Needs Assessment and Analysis

Team 13

Extra Lightweight Thermal Design for PV Converter

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September 30, 2016

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ABSTRACT

This report will discuss the constraints and needs of project 13 for creating a lightweight heatsink structure and testing under certain thermal conditions created by power electronic switching devices. These switches naturally generate heat through losses in the mechanical components and resistance inherent in the materials of the devices. These losses can also be generated through parasitic components due to the switches themselves. The current heatsink that was created has been over-designed and this is a critical issue when considering cost and weight. While power loss calculations provide the general temperature guideline that the heatsink will need to dissipate, the design of the heatsink will be improved upon to allow for cost-effective heat dissipation while reducing its size and weight. Design parameters such as weight, materials, fin configuration, optional fans, etc. will be considered when simulating the heatsink structure to test for air flow velocity and temperature dissipation. The time-critical nature of this project will keep the team focused on completing the background research and initial designing of the structure before the end of 2016 in order to have a prototype for a possible conference in early 2017. Constraints for the project include reducing the weight to 6.5kg and preventing the power modules of reaching a maximum operating temperature of 150°C. The targets set forth by the team will be to ensure the power modules stay within a reasonable range from room temperature to 120°C. This project's aim is to be designed and prototyped by the end of Fall 2016 semester.

ACKNOWLEDGMENTS

Team 13 would like to express gratitude to Dr. Li for allowing us to work on the Extra Lightweight Thermal Design of a PV Converter and for providing assistance through her graduate students and laboratory space to conduct our project proceedings. We would also like to thank the graduate students, specifically Thierry Kayiranga and Sandro Martin for providing feedback and support on this project.

Thank you to the FAMU-FSU College of Engineering, Mechanical Engineering Department, and Electrical Engineering Department for providing us the knowledge needed to participate in the Senior Design process where we can showcase our skills and talents.

Lastly, we wish to thank Dr. Gupta and Dr. Hooker for coordinating the team configuration and providing the guidelines needed for a successful semester ahead.

1. Introduction

Extra Lightweight Thermal Design for PV Converter will focus on creating a lightweight, heatsink that is cost effective in order to improve the power density of future power electronic converters more efficient. The designing and initial manufacturing of this project will be completed by December of 2016. The reason for the time-critical nature of this prototype is because of a conference occurring in early 2017 at North Carolina State University where the prototype will be shared. After the conference, optimization of the prototype will take place from January to April of 2017. These results will be achieved by combining the efforts of both electrical and mechanical senior engineering students.

To tackle the time crunch, the team has begun the preliminary background research, and will be developing a Gantt Chart to outline the internal project deadlines, as well as the deadlines associated with the senior design course curriculum. Weekly team meetings on Tuesdays at 2 pm have been established to help the team move through the planning process, and bi-weekly meetings with the sponsor have begun. The team has established a Google Drive folder for file sharing, and will begin working in the lab soon.

Project 13 is being sponsored by The Center of Advanced Power Systems (CAPS) under Dr. Hui “Helen” Li who is also acting as the electrical engineering advisor. As this project is directly related to the research of a current Ph.D. candidate, multiple graduate students working under Dr. Li will be available for questions regarding the nature of this project. Along with providing expertise and advice, the graduate students will assist with materials needed for the testing and prototyping of this project. A requirement of this project is to not exceed a budget of $400.

The design and manufacturing plan to the extra lightweight PV converter and thermal testing project will be broken up into four stages in order to achieve the best results possible. Stage one will include all background research into power switches, power converters, switching loss calculations, heatsink configurations, materials, air flow, etc. Stage two of project 13 will include separate but simultaneous efforts between the electrical engineering students and the mechanical engineering students to begin the simulation process of the project. The electrical engineering students will begin power loss calculations in order to provide these results to the mechanical engineering students who will be designing and configuring the smaller, lightweight heatsink. Stage three will include prototyping the heatsink to meet the specifications determined by stage two along with testing the prototype. The fourth and final stage will include completing the final product.

2. Project Definition

The following subsections will address the needs of the customer for the design and any constraints or concerns that will need to be considered when planning and designing. These constraints will include any physical parameters that must be met in order to meet requirements set by the customer. Research on power loss calculation and design and optimization of heatsinks is summarized to develop a concise picture of the challenges that have been overcome in the power engineering field and to further develop ideas for this project.

2.1 Need Statement

Currently the customer has developed a heat sink for an electrical converter capable of cooling eight power modules operating at a max temperature of 150°C. The current heat sink system uses a fin type design with several cooling fans oriented horizontally along each side. This design once installed into an electrical converter contributes up to 50% of the total weight and takes up a large amount of space. These characteristics reduce the amount of electrical components that can be installed in the converter which also reduces its efficiency. It is also currently over-designed as the heat sink remains cool throughout all operation.

"The current heat sink system is over designed and takes up too much space and is too heavy once installed under the electrical converter."

2.2 Background Research

2.2.1 Power Loss Calculations

Switching losses in power MOSFETs are the dominant power loss in power electronic converters. Parasitic capacitances in power MOSFET include gate-source capacitance, gate-drain capacitance, and drain source capacitance. To calculate the switching loss for a power MOSFET, a common expression used is $P_{SW} = ½ V_D I_D(t_{OFF}+t_{ON})f + 1/2C_{OSS} V^2_D f$ [1]. Where C_{OSS} is the output capacitance given by $C_{OSS} = C_{GD} + C_{DS}$ [1] and is thought to introduce the heating of the MOSFET during turn-on through dissipation of energy. This energy was initially stored in the capacitor during the turn-off cycle. These equations for calculating switching losses are widely accepted and used, however they are not as accurate as other methods [1]. C_{OSS} term for calculating the switching power loss overestimates the turn-off switching loss and underestimates the turn-on switching loss [1]. This overestimation and underestimation do not cancel each other out and in turn introduces erroneous error. However, since the net power loss contribution from C_{OSS} is minimal, the term can be ignored in power loss calculations.

Another error introduced in common power loss calculations is to approximate V_{DS} as a linear waveform which is introduced by the switching power loss from the equation above. Instead, defining the gate charge Q_{SW} as Q_{SW}^* allows us to neglect the gate charge increment accounting for the gate voltage that was still in the plateau. Using the gate current $I_{GS}^* = V_{gs} – V_P/R_g$ and $Q_{SW}*$, we can further estimate the switching power loss in a more accurate model. Table III of [1] shows us the results of using these new tools. It is important to note that in this paper, the parasitic inductance loss in power MOSFETs is not explored and this also constitutes a significant loss.

A newer switching device that is being investigated is the Silicon Carbide (SiC) MOSFET. The SiC MOSFET introduce smaller parasitic capacitance while higher switching speed are achieved. Higher switching speeds contribute to the lowering of losses in switching devices by reducing the losses in the switching cycle which is where most losses occur. A method for calculating power loss, is to assume that the gate driver is an ideal voltage source and the common source stray inductance L_S and gate resistance are varied, a model like the figure above is used to simulate the switching capability of the SiC MOSFET. Due to the face that the parasitic capacitance is listed in the datasheets as combinations of the MOSFET port capacitances, and the fact that these port capacitances play different roles in the switching cycle, these capacitances must be taken into account separately for the model to be as accurate as possible. During the turn-on switching, two things happen, the current rises rapidly through the MOSFET, and the voltage drops. The two currents that are observed are the drain current and the channel current. The channel current contributes significantly more than the drain current, specifically in the falling voltage region. This channel current surge is due to the discharging of C_{ds} and C_{gd}, which were charged during turn-off, so that during turn-on voltage fall phase, Channel current = load current + discharge current of C_{ds} + discharge current of C_{gd} [2]. This charging and discharging can be viewed in terms of energy as $E_{on} = E_{on}(\text{measured}) + E_{oss}$, where E_{oss} is the energy stored in $C_{oss} = C_{gd} + C_{ds}$. The measured energy is calculated by integrating voltage and current that is measured.

These various methods and techniques for calculating power loss offer better insight into possible solution methods for project 13.

2.2.2 Heatsink Design

The purpose of a heat sink is to transfer heat generated by a source to the environment, so that a device is properly maintained and does not overheat. Creating heat sinks that are smaller in size and weight but that still effectively transfer heat is critical as technology advances. Important factors in the heat sink design that will affect its performance include the overall dimensions of the heat sink, the properties of the material used, and the size, shape, and number of fins used. Conduction, heat transfer through a material, and convection, heat transfer through a moving fluid, are both involved in the thermal analysis of a heat sink. Heat sinks can operate by natural convection or, if fans are used, by forced convection. In order to optimize heat sink performance, various fin types have been developed. A study by Annuar and Ismail compared many different configurations of pin fins including inline, staggered, and randomized [3]. Pin fins were shown to dissipate heat better than plate fins. The inline arrangement resulted in smooth airflow; the staggered arrangement had a little better heat transfer performance but resulted in turbulent airflow. The randomized arrangement combined the effects of inline and staggered and resulted in the best thermal performance. A study by Drofenik, Stupar, and Kolar compared heat sinks made out of different materials in order to optimize heat sink performance [4]. The advanced composite materials with high thermal conductivities were not found to have significantly better cooling results than aluminum and copper. Aluminum was found to be the most reasonable option due to its weight, cost, and manufacturability. The thermal performance of a heat sink design can be analyzed using the finite element method (FEM) through software such as COMSOL Multiphysics.

In a study by Ning, Lei, Wang, and Ngo, an analytical model was developed to optimize a heatsink-fan system to reduce the total weight of the cooling apparatus [5]. The heat sink design chosen for analysis was the plate fin heatsink made of aluminum with a cooling fan blowing horizontally along the fins. The design parameters that contribute to the total weight of the system were found to be the heatsink length, fin number, fin height, fin width, channel width and the weight of the fan being used. The MATLAB optimization toolbox was used to optimize the heatsink-fan system based on the parameters previously given. The dimensions and the fan used were then loaded into a thermal analysis tool for thermal resistance verification. The analytical, simulated and experimental model yielded a thermal resistance of 2.5 K/W, 2.47 K/W and 2.44 K/W respectively. This indicates that the procedure of optimization can be implemented as a proven guideline to reduce the weight with optimal heat transfer.

One article titled "Sub-Optimum Design of Forced Air Cooled Heat Sink for Simple Manufacturing" discusses maximizing the power density of a converter with a focus on minimizing the size of the heat sink. The paper studies a few different fin geometries and compares different configurations for fins and fans. The report also compares testing results for Copper and Aluminum heat sinks. In one case, a Copper heat sink was found to be 15 % more thermally resistant than its Aluminum counterpart, but it was also 4 times the weight. The study concludes that Aluminum proved to be better than Copper in the overall improvement of power density for the 5 different heat sink configurations that were looked at. In this study, Kolar and Drofenik also remarked that the largest constraint in designing heat sinks is the limited manufacturing size of Aluminum and Copper Sheets. The article suggests that if the fins could be thinner, the power density would improve significantly [6].

2.3 Goal Statement and Objectives

This project will aim towards creating a cost effective lightweight thermal structure for future photovoltaic converters. This will allow for easier and faster installation time of the future PV converters. Figure 1, shown below, shows a high level diagram of the responsibilities for both electrical engineering students and the mechanical engineering students. Each subset of students will be performing their respective research in order to complete their portion of the overall project. After the students of the electrical or mechanical engineering discipline complete their individual tasks and responsibilities, the two teams will combine their work for testing of the final result. Collaboration between the two disciplines will be crucial in the early stages of planning to ensure the team is headed in a cohesive direction.

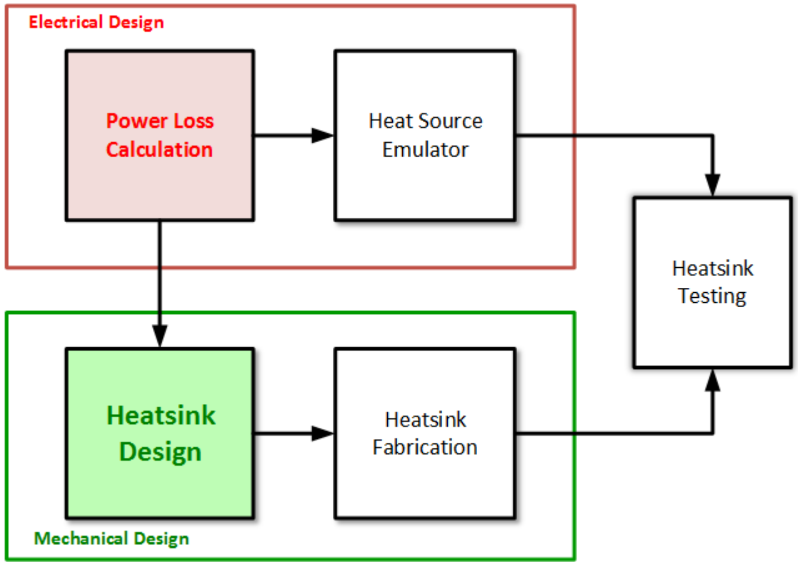


Figure 1 – Responsibilities of EE and ME Students (Image Courtesy of Thierry Kayiranga)

The process of simulating and designing the extra lightweight PV converter will be completed over a number of months; this internal timeline is outlined below in table 1.

Table 1 – Internal Timeline for Team 13

Background Research	Present – October 17
Power Loss Calculations	October 17 – November 14
Heat Sink Simulations	October 17 – November 14
Prototype Specifications	November 14 – December 1
Optimization	December – May

2.4 Constraints

These constraints are set by the sponsor and are targeted towards the customer's needs.

- Must be made of aluminum alloy
- Weigh less than 6.5 kg
- Prevent up to eight power modules from exceeding 120°C
- Project must not exceed the budget of $400.
- Take up less space than current design.

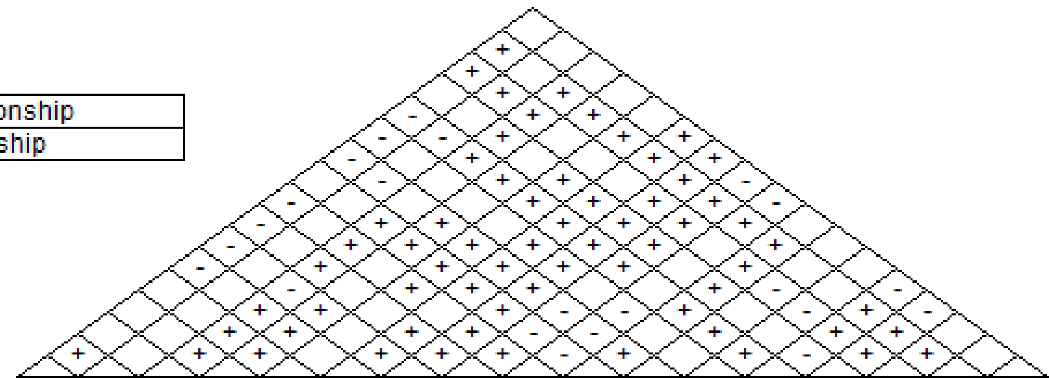
3. Methodology

From the first meeting, it became evident that the main priorities for the project are to minimize the weight and size of a PV converter by optimizing the design of the heat sink which takes between ½ to ¼ of the systems' weight. The current heat sink that is being used is over-designed, and gives the entire system a power density of about 2.5 kW/kg. Researchers at CAPS are interested in doubling this ratio.

In order to prioritize different aspects of the design process, the main customer requirements and engineering characteristics have been laid out in the following House of Quality displayed in figure 2 on the next page. This House of Quality helps determine the engineering characteristics that play the most important roles in this project. One can see from the row labeled "Relative Importance Weighting" that some of the most important characteristics in the design of this heat sink include the shape of the heat sink, the material used, the size of the heat sink, number of fans utilized, and the number of fins or pins. However, due to the constricted internal timeline of producing a prototype, this team is going to need to prioritize its time doing research in certain areas. Due to the budget, available resources, sponsor desires and the issue of time conflictions, this team will not go into grave detail questioning the material that has been selected for the project. It is in the scope of this project to iterate and optimize the design, so considering alternative materials could be something looked into at a later point after the first prototype is complete, possibly in the spring semester. The next stage is to collect material properties, and obtain concrete measurements, and begin calculations analyzing and simulating the advantages and disadvantages of different heat sink designs. Some machining limitation discussions have already taken place, but the team will need more concrete values before engineering analyses can be performed. It is desired to have all background research done by October 17 so the team can start on the power loss calculations, heat sink simulations, and prototype specifications.

+ Positive or Reinforcing Relationship
- Negative or Tradeoff Relationship

Strong (9)	■
Medium (6)	◆
Weak (3)	○



		Engineering Characteristics																
		up	down	up	n/a	n/a	n/a	down	n/a	n/a	n/a	n/a	down	down	n/a	n/a	n/a	n/a
Customer Requirements	**Customer Importance**	Power Density	Total Power Loss	Heat Transfer Rate through Heat Sink	Max Allowable Temperature of Power Switches	Operating Temperature Range	Heat Sink Shape (Pins vs. Fins)	Heat Sink Size (1 large vs. 8 small)	Number of Fins or Pins	Material(s)	Air Flow Velocity (if Fans are Used)	Fan Power Requirement	Fan Weight	Number of Fans	Fan Placement	Reliability	Heat Transfer Coefficient	Easy to Machine
$400 Budget	3		○	○	○		○	○		■	○			○		◆		■
Inexpensive to Manufacture	2		○	○	○		◆	○	○	■	○			○		○	◆	■
Lightweight	5	■					■	■	◆	■			■	■			○	○
Reduced Size	5	■		■			■	■	◆	○			■	■			○	◆
Double the PV Converter's Power Density (5kW/kg)	5	■	○	◆		◆	◆	■	◆	◆		○	■	■				
6063 T5 Alumunum Extrusion Alloy for main material	4	◆		■	◆	■	○	○	○	■				○			■	◆
Keep Temperature Rise within Targets	5			■	■	■	■		■	■	■		◆	◆	○	◆	■	
Operate with an Emulated Heat Source	4			○	■	■	○		○	○	○				○	◆	○	
Complete 1st physical prototype in 2 months	3						■	◆		○				○		◆		○
Iterate the Process	1		○	◆		■	◆	○	○	◆	◆			◆	○		○	
Importance Weighting		159	33	189	120	156	243	183	168	243	78	15	165	207	30	96	138	123
Relative Importance Weighting		6.78	1.41	8.06	5.12	6.65	10.36	7.80	7.16	10.36	3.32	0.64	7.03	8.82	1.28	4.09	5.88	5.24

Figure 2 – House of Quality

4. Conclusion

Through collaboration and synergy of the mechanical engineering and electrical engineering departments, a lightweight, thermal conscious design of heatsinks can be achieved. The research phase is currently underway and will be focused on until mid-October to ensure a solid background in the respective fields of interest. As time goes on, more background research will be included in future reports and presentations. The needs set forth by this report and the customer have been assessed and taken into account when reviewing the literature to ensure a focus is maintained towards the overall project goal. The constraints for this project will be feasible when the designing phase is initiated.

To reduce the weight of the heatsink and ensure proper temperature parameters are met, multiple viewpoints will be considered in the upcoming weeks as outlined by this report when the overall design is discussed.

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