Project Scope & Plan

Team 13

Designing & Testing Thermal Management System for SiC PV Converter

Members:

Melanie Gonzalez	mtg12c
Leslie Dunn	lvd12b
James Hutchinson	jrh12c
Tianna Lentino	tnl13
Colleen Kidder	cmk13

Faculty Advisor/s

Dr. Hui Li

Dr. Juan Ordonez

Sponsor/s

The Center for Advanced Power Systems (CAPS)

PowerAmerica – U.S. Department of Energy

Instructor/s

Dr. Chiang Shih

Dr. Jerris Hooker

January 27, 2017

Table of Contents

Table of Figures

Table of Tables

ABSTRACT

In silicon carbide photovoltaic converters, it is necessary to manage the thermal by-product of power electronic devices to prevent failure of the system. One of the most common methods to remove heat from the system is to use a heatsink. Typically, a heatsink will be about 30% of the overall system weight and significantly impacts the size of the converters. These heatsinks are usually not optimized to fit the specific power module and tend to be overdesigned which translates to wasted material, as well as an increase in the weight, size, and cost of the overall. Team 13 aims to produce an optimal heatsink design as well as a heatsink and fan selection guide to help improve the power density of a PV converter being developed by researchers at the Center for Advanced Power Systems. This project focuses on studying forced convective aluminum heatsinks with two different fin designs: cylindrical pin fins and rectangular plate fins. In this report, the team re-evaluates the project scope and constraints, and explains the approach as well as progress to date. The team explains challenges that have been encountered and the expected schedule and results for the remainder of the projects duration.

ACKNOWLEDGMENTS

Team 13 would like to express gratitude to Dr. Li for the opportunity to work on the Designing and Testing of Heatsinks for PV Converter as well as for providing assistance through her graduate students and laboratory space to conduct project proceedings. Team 13 would also like to thank the graduate students, specifically to Thierry Kayiranga for providing feedback and support on this project.

Thank you to Dr. Wei Guo and Dr. Juan Ordonez for providing insight and assistance with challenges faced by the team.

Thank you to the FAMU-FSU College of Engineering, Mechanical Engineering Department, and Electrical Engineering Department for providing the knowledge needed to participate in the Senior Design. Thanks to FSU CAPS and AME, as well as Power America for sponsoring the project.

Lastly, Team 13 gives thanks to Dr. Shih and Dr. Hooker for coordinating the team configuration and providing the guidelines needed for a successful semester ahead.

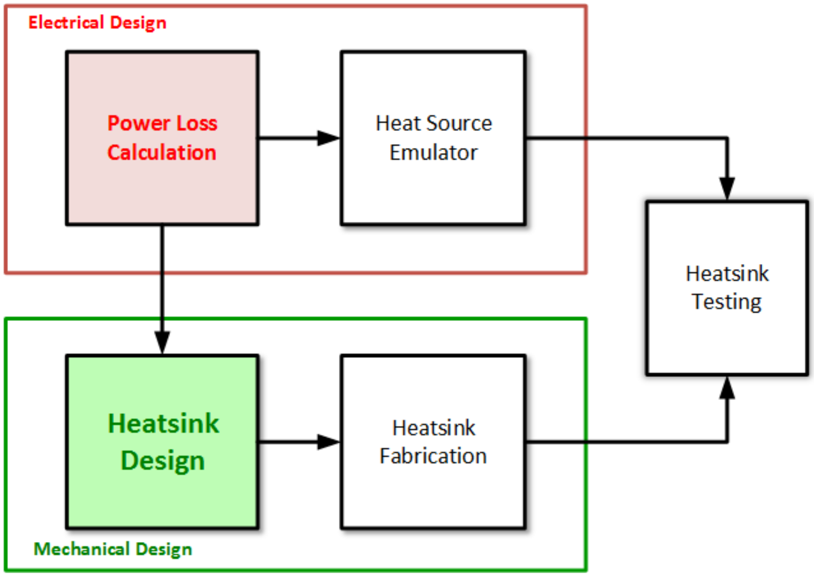
1. Problem Statement

Silicon Carbide(SiC) switching devices are wide bandgap semiconductors that are the future of semiconductor devices. SiC devices can cut power losses in half compared to its counterpart silicon. This is because they switch at higher frequencies and operate at higher temperatures and high voltage. These wide bandgap devices are more efficient but more expensive than the popular silicon choice. Applications of wide bandgap power electronics can impact small electrical devices such as computer chargers, which can be made smaller and more efficient, and large solar farms and wind turbines, which can be connected to the grid efficiently. Many industry leaders, including PowerAmerica, wish to make SiC a viable, cost-effective option for power electronic device manufacturers. To do so, research in converters that incorporate SiC switching devices must be done in order to lower the overall system cost. One way to reduce the cost of power converters is to improve the thermal management system that is used to cool these devices.

Usually, heatsinks are used to remove the heat generated as a by-product from power electronic devices. However, these heatsinks have a flaw in their design – they are rarely optimized for the specific application and this can significantly impact its overall design. Not optimizing a heatsink can result in a much larger, more expensive, and a heavier thermal management system. This project proposes a way to improve the thermal management system for a SiC photovoltaic converter to make the system cost effective, smaller, and lighter.

2. Project Goals and Objectives

This project will aim towards creating a lightweight thermal structure for future photovoltaic converters. This will allow for easier and faster installation time of the future PV converters. By decreasing the weight of the heatsink that is the PV converter's cooling system, the power density of the converter will in turn increase. This will be done with the implementation of an optimized bi-modular pin fin heatsink design with the appropriate fan sizes and speed, allowing for the optimal performance of the silicon carbide PV converter. Team 13 will also create a heatsink selection guide that will provide the insight in selecting the appropriate heatsink and fans for the overall system. Figure 1, shown below, shows a high level diagram of the responsibilities for both electrical engineering students and mechanical engineering students. Each subset of students have been 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 is crucial in the early stages of planning to ensure the team is headed in a cohesive direction.



2

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

3. Approach

To implement a smaller, lightweight heatsink design for a SiC PV converter, two aspects need to be explored. One is optimizing the overall heatsink design, and the second is testing this design. In this section, both aspects will be shown in detail explaining how team 13 plans to do the lightweight design.

3.1 Heatsink Design

The heatsink weight is a crucial aspect of its design for this project. To increase the power density of the PV converter, the weight of the heatsink must be lowered. The weight of the original heatsink created by CAPS researchers, shown in Figure 2, is 6.45 kg. This heatsink has a length of 374.65 mm, width of 279.4 mm, and height of 80 mm. A plate fin design was used with 24 evenly spaced fins that are approximately 2 mm thick and extend along the width of the heatsink. The heatsink is cooled by 8 fans that each have a max flow rate of 1.94 m^3/min with half the fans being fixed to one side of the heat sink and half to the opposite end.

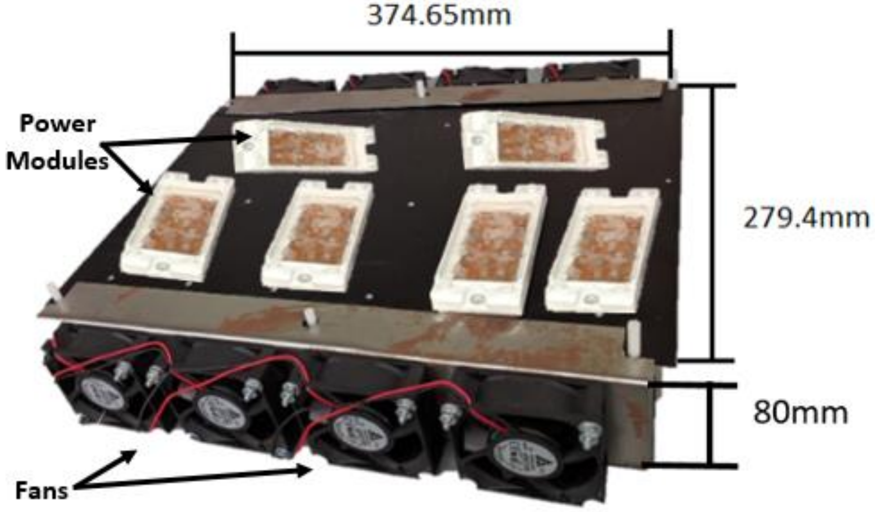


Figure 2 – Heatsink designed by CAPS researchers

The heatsink system that CAPS has developed has a power density of 2.5 kW/kg. Team 13 aims to design a heatsink that will greatly improve the overall power density. The original design has a total of 8 power modules. Stage 1 consists of 2 modules laid horizontally along the top of the heatsink baseplate and have an efficiency of 98.5%. Stage 2 has 6 modules laid vertically under stage 1 and have an efficiency of 97.0%. The modules each have a power loss of approximately 60 W. The maximum allowable junction temperature for the power modules is 150°C. The original heatsink is over-designed, which can be observed when the power modules are in operation and the bottom of the heat sink is cool to the touch. More heatsink material and fans were used than are necessary to maintain the modules at a safe temperature. Therefore, reducing the heatsink size and weight is a feasible way to increase the power density of the system.

For the overall design concepts, it was concluded that a bi-modular concept would be the best choice in reducing the weight and producing the heat transfer needed to dissipate the heat from the power modules. This concept will implement a 4 separate heatsinks each with a total of two power modules operating on the base. Even though the original heat sink housed all of the necessary power modules, about 15% of its surface area was unused and only increased the weight of the system. By implementing a bi-modular design, the unused area can be eliminated and thus decreasing the overall weight.

Another important aspect of the bi-modular design is its potential for an increase in overall heat transfer. Due to its smaller size, the channels for airflow will also be reduced. This ensures that a constant flow of cool air supplied by the fans which will quickly enter and exit through the heatsink. The longer channels in the previous heatsink had the potential to increase the air temperature as the air would have taken a longer time to travel throughout the entry and exit points. This increase in air temperature would have had negative effects on the air flow characteristics and the heat transfer. By choosing a bi-modular concept, Team 13 can ensure that unnecessary weight and undesired air flow can be kept to a minimum. All design concepts will be made from Aluminum T-5 6063 due to its high thermal conductivity, low density, light weight, high thermal conductivity, low cost, and manufacturability.

Pin Fin Heatsink

The pin fin heatsink has 313 small circular fins and an overall length, width, and height of 113.7 mm x 113.7 mm x 17.8 mm. The pin fin also has a staggered design in which the spacing between the rows of fins alternate, rather than being equidistant. The baseplate has a thickness of 4.7 mm, and the pins each have a diameter of 3.2 mm. The inline rows of pins are spaced 9 mm apart while the alternating staggered rows are spaced 4.5 mm from the adjacent inline rows. The heatsink has one fan, approximately the size of its baseplate, fixed over the tops of the pins, which allows air to flow in the axially direction of the pins. The max flow rate of the fan is 3.03 m^3/min.

The overall weight of the heatsink including the fan is 0.553 kg. Two power modules will be placed along the topside of heatsink. The setup of the pin fin and its significant geometric features are shown in Figure 3.

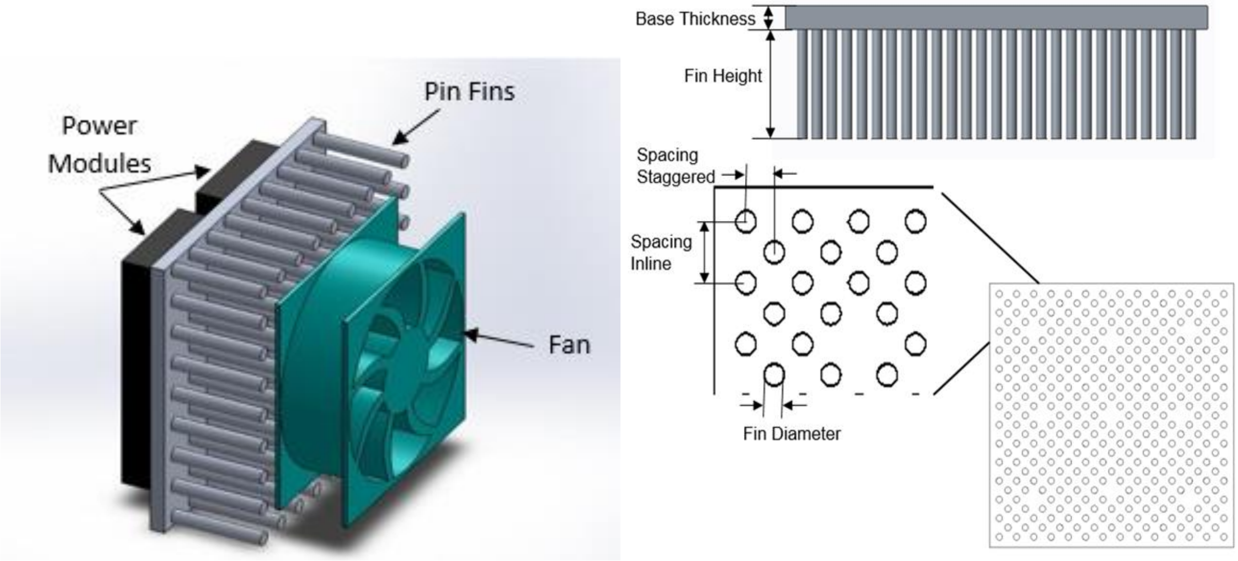


Figure 3 – Pin Fin Configuration

Due to the fan being mounted axially along the base, a larger dimensioned fan is needed to cover the area of the pins, which causes the weight of the system to increase. The fan is to be mounted in a manner where any fasteners, screws or bolts do not impinge on the pins and without changing the overall geometry of the heat sink as well. Team 13 has developed a bracket to connect the fan to the heatsink, which is shown in Figure 4. The fan is secured with 4 of these connectors, which are positioned near each of the corners of the heatsink. The short end of the bracket screws into the side of the heatsink while the long end fixes the fan in place with a nut and bolt.

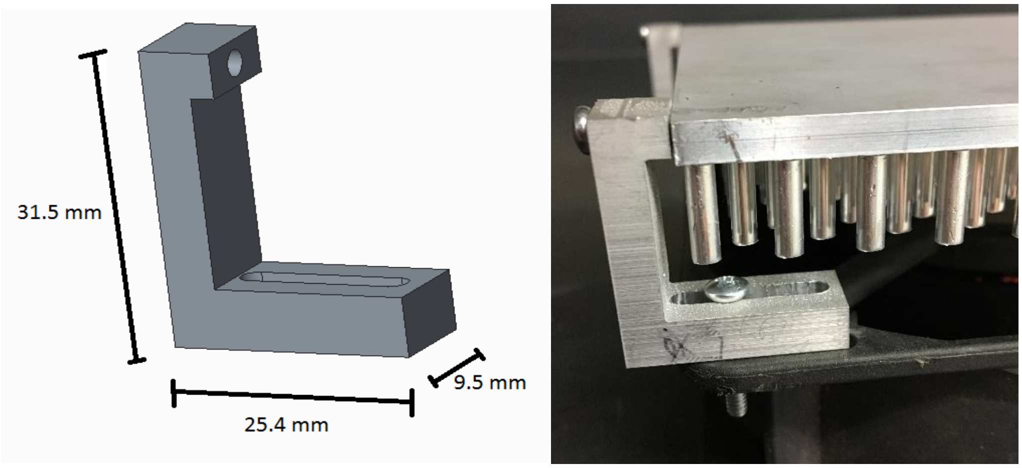


Figure 4 – Pin Fin Connector Bracket

One challenge that Team 13 faces with this heatsink is in the analytical calculations. Since the airflow going through the heat sink is in the turbulent regime, highly complicated equations are needed to determine the pressure drop and overall thermal resistance of the system. Due to the unpredictability of the turbulent regime, calculated values could differ significantly from actual experimental values. This could lead to an undesirable model for fabrication. Team 13 is still brainstorming ways to reduce the error in these calculations.

Plate Fin Heatsink

The plate fin heatsink selected for study has 9 rectangular fins and a length, width, and height of 127 mm x 127 mm x 69.2 mm. The baseplate is 6 mm thick while the fins each have a thickness of 2.5 mm. Two power modules will be evenly placed on top of the heatsink baseplate. The plate fin is cooled by 2 fans fixed to the side of the heatsink that each have a maximum flow rate of 1.73 m^3/min. The air flows over the fins in the lateral direction. The total weight of the plate fin heatsink including the fans is 0.954 kg. The configuration of the plate fin and its important geometric features are shown is Figure 5.

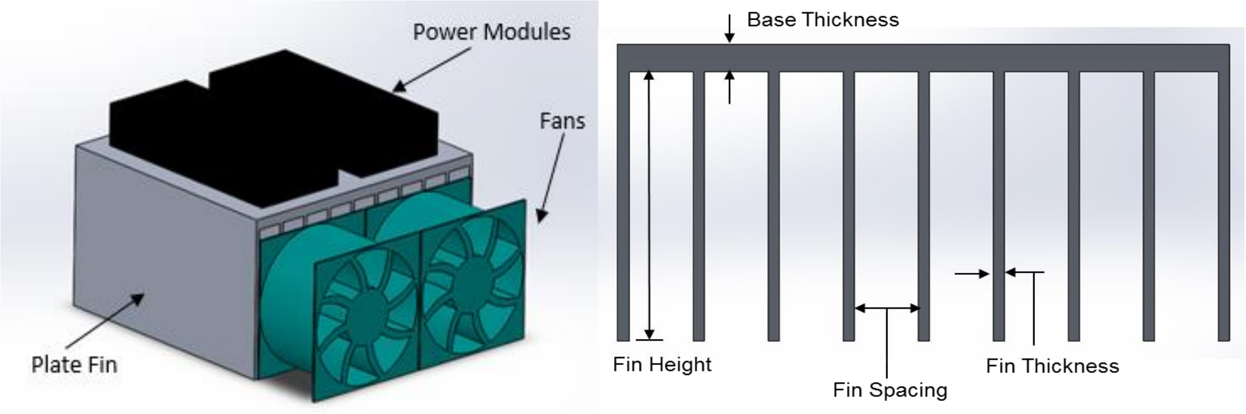


Figure 5 – Plate Fin Configuration

The plate fin design contains two main advantages, one being that the air flow will act in the laminar regime making the analytical process less complicated and more in line with experimental testing. However, there will be a slight decrease in heat transfer due to the laminar airflow. The manufacturability of the design is also an advantage as plate fin heat sinks are cheaper and more customizable as compared to their pin fin counterparts. This advantage will help Team 13 significantly as the more customizations will result in more possible configurations for reducing the weight of the heat sink, and the low cost will help maintain Team 13 within the budget.

Heatsink Analysis

Analysis was conducted for both Bi-Modular designs assuming steady-state heat transfer, incompressible air flow, an ambient temperature of 20°C, and a heat source of 120 W. The analysis included mathematical formulas to obtain the thermal resistance and pressure drop along with COMSOL simulations to determine the base junction temperature. The overall weight of the designs was determined through SolidWorks program and product specification sheets.

The plate fin heatsink was determined to have a weight of 0.954 kg, a pressure drop of 7.406 Pa, a thermal resistance of 0.335 K/W, and a max junction temperature of approximately 41°C. The pin fin heatsink was determined to have a weight of 0.553 kg and a max junction temperature of 36°C. The original heatsink holds 8 power modules while the bi-modular design can fit 2 modules. In order to properly compare the weight of the original heatsink to that of the bi-modular plate fin and pin fin designs, their overall weights must be multiplied by four. The adjusted plate fin weight is approximately 3.816 kg while that of the pin fin is 2.212 kg. The bi-modular design reduces the weight of the heatsink system by 40.8% for plate fin and 65.7% for pin fin. With these values known, a baseline is able to be made for the experimental testing of the two designs.

3.2 Heat Source Emulator

In order to test the proposed heatsink design and not risk any damage to the power modules used in the SiC PV converter, a heat source emulator has been constructed. Each power module has a 60W power loss that physically manifests as heat generated. To emulate this loss, a heat source will be constructed using high power resistors, capable of consuming 60W.

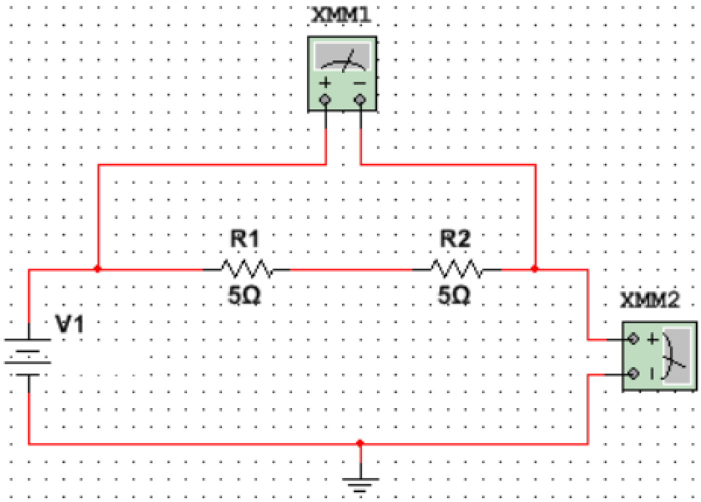


Figure 6 – Circuit Diagram for 1 Emulator

Team 13 acquired ten 5 **Ω**, 50W resistors to use for the heat source. In order to achieve a 60W power loss, at least two of these resistors must be used per heat source. The figure above shows the circuit diagram of this configuration to reach the desired power loss. With two 5 ohm resistors in series, and an input of 24.5 V, the desired 60W of loss is achieved.

In order to model the power modules, a copper base plate must be used for the heat source to distribute the heat generated by the resistors. The copper plate is less than an eighth of an inch thick has dimensions of 46mm by 108mm. To secure the heat source to the heatsink for testing, screws will be placed through the resistors and copper plate corners and one screw in the middle of the copper plate. To enhance thermal conductivity, a layer of thermal grease will be used between the resistors and the copper plate, and another layer between the copper plate and the heatsink.

$$\frac{T_j - T_a}{P_d} - R_{jc} - R_{ch} = R_{ha}$$

The purpose of testing the emulated heat source is to determine the heatsink thermal resistance. This will be determined by measuring the junction temperature, Tj, and using the equation above [1]. Ta is the ambient temperature, Pd is the power dissipated, Rjc is the thermal grease thermal resistance, Rch is the power module resistance, and Rha is the desired heatsink thermal resistance. The thermal resistance of the heatsink can be calculated after testing using the above formula. The thermocouple between the copper plate and heatsink will measure what is known as the junction temperature. The thermal resistance is an important parameter of heatsink design which described the thermal conductivity of the heatsink. The lower the thermal resistance of a heatsink, the more effective the heatsink is at dissipating heat. For the proposed bi-modular design, two heat sources must be used on a single heatsink.

Testing of Heat Source and Heatsink

The testing procedure to determine the thermal resistance in order to optimize the heatsink is as follows:

1. Place 2 heat source emulators on the base of the heatsink. Make sure to place the K-type thermocouple underneath one of the heat sources.
2. Connect a DC power supply to the heat sources and the fans appropriately.
3. Measure the ambient temperature of the setup with the thermocouple.
4. Apply an input of 24.5 V to the heat sources and an input of 0.5A for the fans.

5. Take measurements every 5 minutes until a steady state temperature is reached and record values. A steady state temperature is reached when the temperature is unchanging for 20 minutes.
6. A thermal camera may be used to record the final temperature of the system.
7. Once a steady state temperature is reached, record final temperature value as indicated by thermocouple and calculate thermal resistance.

4. Challenges and Constraints

4.1 Project Constraints

As the design moves into its finals phases, the constraints of the project have become more defined in order to guide the project to the finalized build. These constraints were adjusted back at the end of the fall semester and will remain unchanged throughout the end of the project.

- Heatsink must be made out of Aluminum alloy.
- Heatsink must weigh less than 6.5 kg
- Prevent eight power modules from exceeding 120˚C (30 degrees below failure point)
- Reduce size of current design
- Heatsink must have a maximum thermal resistance below 0.792 K/W

4.2 Challenges

Multiple challenges have been noted during the length of this project, both stemming from the analytical and design fields. In the analytical realm, our group is still struggling to come up with accurate calculations that can predict the thermal resistance for the pin fin heatsink design. Currently our analytical estimations produce a high amount of error when compared to the design's manufactured specifications. The primary source of this error is due to the air flow. The air flow in pin fin heatsinks tend to operate in the turbulent regime making mathematic modeling highly difficult due to the unpredictability. In the future we plan on speaking to Dr. Kumar, a thermal fluids professor, and doing more research to develop an accurate analytical method to reduce the error.

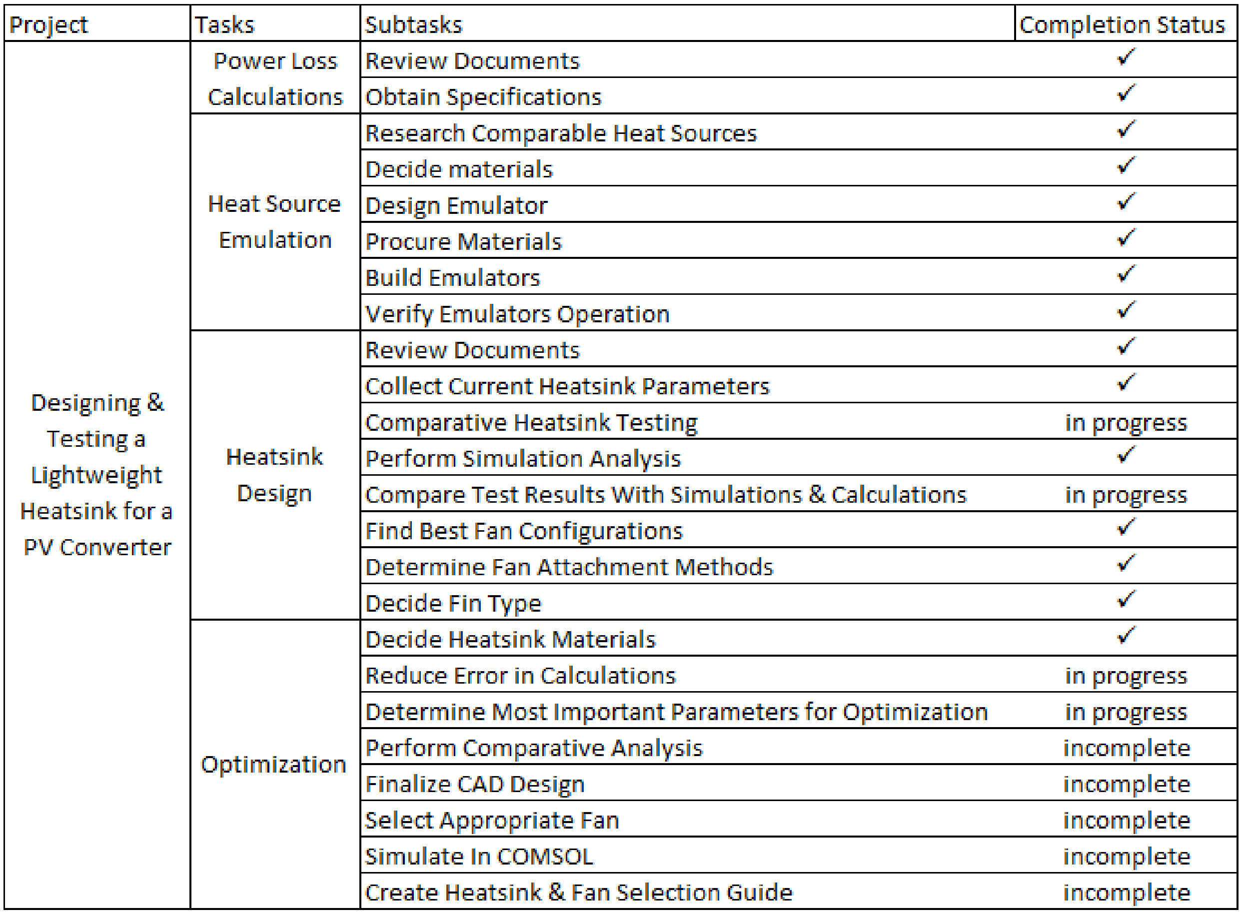
In the spectrum of design, another challenge would be the manufacturing of the optimized heatsink. During the optimization process, the heat sink will undergo many geometrical variations until the final design is reached. This finalized design however may not be inexpensively manufacturable possibly due to spacing, length or any of the other variable geometrical features. Due to this, finding vendors that can manufacture customizable heatsinks will be of major importance.

5. Deliverables and Schedule

In order to compensate for the fact that the finalized design may not be economical to be produced, Team 13 has made the decision to also develop a heatsink selection guide to present to the Sponsor by the end of the year. The team will also deliver the optimal design to Dr. Li. These resources will provide her with enough information to select a sub-optimal heatsink design which will still significantly reduce the weight of the thermal management system for the PV Converter.

In Table 1 a work breakdown structure has been provided for this entire project. The subtasks that have been completed have a check mark in the 'Completion Status' column. The tasks that are in progress and the ones that are not yet completed are labeled as so. Many of these tasks are also laid out in a Gantt Chart shown in Figure 7. This Gantt Chart does not show the tasks that were completed last semester, but lays out what is expected to be done for the remaining time available.

Table 1: Work Breakdown Structure



Project	Tasks	Subtasks	Completion Status
Designing & Testing a Lightweight Heatsink for a PV Converter	Power Loss Calculations	Review Documents	✓
		Obtain Specifications	✓
	Heat Source Emulation	Research Comparable Heat Sources	✓
		Decide materials	✓
		Design Emulator	✓
		Procure Materials	✓
		Build Emulators	✓
		Verify Emulators Operation	✓
	Heatsink Design	Review Documents	✓
		Collect Current Heatsink Parameters	✓
		Comparative Heatsink Testing	in progress
		Perform Simulation Analysis	✓
		Compare Test Results With Simulations & Calculations	in progress
		Find Best Fan Configurations	✓
		Determine Fan Attachment Methods	✓
		Decide Fin Type	✓
	Optimization	Decide Heatsink Materials	✓
		Reduce Error in Calculations	in progress
		Determine Most Important Parameters for Optimization	in progress
		Perform Comparative Analysis	incomplete
		Finalize CAD Design	incomplete
		Select Appropriate Fan	incomplete
		Simulate In COMSOL	incomplete
		Create Heatsink & Fan Selection Guide	incomplete

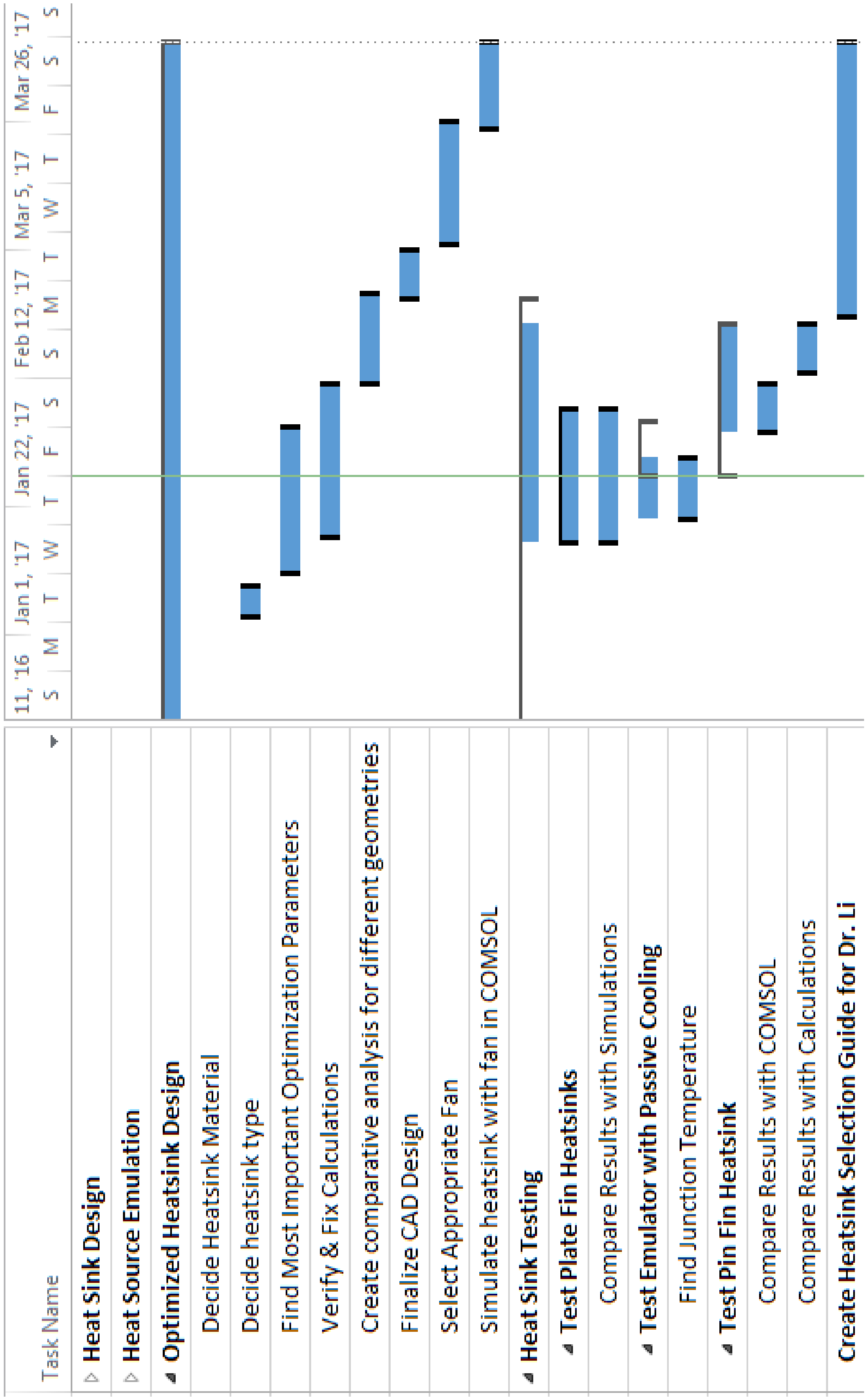


Figure 7: Gantt Chart

Currently, Team 13 is performing tests with the heat source emulators to verify their performance and see how the test results compare with simulations done in COMSOL. The team is also working to alleviate calculation errors for the pin fin design, as well as to identify the most important parameters for optimization of the heatsinks weight. Once this is complete, Team 13 can see how these parameters relate to one another and finalize the optimal heatsink design. The team can select a fan, and simulate this thermal design in COMSOL. The team will then evaluate if there is enough time and funding to actually manufacture the optimal design and will simultaneously begin work on the heatsink and fan selection guide.

6. Summary

To summarize, Team 13 aims at optimizing a heatsink provided by CAPS researchers to improve the performance of a PV converter system. This involve reducing the size and weight of the heatsink simultaneously to increase the power density. The team re-evaluated the scope of the project, making very few changes overall. The most significant changes would be the decision to eliminate the procurement process, and the decision to pursue a pin fin design. Providing an optimal design and heatsink selection guide to the sponsor will simplify this task as CAPS researchers continue their work on the PV Converter. In order to tackle completing the optimized design, Team 13 plans to continue testing while also reducing the errors in the analytical models. Once these two stages are complete, a thorough optimization process will follow in which different geometrical parameters will be varied on the selected heatsink. This method will ensure that the heatsink will have the best heat transfer while keeping the size and weight to a minimum.

References

[1] Miao, Wenjie. ‘Thermal Analysis and Heatsink Design for Silicon Carbide-based T-type Inverter’, Florida State University, 2015.