Project Initialisation Document

Thermal Modelling and temperature prediction of an IMS PCB power module

Project Description

This research project focusses on developing a thermal characterisation model of an insulated metal substrate (IMS) PCB containing a H-bridge to predict its temperature. The key aims of the project will begin with some background research on why temperature prediction models are increasingly becoming more important, the theory behind characterising the thermal behaviour of a system and how to produce a suitable thermal model. Following this, the operation of the circuit being modelled will be studied, such as how to measure temperature data from the digital temperature sensors and the general operation of the components. A repeatable and extensive testing procedure will then be designed and used to measure and extract the parameters needed to form a thermal model. Finally, the model will be compared to the actual thermal behaviour of the circuit to produce a temperature prediction system.

Project Specification

1. Research theory behind characterising, predicting and measuring the thermal behaviour of a system.
    a. Understand theory and mathematics on Foster and Cauer RC networks used to characterise exponential heating and cooling.
    b. Understand the relationship between temperature and voltage drop of the body diode within a MOSFET, specifically how to bias the body diode with a constant current source and measure the voltage drop. This can then be related to the actual temperature of the semiconductor using the diode current equation.
    c. Understand how pseudo random binary sequence (PRBS) power dissipation can be used to obtain the thermal impedance of a system.

2. Understand the hardware being used for testing.
    a. Understand behaviour of MOSFETs operating as switches, since in the context of this project they will be used as PWM controlled switches in a H-Bridge configuration.
    b. Understand how digital temperature sensors operate (TC77), such as how to use SPI to communicate with it and extract temperature readings.
    c. Order all required components needed to produce a working circuit.

3. Develop the system to be modelled.
    a. Construct the IMS PCB with necessary components by soldering on the MOSFET's, diodes, digital temperature sensors and header pins used for power and data I/O. Additionally, mount thermocouples onto the four MOSFETs.
    b. Using an Arduino, develop an SPI based data acquisition system that can measure and record temperature readings from the digital temperature sensors to be put into MATLAB to be graphed.

4. Determine the thermal characteristic of the IMS PCB.
    a. Design a repeatable test procedure that measures the temperatures in response to a step change in power dissipation. Sample rate of the digital temperature sensors will be set at a suitable rate to get an accurate graphical representation of the temperature curve.
    b. Apply the test procedure to the circuit in a controlled environment and gather temperature data.
    c. Extract Foster network model parameters from the temperature measurements by measuring the thermal time constant of the system from the MATLAB graph using the measured temperature data.
    d. Measure the temperature response of each MOSFETs by measuring the body diode voltage drop.
    e. Further extract Foster network model parameters from temperature calculations.

5. Using the RC models, develop a temperature prediction system and compare to actual temperature measurements.

Literature Review

As technologies such as electric vehicles become more widespread in their numbers and demand greater power capabilities, there is an increasing demand for power electronics to have a smaller physical footprint and deliver greater power dissipation whilst operation in challenging conditions [1][2]. This trend of operating electronics in these extreme conditions pose a risk to the device's reliability because of the higher operating temperatures and rapid thermal cycling, which causes mechanical stress on the device resulting in cracking and material degradation. In the case of high temperature fluctuations due to large power loads, mechanical stress can cause solder connections to crack, and bond wires within transistor packages to degrade or lift off.

To prevent power electronics being subjected to extreme thermal stresses, it is vital to have the ability to accurately model a system to predict the temperature of these devices in response to changes in power dissipation. In doing so, active cooling can be adjusted or power can be throttled accordingly to prevent damage and increase the longevity of the device. A paper published by Vishay Siliconix [3] describes a simple method with three stages to generate an RC thermal model for power MOSFET's, which are to develop a thermal characterization of the MOSFETs, then generate a thermal model followed by thermally simulating the model in a program such as LT-SPICE. However, this paper does not go into much depth surrounding the mathematics behind the thermal model and bases the model on data obtained from graphs in the manufacturers data sheet such as the transient thermal impedance curve. This project will aim to produce a thermal model from experimental measurements from digital temperature sensors and thermocouples placed in difference locations on the IMS PCB to get a better representation of its thermal behaviour.

Generally, thermal models of a system are generated using a Foster or Cauer RC network, shown in *figure 1,* where the resistors and capacitors represent the thermal impedance of each thermal interface, and the current source on the left represents the power dissipation [4]. There are several techniques that have been used before to extract the values of the thermal resistances and capacitances, such as measuring the voltage across the MOSFETs body diode in response to small changes in the drain current [5]. It is easier to generate a Foster network as each stage has a specific time constant made by the resistor-capacitor combination, although these parameters have no physical meaning. It is simple to extract these parameters from exponential heating and cooling temperature measurements obtained from step response experiments.

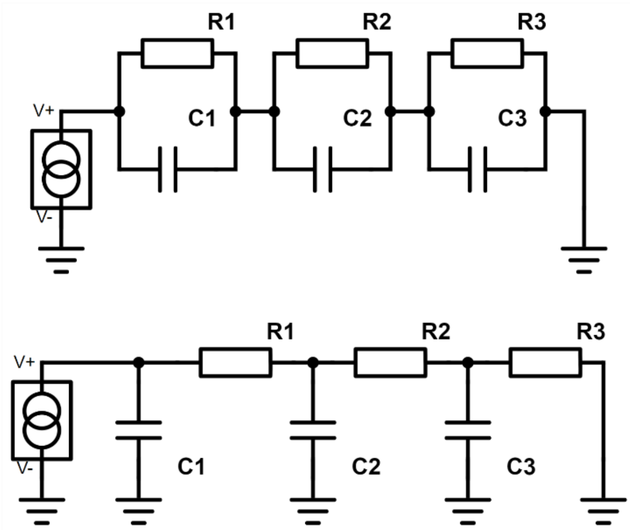


Figure 1: Foster network (top) & Cauer network (bottom).

However, the Foster network has a limitation which means it can only predict the temperature of the semiconductor junction and not the distribution of temperatures throughout the system due to the capacitors being connected node-node [6]. The Foster network can be improved by transforming it into a Cauer model, where due to the capacitors being referenced to ground (ambient temperature), the thermal distribution between interfaces can be determined as each node represents a real temperature [7].

Once a suitable Cauer model has been established, a final system model that can accurately predict the temperate rise can be made. Methods such as using a Luenberger observer can be used, which works using a state variable modelling to estimate the state of a system based on input and output measurements. In the context of this project, a temperature measurement can be taken as reference from one of the onboard temperature sensors, and by comparing it to the temperature expected by the Cauer model, the system can make small corrections to mitigate against inaccuracies in the original model. An example of a Luenberger Observer is shown in *figure 2.* [8]

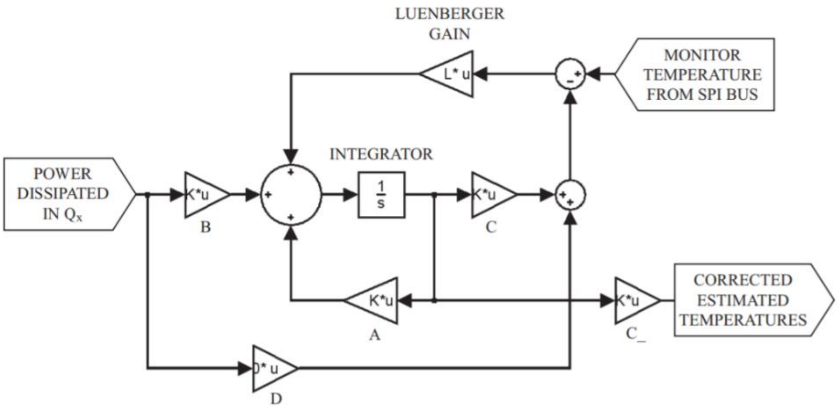
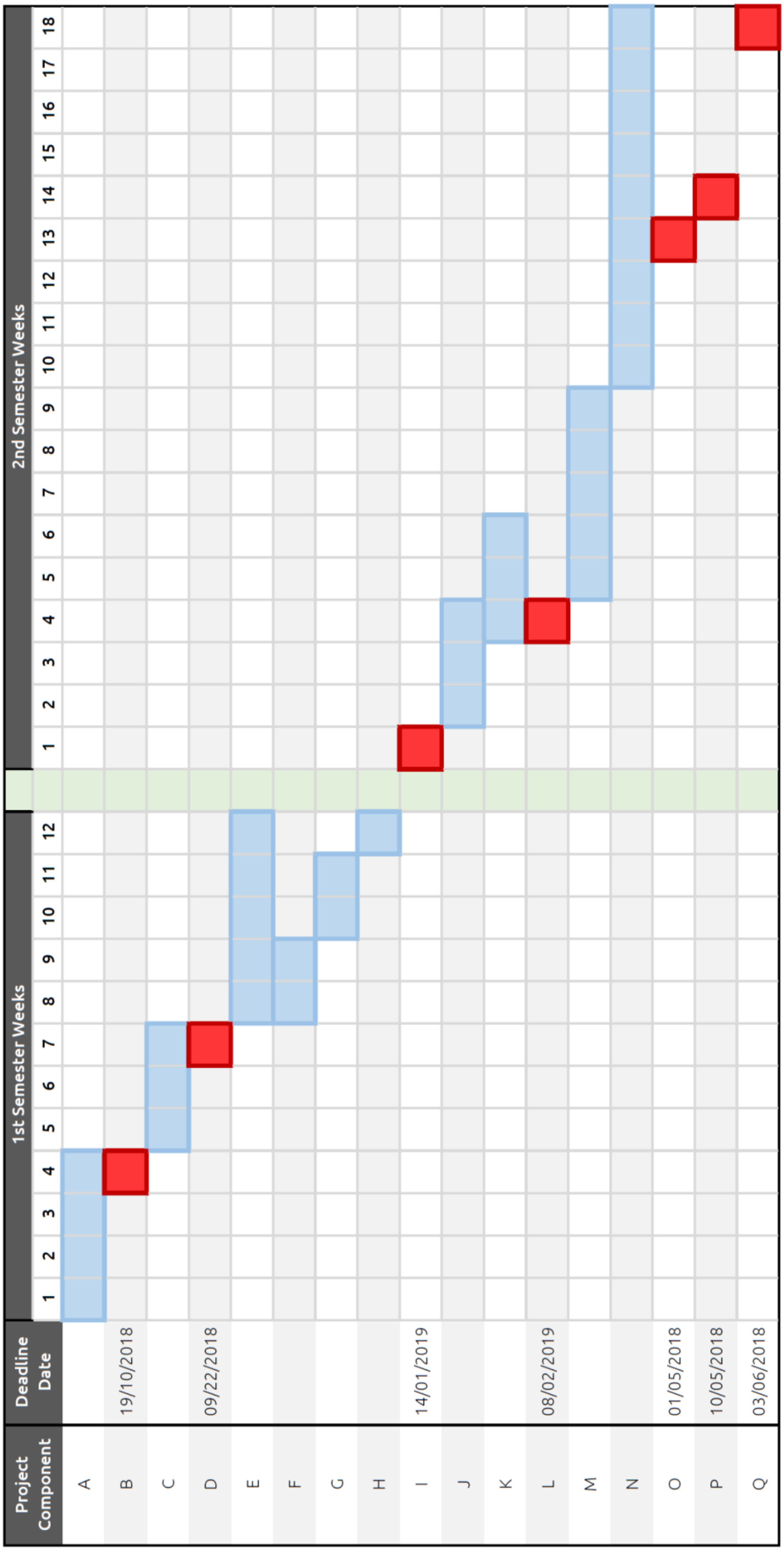


Figure 2: Example Luenberger Observer made in Simulink [8].

Project Schedule

Component	Description	Deadline Date
A	Background research and project specification review	
B	Project initialisation document deadline	19th October 2018
C	Research and documentation of relevant and required theory	
D	Second marker meeting deadline	9th November 2018
E	Understanding circuit operation and ordering of components	
F	Designing test procedures to measure required data	
G	Developing data acquisition system to measure required data	
H	Constructing IMS PCB and testing functionality	
I	Report 2 (interim report) deadline	14th January 2019
J	Temperature measurements in response to power step change	
K	Extraction of Foster model parameters	
L	Second marker viva deadline	8th February 2019
M	Developing temperature prediction system using RC models	
N	Documentation of findings	
O	Symposia (presentations) deadline	1st May 2019
P	Public engagement video & storyboard deadline	10th May 2019
Q	IEEE style article deadline	3rd June 2019

Gantt Chart


Project Component
A
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Deadline Date
19/10/2018
09/22/2018
14/01/2019
08/02/2019
01/05/2018
10/05/2018
03/06/2018
1st Semester Weeks
1 2 3 4 5 6 7 8 9 10 11 12
2nd Semester Weeks
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18

Risk Register

Risk Number	Risk Description	Risk Mitigation	Risk Evaluation	Chance of Risk
1	Loss/corruption of data	Keep multiple document backups and versions.	Medium	Low
2	Parts not arriving on time	Order as soon as possible and have planned work to complete during delivery. Order sufficient spares in case parts are dead on arrival.	High	Medium
3	Not understanding/being able to undertake a certain task	Seek guidance from supervisor sooner rather than later.	Medium	Low
4	Inadequate time to complete necessary tasks	Have a strict time schedule and seek guidance from supervisor if progress is falling behind uncontrollably.	High	Low
5	Going over projects budget	Have supervisor check over order list to ensure correct parts are ordered. Only order what is absolutely necessary.	Low	Low
6	Difficulty communication/organising meetings with supervisor	Check supervisors schedule regularly, contact 3rd year projects leader if difficulties persist.	Medium	Low

References

[1] M. März, P. Nance, "Thermal Modelling of Power-Electronic Systems," Infineon Technologies, Munich, Germany, 2000. [Online] Available: https://www.infineon.com/dgdl/Thermal+Modeling.pdf?fileId=db3a30431441fb5d011472fd33c70aa3

[2] R. E. Simons, "Microelectronics Colling and Semitherm: A Look Back," IBM Corporation, New York, USA, 1994.

[3] K. I. Pandya, W. McDaniel, "A Simplified Method of Generating Models for Power MOSFET's", *18th IEEE SEMI-THERM Symposium*, pp. 83-87, March. 2002.

[4] M. E. Raypah, M Devarajan, A. A. Ahmen, F. Sulaiman, "Thermal characterizations analysis of high-power ThinGaN cool-white light-emitting diodes," *Journal of Applied Physics*, Vol. 123, March. 2018.

[5] J. Marek, et al., "Compact model of power MOSFET with temperature dependent Cauer RC network for more accurate thermal simulations", Slovak University of Technology, Slovakia, Jul. 2013.

[6] Z. Zhou, P. M. Holland, P. Igic, "Compact Thermal Model of a Three-Phase IGBT Inverter Power Module", International Conference on Microelectronics, Serbia, Jun. 2008.

[7] S. Toufik, D. Zohir, "A New Electro-Thermal Modelling of Low Voltage Power MOSFET with Junction Temperature Dependent Foster (RC) Thermal Network," *J. Nano-Electron. Phys.*, vol. 10, no. 4, pp. 2-3, Aug. 2018.

[8] J. Holmes, M. P. Foster & D. A. Stone, "Low Computational Complexity Observer Based Modelling Techniques for Device Temperature Prediction in IMS based Systems," PEDS 2009, Dec. 2009.