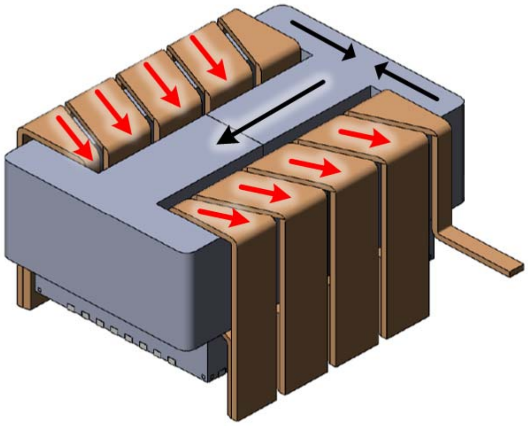

Fig. 4. CAD drawing of proposed inductor

Fig. 4 shows the concept CAD drawing of a typical cooling inductor device. In this design, two sets of coils (8 turns in total) in series are used to increase the inductance. The red arrows in the figure present the direction of current and the black arrows are the flux vectors, an air gap is designed to meet the load requirement. A heat spreader is bonded to the bottom side of each turn of coil without increasing winding resistance. They are used to transfer heat generated by winding loss to the PCB and increase the cooling surface area to improve the system efficiency of heat sink. Aiming at achieving optimal cooling performance without losing efficiency or increasing the current ripple, a modified structural design is required. This inductor winding is based on heat sink fins thus it has large surface area to improve the heat dissipation ability.

This structure imposes a challenge that the inductance is relatively low with such a small flux vector area and a long path. The specifications of the studied DC-DC step down converter is shown in Table 1, 1uH of inductance is required to satisfy the current ripple design standard (peak-peak current ripple should be less than 40% of the DC current). The number of turns can be selected to meet this requirement. At the meanwhile, the window area is enough to accommodate wire with relatively large cross section to reduce the DC winding loss. The multi-functional component is assembled with the active devices in a 3D type, i.e. it locates above the other part of converter as shown in Fig. 4. This structure helps to save the footprint and increase the compactness [6], [7].

Table 1 Specifications of the Studied Buck Converter

Type	*Input (V)*	*Output (V)*	*Max load (A)*	f_{sw} *(kHz)*	*Typical L (uH)*	*Max junction temperature (°C)*
Step down DC-DC	9.0 ~ 15.0	5.0	8.0	800	1.0	125

Two extended structures of magnetic core implementation with separated cores are demonstrated in Fig. 5 and Fig. 6. The design in Fig.5 features a high profile and the one in Fig. 6 has larger footprint. These modified designs could be utilized in the conditions with high temperature sensitivity applications whose volume can be slightly increased. These two structures can achieve higher inductance and better thermal performance which will be resented in the next section, but the fabrication process is more complicate (two-core). The three mentioned structures are all based on the 16-fin heat sink and arranged into 8 turns of winding to increase the inductance. Actually a simple structure shown in Fig. 7 can also be investigated if the requirement of inductance is not high. This prototype is much easier to build: only an E-E core is needed and most important is the winding configuration is much easier to fabricate common shape.

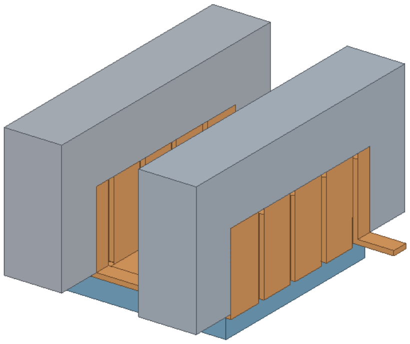

Fig. 5. Core inserted with vertical structure

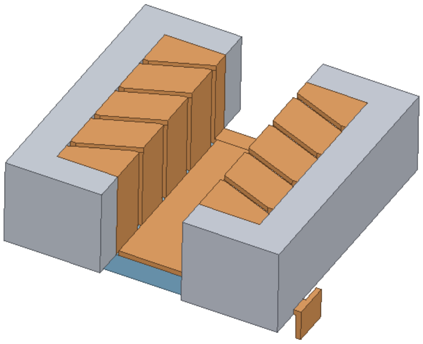

Fig. 6. Core inserted with horizontal structure

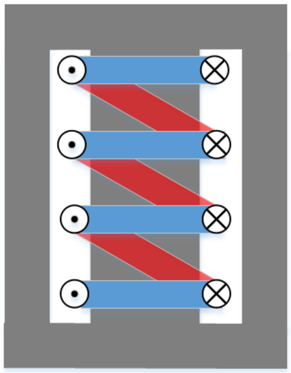

Fig. 7. Single core-single set coil structure

III. ELECTROMAGNETIC AND THERMAL SIMULATION

This section explores the FEA simulation software to pre-verify the performance of the proposed multi-functional component. Firstly steady-state thermal simulation was executed to validate its improvement on air convection thermal performance. In the comparative simulation, there is assumed to be no PCB board and a certain amount of heat is assigned on a 4mm*6mm voltage regulation IC.

Condition #1 dissipates heat by nature convection (at 22°C ambient temperature) on itself while case #2 has the cooling inductor. It can be observed from Fig. 8 and Fig. 9 that the temperature rise of IC only is 2.5 times higher than the IC-heat sink assembly (139°C compared with 54°C). This result indicates that the junction to case is decreased by 70% by adding the cooling device and the thermal performance can be significantly improved. Fig. 10 shows the thermal simulation #3 of IC with a pure heat sink and the

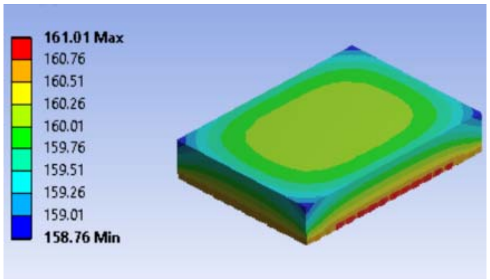

Fig. 8. Thermal simulation # 1with IC only

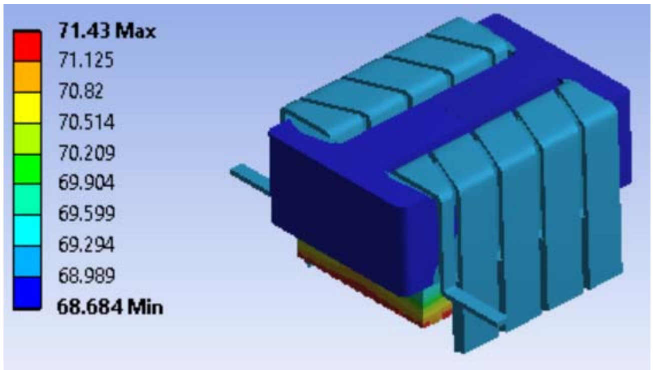

Fig. 9. Thermal simulation #2 with cooling inductor

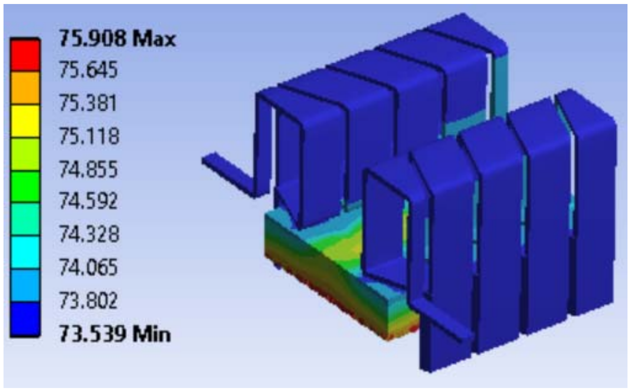

Fig. 10. Thermal simulation #3 with copper finned heat sink

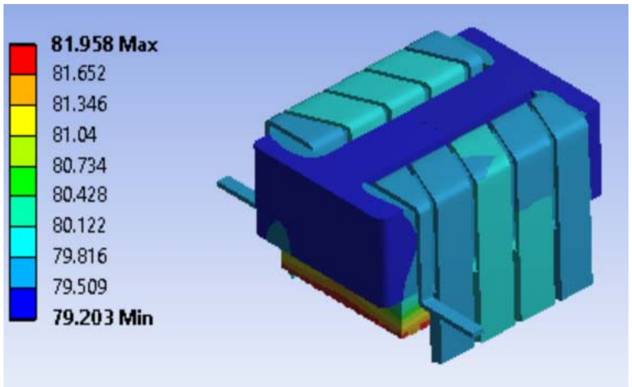

Fig. 11. Thermal simulation #2 with cooling inductor

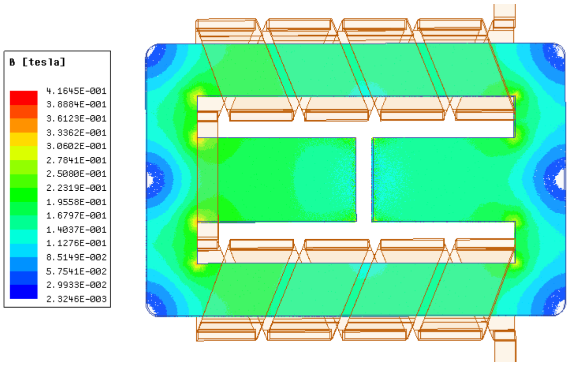

Fig. 12. Simulated flux density at 8A load current

temperature is even lower than adding an original heat sink because adding a core actually enhances the heat transfer ability inside the copper from near heat source to the outside part.

However, the actual case is much different from the simulation in Fig. 9. This is because core and winding losses will be generated in the proposed inductor and in contrast there is no additional loss in the pure heat sink. Thus the cooling performance will be deducted in the proposed converter. To achieve an accurate thermal analysis of the multifunctional power device, loss estimation needs to be employed. The DC winding resistance is calculated by I^2R calculation knowing the length and cross section area of the copper wire (1):

$$R_{wind} = \rho \frac{Nl_e}{A} \tag{1}$$

Where N is the number of turns, le is the effective length of each turn of coil, A is the cross section area of the wire. The core loss can be simulated from MAXWELL simulation and the losses are assigned into the winding and core respectively, the revised thermal simulation is shown in Fig. it can be observed that the temperature is 6°C higher than a normal heat sink but much better than a plain IC. This is a simulation based on the full load condition and in this case the cooling ability is decreased by 10%. The study of the effect by inductor loss on heat sink performance is a critical issue, by analyzing this issue, whether this method is applicable to the target heat source can be decided.

This series of thermal simulation only consider the convectional cooling, especially the natural air flow convectional cooling part. In the real case the conductional cooling takes a more important part and it can also be improved by adding the proposed cooling inductor. The extended heat spreaders under the winding can spread the heat of inductor to the PCB, which eventually improves the thermal performance. The heat conduction ability is also verified in the experiment by the established prototype.

Secondly a series of electromagnetic simulations were executed to verify whether the heat sink-inductor component can get over the special structure and achieve enough inductance and saturating current. The simulation results are exhibited in Table 2 and the simulated inductance is 1.1uH with specified magnetic material and air gap, the maximum flux density is 300mT as shown in Fig. 11 which is also acceptable. The maximum flux which corresponds the saturation condition occurs at the inner corners of the core but the area is very small. Which will not affect the

Table 2 Simulation Results versus Various Thermal Conductivities

Structure of cooling inductor	***Inductance @ 0.1A (uH)***	***Inductance@ 6A (uH)***	***Max flux density@6A (mT)***	***Temperature on copper (°C)***	***Temperature on IC (°C)***
No heat sink	NA	NA	NA	NA	152.5
Finned heat sink	0.048	0.048	NA	73.5	75.9
Single core L	1.133	1.082	330	79.3	82.0
Two core horizontal	1.225	1.193	320	73.7	74.8
Two core vertical	1.247	1.199	320	72.5	73.4

performance of inductor. Thermal and electromagnetic results of other structure are also presented and it can be observed that different types of heat sink inductors can be developed for specific applications. For the two structures with two-core, the thermal performance is further improved compared with the first design thanks to larger surface area and the flux density is also lower.

In conclusion, it is verified by the simulation results that this proposed multifunctional component can realized both functions of heat sink and inductor. The inductance can meet the requirement without increasing winding or core loss. The distribution of flux in the core does not hit saturation condition thus smaller DCR and enough inductance can be achieved in further design. The area of window can be enlarged by using less magnetic material and thicker wire can be selected to build the winding.

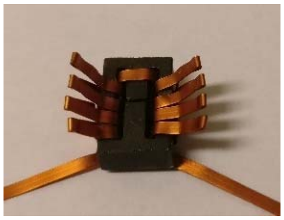

Fig. 13. Prototyped heat sink

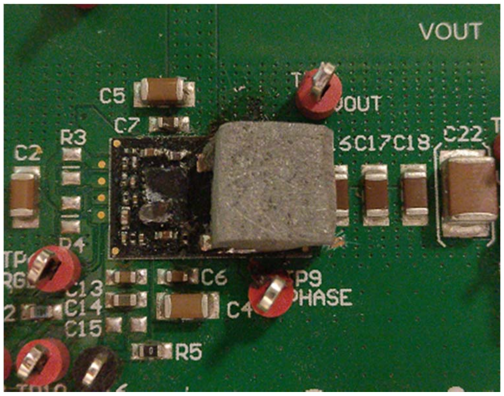

Fig. 14. converter with fixed inductor, no heat sink

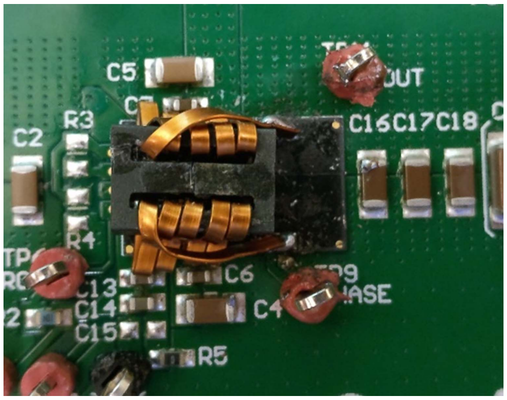

Fig. 15. Converter with the proposed component

IV. PROTOTYPE AND TEST

The prototype of proposed multi-functional heat sink-inductor component is shown in Fig. 13. As a experimental sample, the fin-winding is simply made by constructing a special shape of a copper wire. The wire is shaped as designed in Fig. 3 and each turn is extended to be bonded on the surface of PCB. And as illustrated in Fig. 14 and 15 the new integrated power module can achieve an actually smaller footprint despite adding a heat sink on the board. The converter in Fig. 14 is modified to establish the proposed prototype by removing the inductor and adding the heat sink shaped inductor. If consider adding a heat sink on the converter in Fig. 14, 40% of the total volume can be saved by integrating the two devices together. In this design the footprint of multifunctional component is twice larger than the voltage regulator (in length, 6mm*10mm compared with 4mm*6mm). When assembling the heat sink inductor with the voltage regulator in Fig. 15, the input and output terminals of the inductor are set to be on the left and the IC is right under the left part of heat sink. Due to the thermal conductivity of copper, the left part of component is cooler than the right part and the cooling performance of IC benefits from this configuration.

The input voltage of both prototypes are 12V as a experiment condition and the output voltage is regulated to 5V. The efficiency curves of the original and proposed converter s are shown in Fig. 16. According to the measurement the efficiency at 8A load is 92.7% for the new module which is close to the original power module so it does not increase the inductor loss. Furthermore it has even better peak efficiency (95% at 3A load) thus its core loss is less. According to this efficiency curve it can be concluded that the core can be modified to obtain larger window area and accommodate thicker wire to further increase the efficiency. The switch node and output voltage waveforms are observed in Fig. 17 and it is validated that the voltage regulation is not affected by the exposed conductor and the leakage flux does not impose electromagnetic interference (EMI) issue.

Thermal performance of the integrated converter with heat sink inductor is also verified experimentally. Fig. 18

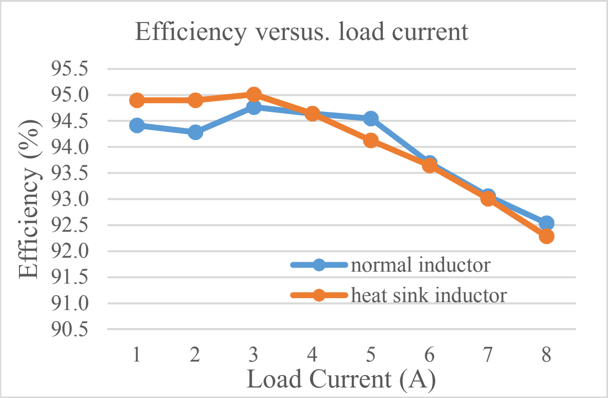

Fig. 16. Efficiency curves of the converters

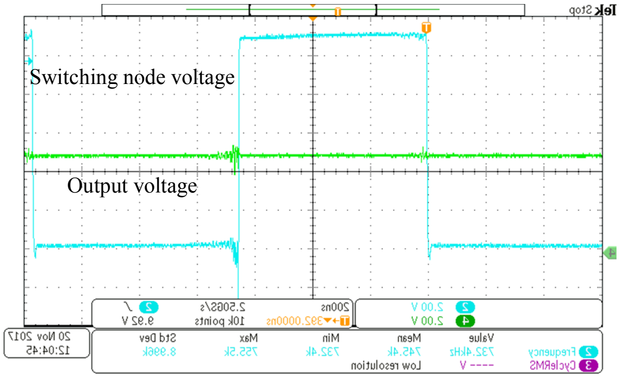

Fig. 17. Voltage waveforms of the proposed covnerter

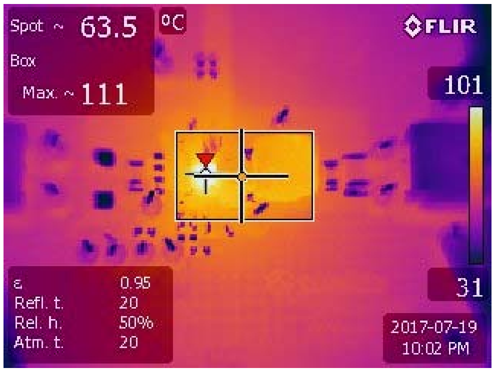

Fig. 18. Thermal image of original converter

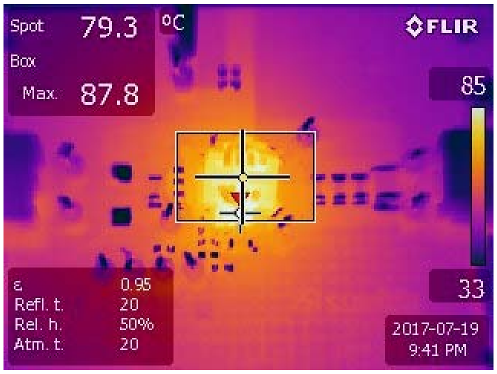

Fig. 19. Temperature of proposed prototype on the core

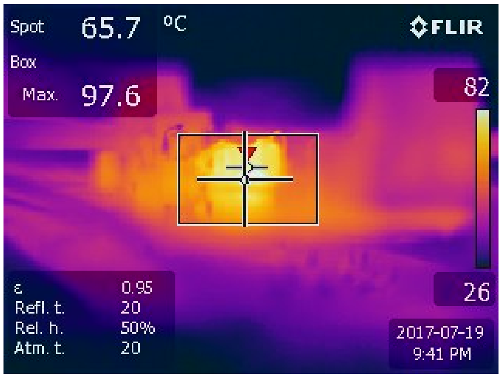

Fig. 20. Temperature of proposed prototype on IC

shows the thermography of the original power converter with the specifications in Table 1, the maximum temperature on the IC is 112°C at rated power. Fig. 19 and 20 show the temperature of the power module with heat sink, it is 80°C on the top of heat sink and 98°C on the IC. These thermographs from infrared (IR) camera are later verified by the measurement results of thermocouples. Thus with the same loss in the voltage regulator IC, the cooling inductor can decrease the operating junction temperature by 14°C. the temperature rise is decreased from 90° C to 76° C which is 17% better.

V. CONCLUSION

A novel multi-functional component which is a combination of a heat sink and an inductor is proposed in this paper. By modifying the structure of paralleled cooling plates (fins) to series coil winding and the adding a magnetic core. The heat sink-shaped inductor is built. Plenty of designs that can apply to different point of load applications are obtained and discussed. The performances are validated by FEA thermal and electromagnetic simulation. A prototype is fabricated and with the functional integrated cooling inductor, the maximum junction temperature can be reduced by 14°C with an even smaller footprint. It can also be verified that the efficiency is not decreased.

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