Interim Technical Report

Thermal Modelling & Temperature Prediction of an IMS PCB Power Module

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1. Project Description

1.1 Topic Area Introduction

With increasing demand for power electronics that possess greater power densities, while being subject to challenging size constraints due to technological trends such as the rise of electric vehicles, the ability to accurately model and measure device temperatures is imperative to device reliability [1][2]. In the case of high-performance electric vehicles, the power modules responsible for driving the electric motors are packed into tight spaces and are subject to extreme operating conditions such as high temperatures and rapid thermal cycling, which causes mechanical stress on the device. These mechanical stresses may lead to a reduced operating lifetime and in some cases permanent failure as a result of solder joints cracking or bond wire lift off within semiconductor packages. To prevent power electronics being subject to these conditions, the ability to accurately model and predict the temperature of the devices is needed so that measures can be put in place such as power throttling or active cooling to keep the devices within safe operating regions.

The problem faced by engineers when trying to measure the temperature of devices is the ability to measure the actual temperature of the semiconductor die, which is more useful for determining performance and reliability compared to the case temperature of the device package. Furthermore, modelling device temperature becomes complex when there are several devices within close proximity to one another as the temperature of each device influences the temperature of other devices.

The primary focus of this project is to develop a suitable thermal model of a power module mounted on an insulated metal substrate (IMS) PCB. This will be achieved by instrumenting the PCB to measure temperatures under a variety of operating condition to produce a thermal equivalent electrical circuit. Once a model has been produced, a method to predict the temperature of the devices on the board due to an input power dissipation will be deployed.

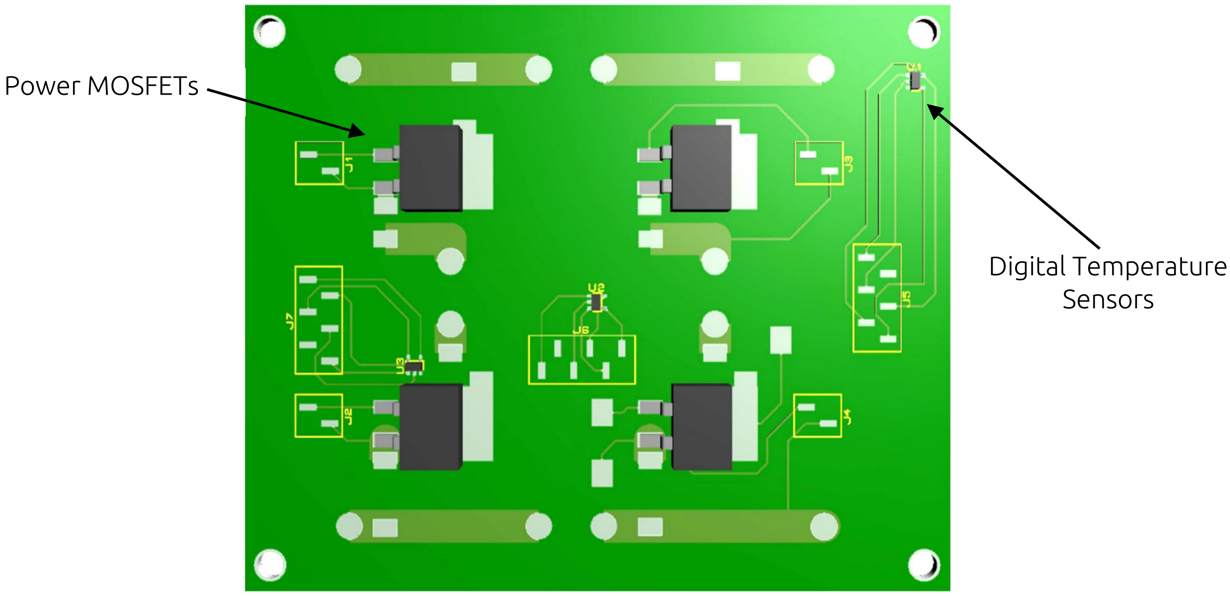

Figure 1: Power module PCB model.

1.2 Key Objectives

The key objectives of this research project are:

- Research and develop understanding of characterising the thermal behaviour of a system, such as the various instrumentation methods that already exist and techniques to produce a thermal model out of the data.
- Design a circuit that allows the reverse diode voltage of MOSFETs to be measured to calculate the temperature of the semiconductor die.
- Develop the system that is going to be modelled by soldering the necessary components onto the PCB and designing a data acquisition system that can record temperature measurements off the onboard digital temperature sensors.
- Design a suitable test procedure to obtain the thermal characterisation data needed to produce a model.
- Perform the experiments to obtain data that represents the circuits thermal self-heating and cross-coupling.
- Fit the thermal data to a suitable RC equivalent circuit.
- Model the circuit using a mathematical software package such as MATLAB so that the thermal impedance data can be used to extract temperature data for a given power input.
- Use the model to predict what the temperature rise of each device will be due to a power input using a Luenberger observer.

2. Project Specification

The project specification is unchanged from the specification presented in the project initialisation document, as shown below.

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 characterises the thermal self-heating and cross coupling of the circuit.
    b. Apply the test procedures to the circuit in a controlled environment and gather temperature data.
    c. Extract Foster network model parameters from the temperature measurements by fitting the curves to an equivalent RC exponential.

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

3. Background Theory

3.1 Temperature Measurement Techniques

A variety of techniques exist to measure the temperature of electronic devices, each with their own advantages and disadvantages. In this project, three methods of measuring temperature are used, including thermo-couples, digital temperature sensors and the relationship between temperature and the voltage drop across the body diode of a MOSFET.

Thermocouples are formed from two wires of different metals joined at their ends, where a voltage is produced when one junction is heated to a higher temperature than the other. The voltage produced is proportional to the temperature difference, hence temperatures can be measured by measuring the voltage produced by the thermocouple. [3]

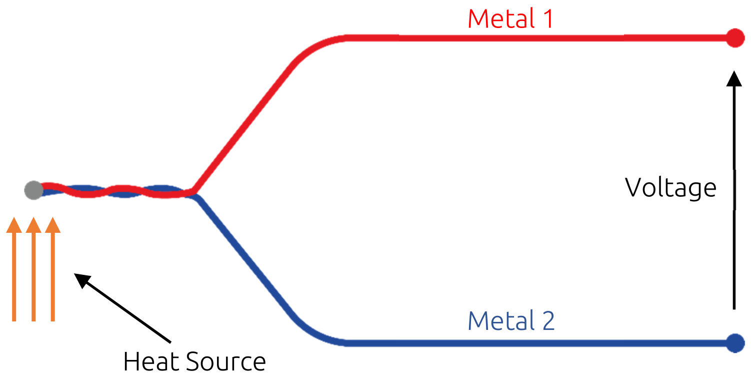

Figure 2: Thermocouple diagram.

The advantages of thermocouples include their fast response times, the wide temperature range that they can measure, and that using them is usually non-intrusive to the operation of the device they are instrumenting. However, in the context of their use in this project, they will not give a true reading of the die temperature under transient conditions due to the thermal impedance through the device's plastic casing and the thermal epoxy used to secure the thermocouple, hence there will be a slight time delay between the temperature of the die being transferred to the case and to the thermocouple. Despite this, they will be used to provide accurate temperature measurements once the whole device has reached thermal equilibrium in an insulated environment, where the die and case temperature are essentially equal.

Ideally, to mitigate the effects of the devices casing on the temperature measurements, the thermocouple would be attached directly to the semiconductor die, which would be impractical and difficult, hence another method is required to take temperature measurements closer to the die.

The body diode of a MOSFET, which is between the source and drain, has a forward voltage drop that is related to the Shockley diode equation (1).

$$V_D = \frac{kT}{e}\ln\left(\frac{I}{I_s} - 1\right) \qquad (1)$$

Therefore, if the conduction current is kept constant, the forward voltage drop V_D will be dependent on the temperature T, allowing the temperature of the device to be measured by inserting a constant bias current into the source and measuring the voltage across the source and drain of the device, as shown in *figure 3*.

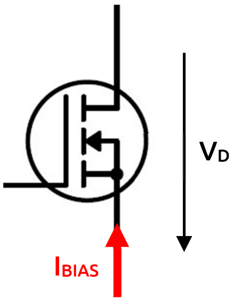

Figure 3: Power Controller Circuit.

The gate of the MOSFET must be grounded so that the conduction channel is completely off, allowing all the current to flow through the body diode, and this technique required calibration, which will be explored later in this report.

3.2 Modelling Techniques

It is possible to model the thermal behaviour of a system using an electrical equivalent network of resistances and capacitances, where the sum of the exponential terms produces the thermal response to a step change in input power. The resistors in the network represent the static thermal resistance, whereas the capacitors represent the thermal capacity.

The thermal impedance and a given time t is then given by the difference between the junction and ambient temperature divided by the difference in power dissipation, as shown in equation (1).

$$z_{TH}(t) = \frac{T_{JUNCTION}(t) - T_{AMBIENT}(t)}{P} \qquad (1)$$

The two generic forms of RC network used for thermal analysis are the Foster network and the Cauer network, as shown in *figure 4*.

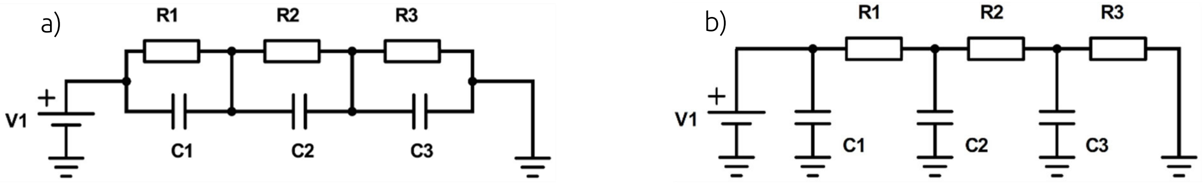

Figure 4: a) Foster network, b) Cauer network.

In the Foster model, the time constants are equal to the RC product of each section, but in the Cauer model, each time constant is dependent on all the R and C values in the circuit, hence the Foster network parameters are easier to extract from temperature response curves. However, due to the node-node capacitor connections on the Foster network, only the far-left node has any actual significance, but in the Cauer network, each capacitor is referenced to ground (ambient temperature), hence each node represents a real temperature in the system.

The self-heating, that is, the heating of a device caused by its own power dissipation can be characterised by performing step changed in power dissipation and observing how the temperature changes, which can then be fitted to a Foster network, described in the methodology.

To characterise the thermal cross-coupling, which is the heating of a device caused by the self-heating of other nearby devices, the Foster network is not suitable as previously explained due to only the far-left port representing a real temperature. To model the transfer impedance between devices, multiple ports that represent real temperature, such as a Cauer style network are required.

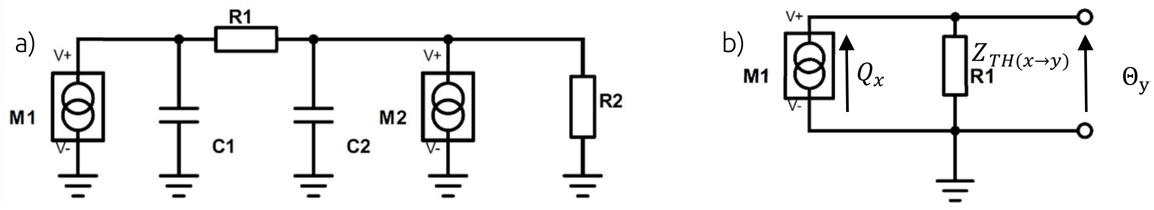

Figure 5: a) Multiple heat source network, b) Cross-coupling equivalent circuit.

Instead, the thermal cross-coupling can be characterised over a frequency range by using a pseudo random binary sequence (PRBS), which is a special signal that is effectively band-limited white noise with a uniform frequency response over its entire bandwidth. An example electrical equivalent circuit of the thermal cross-coupling between two heat sources (modelled as current sources), which can then be simplified to a simple Norton equivalent circuit that shows the impedance between a heat source and measurement point is shown in *figure 5*. $Z_{TH(x\to y)}$ represents the complex transfer impedance in the frequency domain between the heat source and measurement point, Q is the heat flux and Θ is the resultant temperature. The mathematics behind cross coupling is explained in the methodology section of this report.

In addition to the Foster network being unsuitable, the reason PRBS for cross-coupling characterisation is preferred over step response is because the conversion from the measured time domain response to a frequency domain response required for the mathematics is difficult and is susceptible to noise. [4]

By applying a PRBS as a power input waveform to a device on the PCB and observing the resultant temperature curve of a difference device on the same PCB, the cross coupling can simultaneously be measured over a frequency range.

4. Methodology

4.1 Reverse Diode Voltage Temperature Measurement Circuit

In order to measure the temperature response of the MOSFETs, a circuit needs to be designed that allows for the voltage across the body diode to be measured.

4.1.1 Voltage Measurement Circuit

A circuit, shown in *figure 6* contains a constant current source and a difference amplifier that output the different in voltage between the source and drain of the MOSFET.

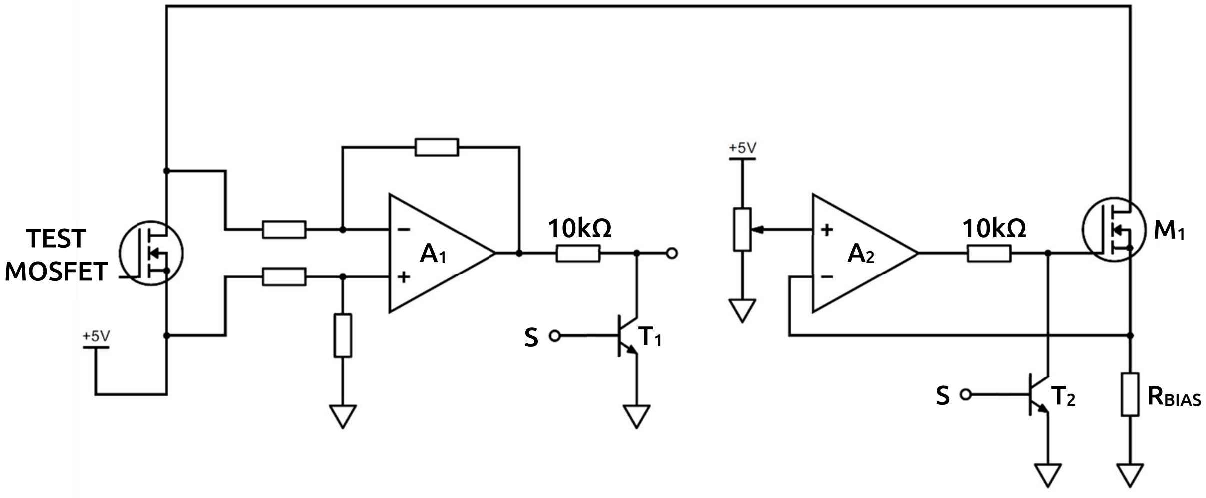

Figure 6: Reverse diode voltage measurement circuit.

The operational amplifier A2, MOSFET M1 and biasing resistor R_{BIAS} on the right-hand side of the circuit form a basic constant current source, where the op-amp ensures the voltage across the biasing resistor R_{BIAS} is always equal to the biasing voltage V_{BIAS}. The difference amplifier, formed by the op-amp and resistors on the left-hand side of the circuit will output the voltage difference between the source and drain of the MOSFET, hence providing the reverse diode voltage V_D which can be measured and recorded by an ADC. The transistors T_1 and T_2 turn off the circuit by pulling the output of the difference amplifier and the gate of the current source MOSFET to ground, which are controlled by the control signal S.

4.1.2 Power Dissipation Controller

Practically, the temperature will need to be measured under real working conditions where the MOSFET is dissipating power. For this, a circuit is needed that can control the power dissipated in the MOSFET depending on an input power waveform, which will become useful when performing characterising the circuit using a PRBS.

The circuit shown in *figure 7* allows the voltage across the MOSFET and its current to be controlled by an input voltage.

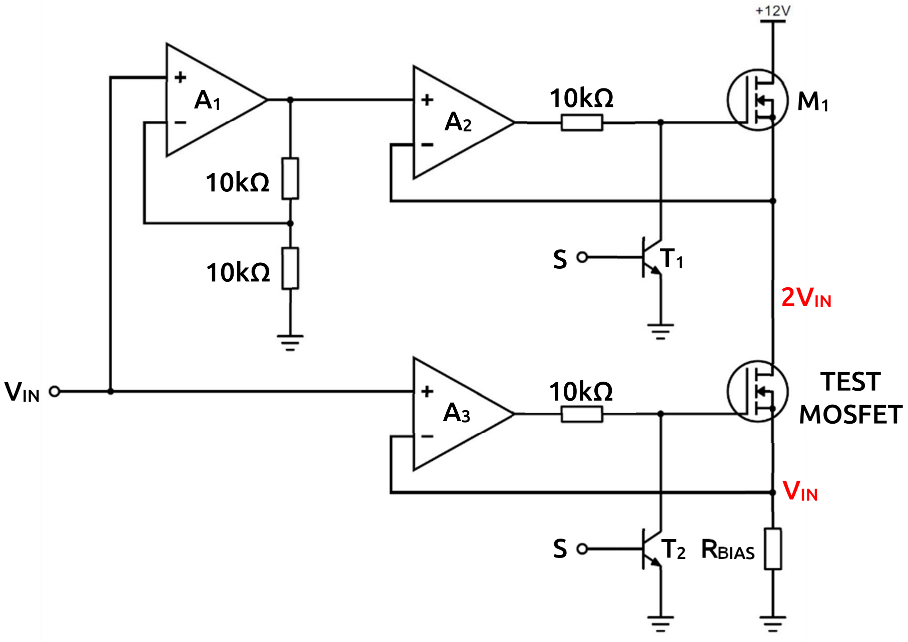

Figure 7: Power Controller Circuit.

The first op-amp circuit A_1 doubles the input voltage V_{IN} to produce $2V_{IN}$, so that the source voltage of the MOSFET M_1 is kept at $2V_{IN}$ due to the feedback into op-amp A_2. The circuit involving the test MOSFET and the op-amp A_3 is a constant current source that keeps the voltage across the biasing resistor RBIAS constant, hence the current through R_{BIAS} and the test MOSFET is also constant. Because the source voltage of M_1, and hence the drain voltage of the test MOSFET is kept at $2V_{IN}$, the voltage across the test MOSFET is kept at V_{IN}, allowing precise control over its power dissipation via carrying V_{IN}. Similar to the voltage measurement circuit, the transistors T_1 and T_2 pull the gate of each MOSFET to ground when the control signal S is high, allowing the circuit to be turned on/off.

4.1.3 Combined Function Circuit

Ideally, both the circuits presented should be combined to allow the temperature to be measured during operation. However, since measuring the temperature by measuring the voltage across the MOSFET's body diode requires a biasing current to flow in the reverse direction, the two circuits cannot work simultaneously. A work around is to rapidly switch between power dissipation and temperature measurements modes. This would involve dissipating power in the MOSFET using the previously described circuit, and then for a short time during the dissipation cycle, cease the power dissipation and turn on the voltage measurement circuit. [5]

By combining the power dissipating and voltage measurement circuits together with isolated between them (since the measurement circuit requires a voltage of the reverse polarity), as shown in *figure 8*, it is possible to switch between them.

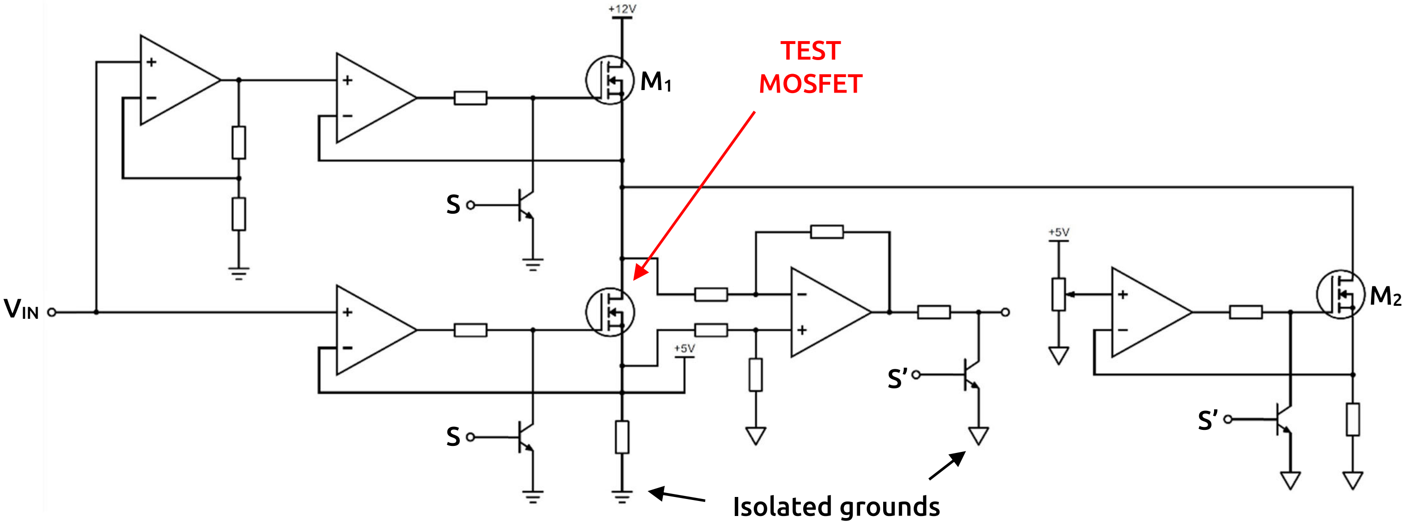

Figure 8: Combined power dissipation and voltage measurement circuit.

When S is set low, S' is high, hence the measurement circuit is turned off and disconnected from the test MOSFET due to M_2 turning off. In contrast, the power dissipation circuit is turned on, and the test MOSFET dissipates power due to V_{IN}.

Component wise, since the op-amps need to run on a single supply and still achieve an output voltage near to 0V to effectively control gate of the test MOSFET, the TLV2374IN quad op-amp package was chosen, which can achieve output voltages within tens of mV's to the supply rails. For the transistors that turn on/off each circuit in response to the control signal S, the ZTX653 BJT was chosen, and 0.1% tolerance resistors were used for the voltage doubler and the difference amplifier. The Arduino responsible for sampling and recording the voltage measurements and controlling the control signals will be powered by the measurement's circuits 5V power supply. The problem that arises is how to control V_{IN} and the control signals on the dissipation circuit because it operated on a separate supply, and therefore cannot be controlled directly from the Arduino pins. Instead, digital signal isolation is required, such as an isolated opto-couple based gate driver. However, opto-couples don't have great switching performance at higher frequencies, hence the capacitive based Si8232 gate driver was chosen which contains two separate isolated driver channels. This will allow the digital signals from the Arduino to control V_{IN} and switch the control transistors on/off on both circuits.

4.1.4 Calibration

In order to be able to convert the voltage measurements into temperature readings, the gradient and intercept of the relationship between the diode voltage and temperature must be measured. This is achieved by heating the MOSFET inside of an insulated box to a defined temperature using an external heat source such as a hot plate and connecting the MOSFET to the voltage measurement circuit to measure the diode voltage drop at that given temperature. A thermocouple is attached to the case of the MOSFET and a settling time is permitted so that whole device reaches the temperature of the hot plate. This experiment, illustrated in *figure 9* is repeated across a temperature range to produce a graph that shows how the diode voltage varies with temperature. [6]

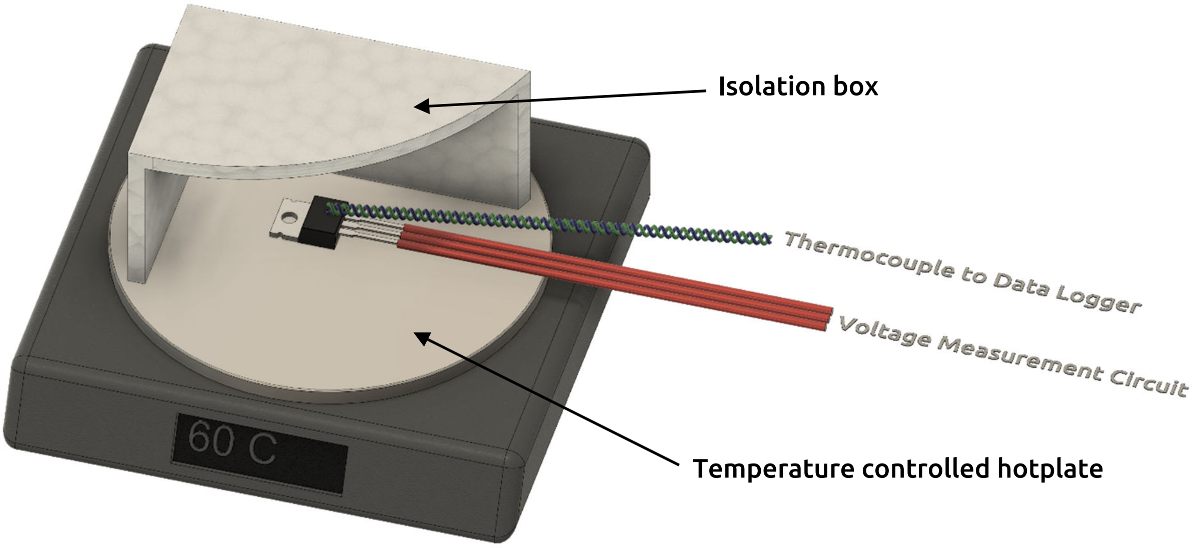

Figure 9: Apparatus for calibration experiment.

Once calibration is complete, the intercept and gradient of the relationship can be determined from the graph, and the junction temperature can be calculated using equation (4).

$$V_d = m \cdot T_j + V_0 \tag{4}$$

Where:

T_J = junction temperature (°C)
M = gradient (°C/V)
V_d = diode voltage drop (V)
V_0 = intercept (V)

4.2 Experimental Procedures

There are several experiments that need to be carried out to obtain the data necessary for characterising the self-heating and thermal cross-coupling behaviour of the circuit with the intention of creating an RC thermal model. The difference experiments and their procedures will now be explained.

4.2.2 Power Dissipation Step Response

The transient thermal impedance can be measured by performing a step change in power dissipation in the device, and observing the exponential rise and fall in temperature as seen in *figure 10* using the voltage measurement circuit.

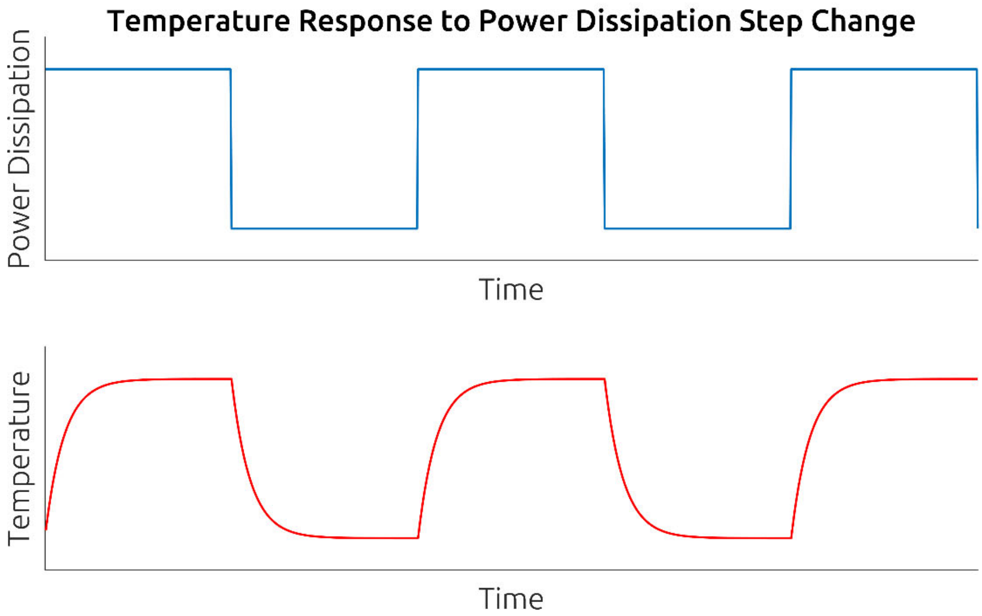

Figure 10: Power dissipation step change example graph.

Thermocouples are be mounted on all four of the MOSFET on the PCB using special thermal epoxy and connected to a data logger. The resultant curve will be assigned R and C values to fit the correct exponential shape.

4.2.3 PRBS

As previously described in the theory section, a PRBS signal (to be designed later in the project) will be dissipated in a single device on the board, while the resulting temperature response of the other devices will be measured and recorded. This experiment will be repeated for each device on the board, but if the thermal cross-coupling turns out to be very similar between each device due to their symmetrical arrangement, it can be assumed the cross coupling between is device is the same, which should reduce the computation complexity during mathematical modelling.

4.3 Thermal Modelling

Since the circuit contains multiple heat sources, each with their own thermal impedances between one another, the temperature of the devices under load will be dependent on both their own self-heating as well as the thermal contributions from neighbouring devices. Hence, a mathematical way to work out the junction temperature as a superposition of all the heat sources is required, which is in matrix form as seen in equation (5).

$$\begin{bmatrix} T_{j1} \\ T_{j2} \\ T_{j3} \\ T_{j4} \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & Z_{13} & Z_{14} \\ Z_{21} & Z_{22} & Z_{23} & Z_{24} \\ Z_{31} & Z_{32} & Z_{33} & Z_{34} \\ Z_{41} & Z_{42} & Z_{43} & Z_{44} \end{bmatrix} \cdot \begin{bmatrix} P_1 \\ P_2 \\ P_3 \\ P_4 \end{bmatrix} \tag{5}$$

Where T_{j1} – T_{j4} are the junction temperatures of each MOSFET on the PCB, P_1 – P_4 are the power dissipations for each device and the Z_{ij} matrix are the self and cross impedances. The non-diagonal elements in this matrix, where $i \neq j$, represent the cross-coupling impedance between the devices, and the diagonal elements in this matrix, where $i = j$ are the self-heating impedances of the devices.

By inserting the frequency-dependant thermal impedances into this equation, the temperature rise of each device can be determined due to an arbitrary power dissipation in each device, which can then be implemented into a temperature prediction system [7]

5. Results and Analysis

5.1 Reverse Diode Voltage Measurement Circuit

To test the functionality of the ordered components, the circuit was first constructed on breadboard as shown in *figure 11*. A push button was connected to the Arduino to allow toggling between dissipation mode and measurement mode and the Arduino terminal displayed the voltage output of the difference amplifier when in measurement mode.

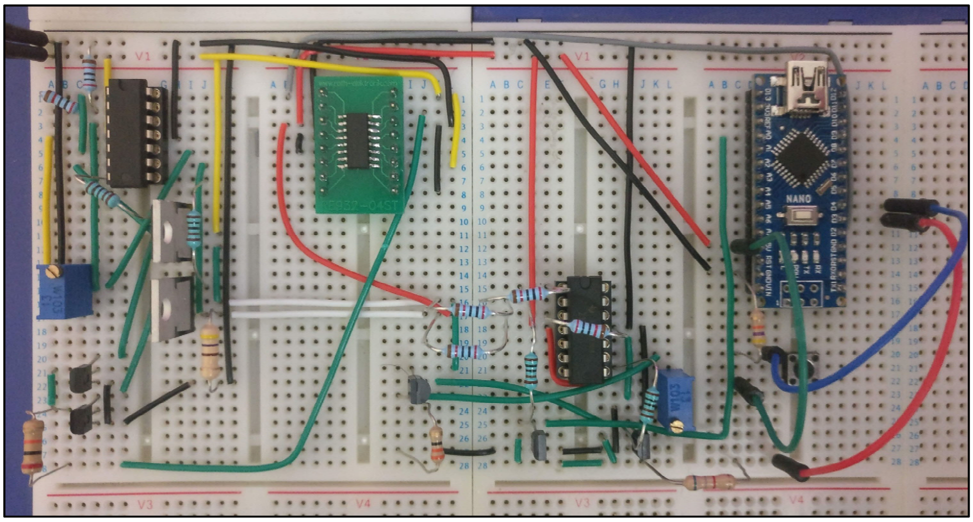

Figure 11: Voltage measurement circuit constructed on breadboard.

The circuit performed as expected, where the isolated gate driver correctly switched the transistors on the isolated part of the circuit, allowing fast switching between dissipation and measurement modes. To check the voltage measurement circuit worked I placed a heat source on the back of the test MOSFET and witnessed the voltage readings decrease as expected.

The circuit was then constructed on veroboard for its final form as shown in *figure 12*, with block terminals used to connect the power supplies, test MOSFET and bias resistor R_{BIAS} needed for the power controller's constant current source. A small addition to the circuit, whereby another pull-down transistor was added to the input terminal V_{IN}, so that the Arduino can digitally turn on/off the voltage input to control power dissipation, which can be used to use PRBS as an input waveform.

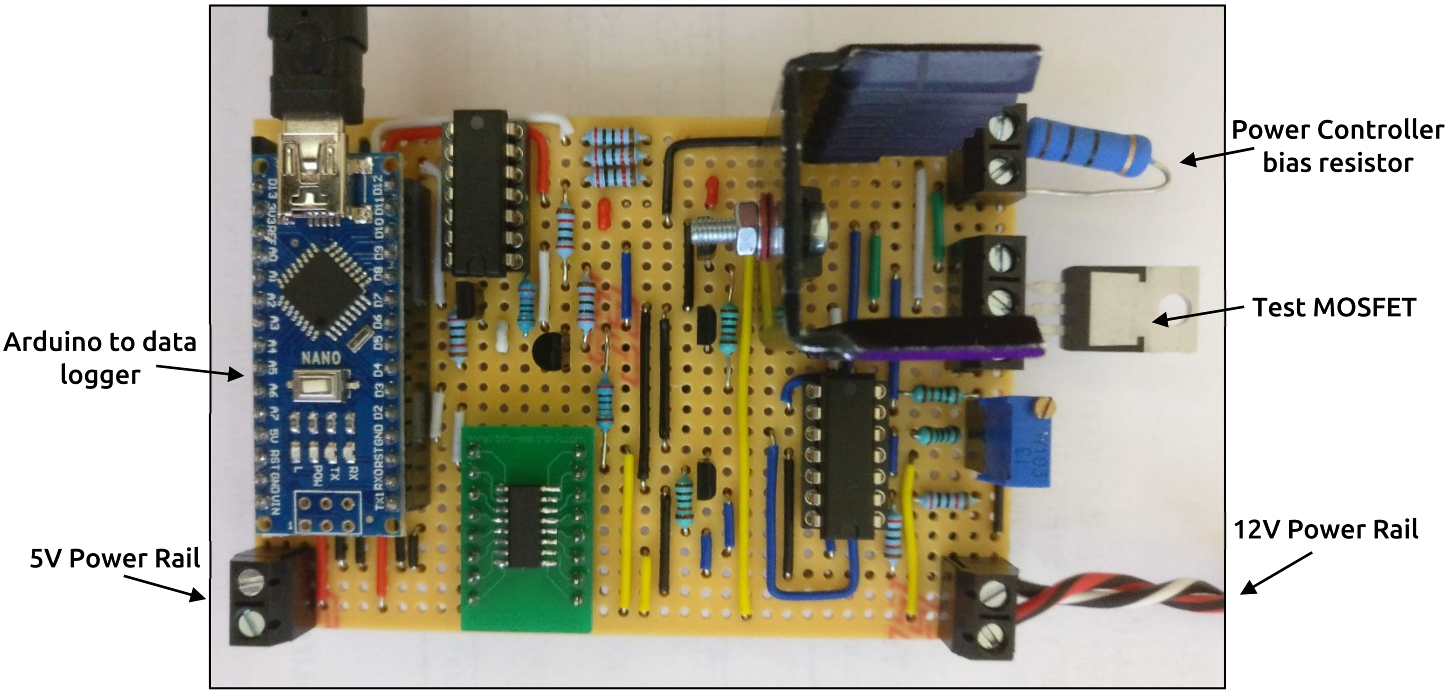

Figure 12: Final circuit constructed on veroboard.

There are a few inherent problems with the Arduino regarding the performance of its ADC, which is responsible for measuring the voltage across the diode, and because the diode only experiences small voltage changes across its temperature range (~100-200mV), it is important the ADC can produce accurate and repeatable voltage measurements. The ADC measurements performed by the Arduino are a function of the 5V rail, which is provided by the USB interface used to extract data by the data logger. The problem arises when the 5V provided by the USB connection is not stable or fluctuates, for example, the USB supply voltage may be 5.2V on one machine, but 4.9V on another, and even these voltages fluctuate over time. It becomes obvious that these fluctuations and inconsistent supply voltages will cause significant uncertainty in the voltage readings, which could lead to unreliable temperature measurements if the circuit is calibrated on one 5V supply, but used to instrument a circuit on another 5V supply.

A way to mitigate this is to use the Arduinos ATMega 328P integrated ability to measure its power supply voltage using a built-in precise voltage reference of 1.1V, which can be used to back-calculate the actual power supply voltage using some simply algebra. This would allow the Arduinos ADC to produce reliable and repeatable voltage measurements no matter which computer it is plugged into. The code that achieves this is shown in *appendix figure 1*. In reality, the voltage reference is not exactly 1.1V and is calibrated by adjusting the value on line 9 of the code until the V_{CC} value measured is equal to the voltage measured on a DMM. [8]

5.2 Calibration

Unfortunately, a temperature-controlled hotplate was unavailable at the time for the voltage measurement calibration experiment. However, the calibration could still be achieved by using the power controller to heat up the MOSFET instead in an isolated box, with a thermocouple attached to measure the devices temperature. The MOSFET being tested (IRF640S) has a maximum steady state junction-ambient thermal resistance of 40°C/W, hence the maximum dissipation needed to sufficiently heat the device for the calibration is 2W. The supply voltage is +12V, hence V_{IN} should not exceed 5-6V so circuit is still able to set the test MOSFET drain at $2V_{IN}$. Therefore, the bias resistor R_{BIAS} needed to dissipate 2W of power at a voltage of 5V is 12.5Ω, so a 3W 10Ω value was chosen.

Using the potentiometer to control the voltage across the MOSFET and hence the power dissipation in the MOSFET, the power was increased in increments of 200mW, and after a brief settling time to allow the MOSFETs temperature to reach steady state by monitoring the thermocouple readings, the circuit was rapidly switched to voltage measurement mode and the voltage was recorded. The voltage was measured three times per temperature increment so that an average could be obtained. The results of the three experiment runs are shown graphically in *figure 13*, with the recorded data shown in *table 1.*

An isolation box was not available before the end of the semester, hence the results for this experiment were obtained in a non-thermally isolated environment, hence the actual die temperatures would be slightly higher than measured, but the relationship is more or less equal.

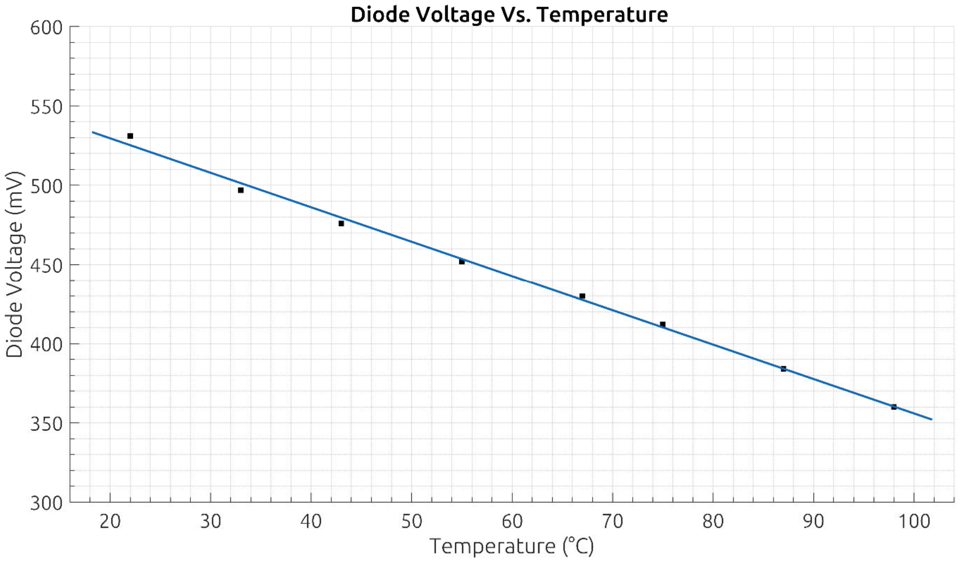

Figure 13: Temperature and voltage drop relationship.

The curve can be approximated as a linear relationship over the temperature range of interest, meaning that after the gradient of the curve has been found using equation (5), the temperature of the MOSFETs die can now be calculated from diode voltage measurement using equation (6).

$$m = \frac{dV_d}{dT_j} = -0.0021951 \tag{5}$$

$$V_d = -0.0021951 \cdot T_j + 0.577$$

$$T_j = \frac{V_d - 0.577}{-0.0021951} \tag{6}$$

Power Dissipation (W)	V_{IN} Required (V)	Temperature (°C)	Diode Voltage (mV)			Average (mv)
			Test 1	**Test 2**	**Test 3**	
0	0	22	530	532	531	531
0.2	1.41	33	497	497	497	497
0.4	2.00	43	476	476	477	476
0.6	2.45	55	452	453	452	452
0.8	2.83	67	430	430	430	430
1.0	3.16	75	413	413	411	412
1.2	3.46	87	384	384	384	384
1.4	3.74	98	361	360	360	360

Table 1: Calibration experiment measurement data.

6. Discussion & Conclusions

Overall, this report has highlighted the importance of accurate thermal modelling in certain application, and has given a brief overview of the modelling techniques that are used along with their advantages/disadvantages, and methods to mitigate some of the limitations of particular techniques. Furthermore, it has described the process and methods required to thermally characterise a system so that its thermal behaviour can be represented by a model.

The findings and outcomes of this research project are useful for a diverse range of applications where there are thermal restrictions placed upon electrical systems, where the ability to monitor and control the temperature is essential for the systems life span and reliability. Using electric vehicles as an example, the power modules used to drive the motors generally have tight space restrictions placed upon them in order for them to fit within the chassis and offer more space for batteries. This often leads to the module being subject to little air flow and the power devices being positioned at close proximity to one another, making thermal cross-coupling a major factor in the temperature of the devices. By developing a model that takes account for this thermal cross coupling and a method that predicts what the temperature rise will be due to driver inputs, measures can be introduced to limit the temperature via adjusting the liquid cooling or throttling the power output temporarily.

The key achievements in this project to date include successfully designing, testing, and constructing a dual-purpose testing circuit capable of dissipating a defined power into a MOSFET and measuring the voltage developed across its body diode. Furthermore, the circuit has been calibrated to show that there a linear relationship so that the temperature of the die can be measured during the device's operation, which will become useful for the upcoming experiments that will be carried out in order to thermal characterise the circuit.

A consistent issue during the circuit testing was getting the ADC on the Arduino to produce precise and consistent voltage readings, even with the measures put in place as described in the results section, the measurements were consistently 50-100mV off compared to the actual voltage at the pin. Initially, it was thought that the V_{CC}, measuring technique was culprit, because in practice, it wasn't particularly reliable and produced voltage reading that fluctuated significantly causing uncertainty in the measures data. To try and improve this, the circuit was slightly changed so that an external power source was connected to the Arduinos V_{IN} pin so that the 5V line was produced by the onboard regulator. Upon each use of the circuit, the program prompts the user to measure the actual 5V line externally using a mustimeter so that the voltage measurements were referenced to the correct voltage. In doing this, the voltage readings were less erratic, but they were still off by a significant amount. After some analysis of the code, the reason for the errors was discovered, being that during the voltage calculations, there was an integer present in a fraction, which caused the whole fraction to be treated as an integer, causing a rounding error. This was fixed by adding a '.0' to the end of each integer in the equation so that the program treats them as floats. The measurements produced now only had a difference of 2-5mV compared to the readings taken by an external multi meter, giving a worse case error of 1.14% assuming the lowest diode voltage within the temperature range is 350mV, which is satisfactory for this project.

However, due to the unavailability of a hotplate and a thermal isolation box at the time, the calibration experiment will need to be repeated in a more controlled way to obtain results that better represent the actual performance of the devices being used in the power module. Nevertheless, the experiment validated the functionality of the circuit and shows how there is an almost linear relationship between the junction temperature and the diode voltage.

7. Milestone Evaluation

By observing the project plan presented in the project initialisation document, by the end of the first semester, the development of the required test procedure should have been designed, the voltage measurement circuit should have been designed and built, and the IMS PCB that forms the power module should have been constructed. As described in the methodology section of this report, the experimental procedures needed to fully thermally characterise the circuit have been explained, and the design process of the voltage measurement circuit is shown along with its calibration procedure. Ideally, as soon as the voltage measurement circuit had been constructed and calibrated, the step response experiments to model the self-heating of the devices could have been completed, but the unavailability of precise thermo-couples and an isolation box meant that the voltage measurement circuit required for the experiments could not be fully calibrated, hence the experiment could not be carried out.

Furthermore, the project so far has been within the allocated £50 budget, with the components for the voltage measurement circuit only costing ~£20.

Shown below in *table 2* is a revised project schedule for the second semester, with the graphical Gantt chart shown in *appendix figure 2*.

Component	Description	Deliverable Dates
A	Report 2 (interim report) deadline	14th January 2019
B	Fully calibrate voltage measurement circuit	
C	Second marker viva deadline	8th February 2019
D	**Characterise thermal self-heating**	
D i)	Perform power dissipation step change and record temperature	
D ii)	Repeat for each device on the PCB	
D iii)	Fit the curve to an equivalent RC exponential	
E	**Characterise thermal cross-coupling**	
E i)	Design PRBS signal type	
E ii)	Perform PRBS power dissipation and record temperature	
E iii)	Repeat for each device on the PCB	
F	Extract the Foster model parameters	
G	Develop mathematical model using measured data	
H	Test model by comparing actual and modelled temperatures	
I	Develop Luenberger observer for temperature prediction	
J	Test final model against measurements	
K	Symposia (presentations) deadline	1st May 2019
L	Public engagement video & storyboard deadline	10th May 2019
M	IEEE style article deadline	3rd June 2019

Table 2: Project schedule for remaining tasks.

8. References

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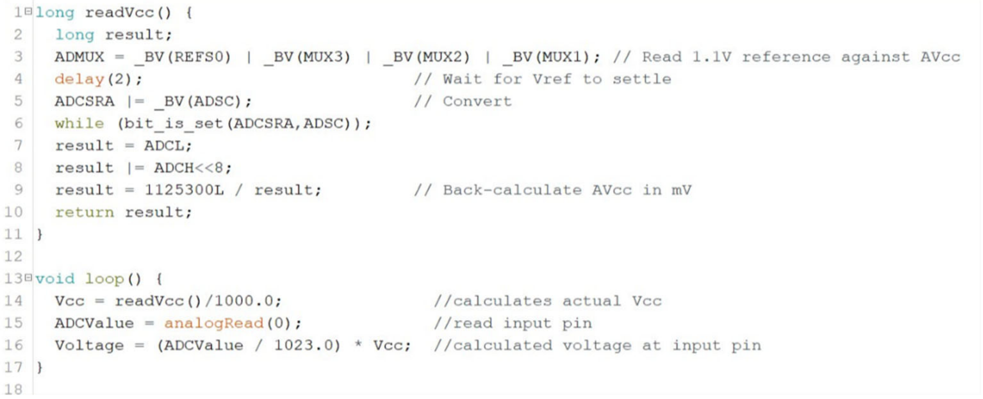
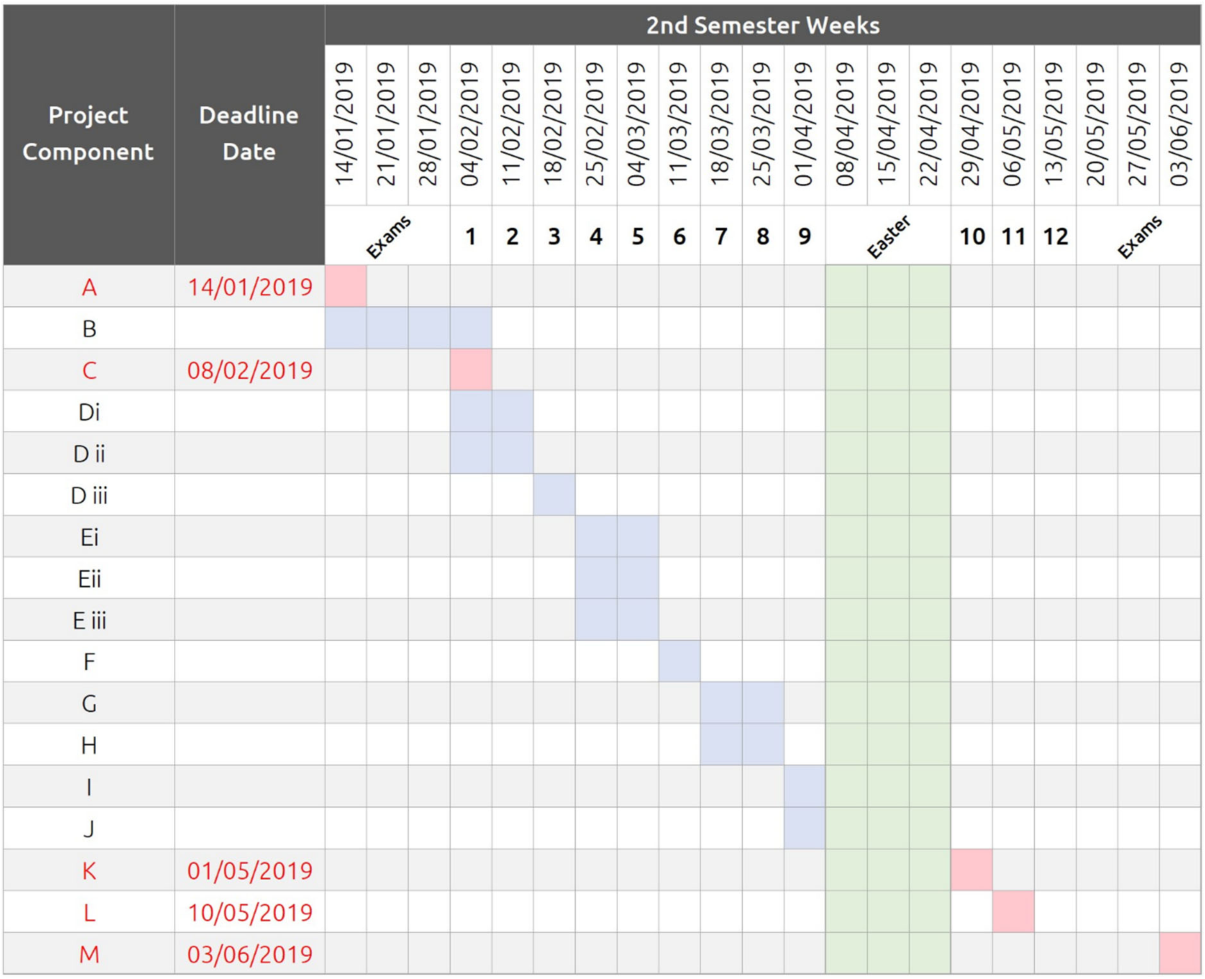
9. Appendix



```
long readVcc() {
  long result;
  ADMUX = _BV(REFS0) | _BV(MUX3) | _BV(MUX2) | _BV(MUX1); // Read 1.1V reference against AVcc
  delay(2);                          // Wait for Vref to settle
  ADCSRA |= _BV(ADSC);               // Convert
  while (bit_is_set(ADCSRA,ADSC));
  result = ADCL;
  result |= ADCH<<8;
  result = 1125300L / result;        // Back-calculate AVcc in mV
  return result;
}

void loop() {
  Vcc = readVcc()/1000.0;              //calculates actual Vcc
  ADCValue = analogRead(0);            //read input pin
  Voltage = (ADCValue / 1023.0) * Vcc; //calculated voltage at input pin
}
```

Appendix figure 1: Code snippet that measures the actual supply voltage.



Project Component	Deadline Date	2nd Semester Weeks																				
		14/01/2019	21/01/2019	28/01/2019	04/02/2019	11/02/2019	18/02/2019	25/02/2019	04/03/2019	11/03/2019	18/03/2019	25/03/2019	01/04/2019	08/04/2019	15/04/2019	22/04/2019	29/04/2019	06/05/2019	13/05/2019	20/05/2019	27/05/2019	03/06/2019
		Exams			1	2	3	4	5	6	7	8	9	Easter			10	11	12	Exams		
A	14/01/2019	🟥												🟩	🟩	🟩						
B		🟦	🟦	🟦	🟦									🟩	🟩	🟩						
C	08/02/2019				🟥									🟩	🟩	🟩						
Di					🟦	🟦								🟩	🟩	🟩						
D ii					🟦	🟦								🟩	🟩	🟩						
D iii							🟦							🟩	🟩	🟩						
Ei								🟦	🟦					🟩	🟩	🟩						
Eii								🟦	🟦					🟩	🟩	🟩						
E iii								🟦	🟦					🟩	🟩	🟩						
F										🟦				🟩	🟩	🟩						
G											🟦	🟦		🟩	🟩	🟩						
H											🟦	🟦		🟩	🟩	🟩						
I													🟦	🟩	🟩	🟩						
J													🟦	🟩	🟩	🟩						
K	01/05/2019													🟩	🟩	🟩	🟥					
L	10/05/2019													🟩	🟩	🟩		🟥				
M	03/06/2019													🟩	🟩	🟩						🟥

Appendix figure 2: Revised project Gantt chart for remainder of project.