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Thermal Modeling and Management of Automotive DC-DC Converter

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***Abstract*— Nowadays, world is shifting away from traditional fuel vehicle to electric vehicles. DC-DC converter is key component of electric vehicle, which is mainly used to convert the voltage from one level to another. And there is always heat loss during the power conversion processes in the converters. This heat must be dissipated properly into the environment because high temperatures can shorten the lifespan, as well as the operation of the DC-DC converter and the nearby circuits. To understand the mechanism of the heat transfer in the system and to forecast the Maximum temperature on each part of assembly, initially Steady state thermal simulation of the DC-DC Converter was conducted using ANSYS Mechanical. Based on the results of the simulation, various areas are identified which are necessary to work for the better thermal management of the system at 55°C operating temperature. The base line simulation is carried out for finding the possible ways to have better heat dissipation in the system which includes change of thermal conductivity of heatsink material, potting material (Bottom sided), thickness of potting material, bottom plate addition, bottom plate thickness. Results were computed by changing these parameters. Comparison is made for the results and suggested a method for getting improved heat dissipation in DC-DC converter. This study shows that it is feasible to reduce the temperature of the DC-DC converter by up to 20°C using the proposed method.**

***Keywords*— DC-DC Converter, heat dissipation, heat transfer mechanism, Steady state thermal simulation, thermal management.**

I. INTRODUCTION

There are many reasons for the failure of electronic device such as heat generation in device because of electronic components, improper material selection, design flaws, working environment for the device and many more. Temperature is most effective factor for the device failure. If the temperature of the component exceeds beyond its safe limit temperature, that component will fail first, affecting temperature sensitive components and finally the entire system will fail. This can cause further mechanical deformation, chemical reaction, electrical parameter drift and electromigration [1]. This has an impact on the DC-DC Converter's reliability. For this reason, the thermal management of the DC-DC converter is essential to safeguard the overall system.

Thermal management of any system begins with mapping the temperatures of the system to identify hotspots. Temperature mapping techniques [2] involves Flow network modeling (FNM), Physical testing (Heat Run Test using heat chamber or Thermal Imaging using Infrared (IR) camera, and Virtual Simulation (Steady state thermal simulation) through which will get work areas to prevent overheating of the devices. Performing physical test at each level of design or initial level is not practicable, since physical testing needs setup, assembled samples, and skilled engineers which is again costwise and timewise not effective. Alternate option for this is virtual simulation, in simulation we can get idea about critical components, critical path which is leading for improper heat dissipation in the system. And finally, these results can be taken for next design iteration.

Simulation contributes more in the optimization of any devices and, Optimization of the heat generation from the designed device leads to increase in the lifespan of components and a whole system [3]. Vasin and Okunev [3] have presented a way that allows one to significantly reduce the cost of constructing a final product by foreseeing and addressing the issue of heat generation of the most critical components, as well as the overall design.

Kesav Kumar Sridharan and Ravish Masti [4], have discussed the robust and ideal thermal design of an air-cooled DC-DC Converter to keep the temperature (the primary design parameter) of each device at a minimum and below the corresponding permissible limit of the device. Steady-state thermal analysis output is the temperature field contours at different temperature levels, which can be further used for the layout optimization and to reduce and balance the heat distribution as per the analysis results. Steady-state thermal analysis and layout optimization of DC/DC converter is explained by Cheng Gao and Haitian Liu [1].

Walker and Williams [5] demonstrated study of the challenges with conduction, natural convection, and forced air convection for the removal of heat. Applications of thermal resistance are also described. The topic of thermal derating and how it relates to the converter is also covered in the discussion.

In current work, we have conducted detailed thermal modeling of the 150 Watt DC-DC Converter which have 90% efficiency. This is the buck converter, commonly known as a step-down converter. The respective converter's input voltage is 30-60 V with a current of 10 A and an output voltage of 12-15 V with a power output of 150 watts. Basically, the thermal modeling is done to analyze the thermal hotspots in the system to keep the PCB and its component's temperature below the safe limit at specific operating range.Fig.1 is showing the top-side PCB of 150 W along with the components considered for the thermal simulation.

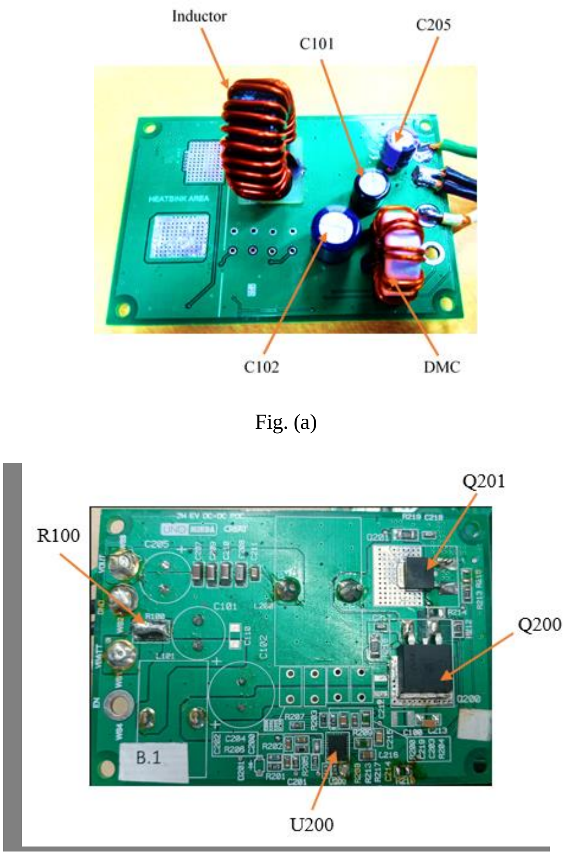

Fig. (a)

Fig. (b)

Fig. 1. Top (a) and Bottom Side (b) PCB view of 150 Watt DC-DC Converter

The detailed components of DC-DC convertor shown in Fig. 1 are,

- HS MOSFET- Q200
- LS MOSFET- Q201
- IC- U200
- Inductor- L201
- O/P Capacitor- C205
- Input Capacitor- C102
- Input Capacitor- C101
- DMC- L101
- Fuse- R101

The electric components of DC-DC converter are diodes, MOSFETs, inductors and capacitors. Among these components, the MOSFET is a higher heat generating component which can lead to overheating and breakdown of PCB board. For this, an optimised initial design simulation is required.

To find out the hotspots in the DC-DC Converter Steady state thermal simulation has been performed using the ANSYS Mechanical software. Initially the Steady State thermal simulation methodology is presented and then the heat flow path for the system has been discussed in the paper. For better thermal management some parameters change is possible like [6] material thermal conductivity, thermal contact resistance at interfaces, air gap thickness between the parts and convective heat transfer coefficient at the two end spaces. In this scenario, because the air gap is closed with potting material, one can may focus on changing the thermal conductivity of the heatsink, potting material, and bottom plate, which are more responsible for extracting heat from the electronic components. Finally, the Thermal modeling results and results outcomes changing the above-mentioned parameters are presented and discussed in the present research work.

II. THERMAL MODELING OF DC-DC CONVERTER

Thermal modelling of any device involves six steps as shown in Fig. 2. In order to make the thermal modelling more accurate and reduce the temperature error occurring in the results, mesh refinement or improved modelling methodology could be used. It is also difficult to determine the convection coefficient for the natural convection, however, thermal modelling can assist in varying this coefficient values, geometry size or boundary conditions.

To conduct the Thermal simulation first step is to prepare a 3D CAD geometry. This 3D geometrical model should contain components which are dissipating the heat also, the components [9] who are not responsible for heat generation but carrying the heat away from components to ambient such as the printed circuit board, heatsinks, Potting, Bottom Plate and large components with almost no power dissipation. Although they do not dissipate power, they affect the thermal behavior of the system. Also, the Geometric models should contain the physical description of each component: package, material, size and the detailed construction of required components like MOSFETs, diode and Inductors. DC-DC converter taken for study has 4-layer PCB means 4 layers of copper and 3 layers of dielectric material. So, care has been taken to model the geometry correctly.

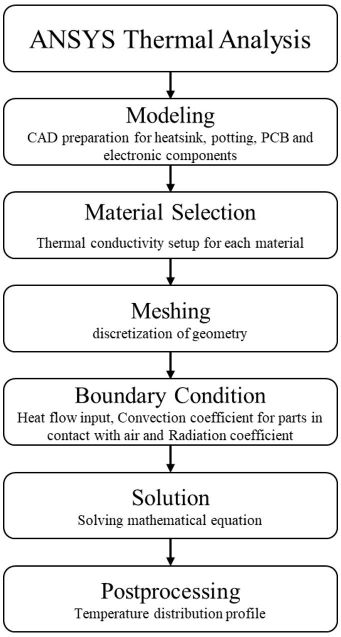

Fig. 2. Steady State Thermal Simulation.

Fig.2 explains about the simulation steps followed during the Thermal modeling of electronic devices. ANSYS Mechanical 2022 version was used for the simulation.

A. *Material Properties*

Table 1 summarizes the material properties used in the Steady State Thermal simulation. These material properties are taken from the datasheets of respective part. For the thermal analysis in ANSYS Mechanical the important material property considered is thermal conductivity.

TABLE I. THERMAL MATERIAL PROPERTIES USED FOR SIMULATION

Sr.No.	**Thermal Property**				
	Component	***Material***	***Thermal Conductivity (W/m K)***		
1	Housing	ADC12	96		
2	Soft Potting	Epoxy	0.465		
3	PCB	FR 4	X	Y	Z
			0.8	0.8	0.3
4	Thermal Pad	Silicon	4		
5	Copper Layer	Copper	385		
6	Hard Potting	Epoxy	0.49		
7	Components	Ferrite	4		

B. *Loss Calculations*

To conduct electronic thermal simulation loss from convertor/system in watts should be taken as input boundary condition. Converter mainly contains the three losses Conduction loss, Switching loss and Core Loss. All these losses have calculated analytically and taken as a heat flow for the simulation mentioned in Table 2.

TABLE II. HEAT LOSS CONSIDERED FOR THE SIMULATION

Sr. No	***Component***	***Designation***	***Power Loss (W)***
1	HS MOSFET	Q200	4.8
2	LS MOSFET	Q201	3.2
3	IC	U200	1.46
4	Inductor	L201	2.9
5	O/P Capacitor	C205	0.4732668
6	Input Capacitor	C102	0.3042
7	Input Capacitor	C101	0.00622
8	DMC	L101	1.2
9	Fuse	R101	0.8
		Total	15.143687

C. *Base Model Results*

After completion of the solution, calculations (rated load), the analysis findings have displayed as temperature field contours using a postprocessor. This entire assembly has been simulated at the customer-specified ambient temperature of 55°C. The outcomes that is temperature distribution over the heatsink, PCB and heatsource have displayed in Figures. 3, 4 and 5.

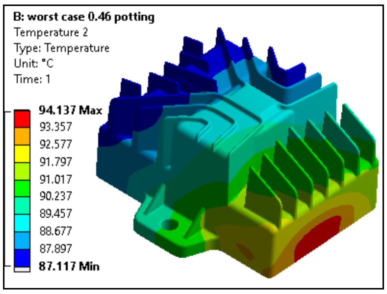

Fig. 3. Temperatures on Heatsink

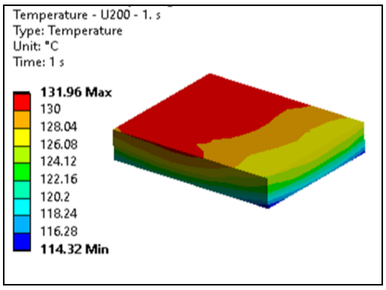

Fig. 4. Temperatures on IC U200

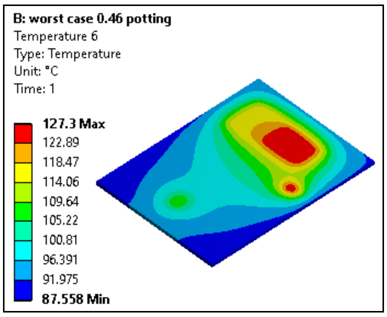

Fig. 5. Temperatures on PCB

When compared with top-sided components, the maximum temperature has been seen on the bottom-sided components. The highest temperature recorded on the IC U200 is 132°C shown in Fig.4, whereas the temperature recorded on the Q200 HS MOSFET is 128°C. PCB temperature is reaching a maximum of 127°C shown in Fig.5.

The objective of the present work is to reduce the maximum temperature of electronic components (MOSFETS) from 131 °C to below 125 °C, because safe operating temperature of these electronic components is 125°C as per the datasheet and if we consider factor of safety then that will be the greater safety margin to ensure the reliability of whole product. In this case 1.11 factor of safety has considered and from that IC temperature should be less than or equal to 112.5 °C. To achieve this limit following study has been done.

III. PARAMETER CHANGE STUDY TO IMPROVE THERMAL PERFORMANCE OF DC-DC CONVERTER

This study has done to investigate the influence of various parameters on the heat transfer from heat source to ambient. The thermal performance of DC-DC Converter is imposed without changing the electric components, their positions, and Heatsink design. The only changes are made in material thermal conductivity, dimensions, boundary conditions and emissivity. Fig. 6 explains the different steps involved to suggest the best suitable approach or way to have better thermal management.

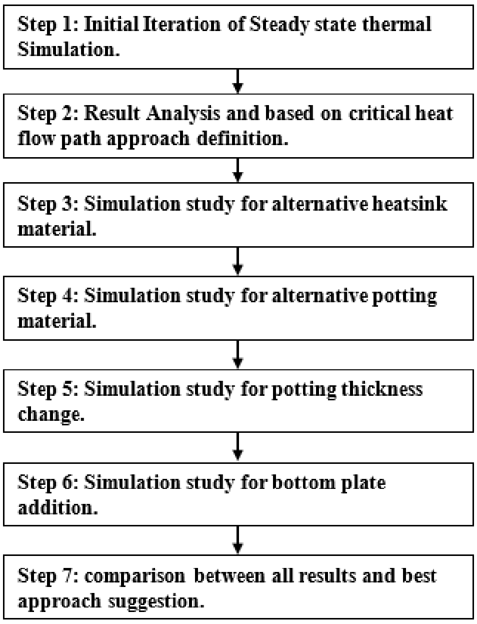

Fig. 6. Steps involved in suggesting best suitable approach for the better thermal management.

A. Results for Aternative heating material

Different materials are identified with high thermal conductivity values than ADC 12. Also, the material properties like dimensional stability, machinability were taken similar or even better than base material. Some materials like DX 19, DX 17, A413 and B390 which are suitable and available for respective heatsink has been compared with the ADC12 and analysis was conducted whose results are shown in Fig 7.

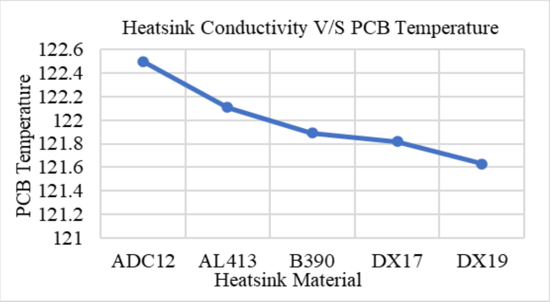

Fig. 7. Comparison between Heatsink Thermal conductivity change and Temperature on PCB board

It is observed that by changing heatsink thermal conductivity from 96 W/mK to 160 W/mK, only 0.7- 0.8% improvement in the overall performance of the DC-DC Converter has been observed. Though the thermal conductivity of alternative heatsinks materials is more than ADC12, we are getting poor outcomes because of small area of contact of the heatsink to hard potting which is in contact with high heat generating components.

B. Results for Alternative Potting Materials

Most of the electronic components were enclosed into the potting material to transfer the heat through conduction from source to heatsink instead of having convection. Other than material thermal conductivity important properties that has taken in consideration while searching alternative potting material are viscosity, hardness and die-electric strength of alternative materials [7]. Based on these properties potting material with higher thermal conductivity are searched and by keeping all other things same, simulation has performed and then comparison is made. It has been observed that PCB temperatures are significantly dropping when the hard potting's thermal conductivity is improved. Figure 8 shows comparison between thermal conductivity of potting vs PCB temperature

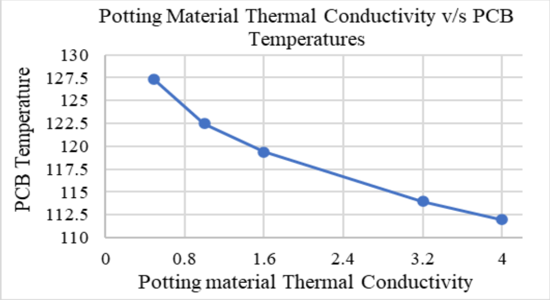

Fig. 8. Comparison between Thermal Conductivity of Potting v/s PCB Temperatures

The highest temperature reached with thermal conductivity of 0.49 W/mK is decreased by 6% when it is changed to 1.6 W/mK. The decrease in PCB temperature after increasing thermal conductivity from 3.2 W/mK to 4 W/mK is 1.75%. Maximum results are obtained in the 1 W/mK to 3.2 W/mK range. Therefore, it has been advised to utilize potting with 3.2 W/mK thermal conductivity.

C. Results for the Potting Thickness change

Next simulation is done by keeping the same potting material and changing the potting thickness to study the effect of hard potting thickness on system temperature. To provide the proper dielectric strength and high-temperature stability, the potting thickness between the components and the heatsink must be maintained; the potting must be at least 3 mm thick. If the thickness of the potting material is greater than the minimal requirement, there will be a chance to reduce it. Study has done for hard potting because hotspots observed from the base simulation are at the bottom side. Figure 9 shows variation of PCB temperature with respect to potting thickness changes.

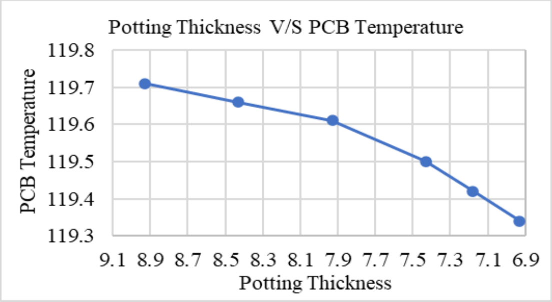

Fig. 9. Comparison between Potting Thickness V/S PCB Temperature

According to the research done for different potting thicknesses by reducing the potting thickness from 8.93 mm to 6.93 mm, the temperature is only decreased by 3%. Therefore, this strategy is working properly but has a little impact on the system performance.

D. Results for the Bottom Plate addition

The heat from the hard potting, which is in touch with the greater heat dissipating components can be easily extracted with the insertion of the bottom plate after the hard potting. Accordingly, it has been found in the study that adding 1mm AC4C steel bottom plates with higher thermal conductivities are beneficial because doing so reduces PCB temperature by 3 to 4°C. Further investigation has been done to determine plate thickness, and it is beneficial to choose 2mm of steel plate since it further lowers the temperature by 1.5°C. Figure 10 describes comparison between bottom plate thickness with PCB temperature.

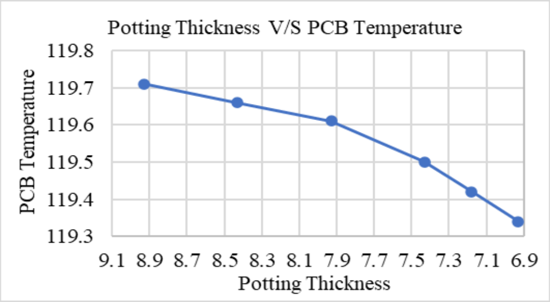

Fig. 10. Comparison between Bottom Plate Thickness V/S PCB Temperatures

The Thermal modelling results are shown in Fig.11 below, where it is compared to first modelling and the proposed modelling results. Since, the less influence of increased heatsink thermal properties and changed potting thickness on system temperature. In proposed model we have just proposed higher thermal conductive potting and steel bottom plate with 2 mm thickness and the modelling has done for the proposed one.

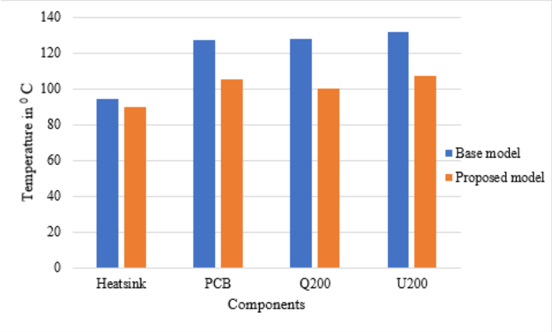

Fig. 11.Comparison of temperatures of Base model and Proposed model.

As we have discussed previously, changing the hard potting thermal conductivity helps to decrease the temperature of electronic components. It is observed as MOSFETS cooling has improved strongly, as the heatsink is in contact with the hard potting from bottom side area, heatsink temperature is also decreased. Compare to other methods changing the hard potting to higher thermally conductive one gives the highest thermal cooling improvement and thermal distribution throughout the system.

IV. CONCLUSION AND FUTURE SCOPE

After Comparing the maximum temperature observed from the simulated results of DC-DC converter, it was found that the temperatures differ within 20° to 22°C with base model. A proposed methodology is providing the improved cooling for most critical components of Converter. The Heatsink temperature was decreased by 4°C compared to original one and the temperature of PCB was decreased to 105°C from 127 0C. In case of bottom sided components, we got huge temperature difference compared to the first model. MOSFET Q200 temperature decreased to 100 0C and now it can work it's below the safe operating temperature.

This entire paper examines thermal management by varying thermal and mechanical parameter, without affecting the hardware design or components selection. For getting further improvement in the performance of the DC-DC Converter can obtained by reducing the power loss. Power loss can be optimized by changing the component material from silicon metal oxide to Gallium nitride. Additionally, component placements may result in improved heat management.

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