Pressure Cooker DC Conversion kit - the Conficio approach

AC Electric Pressure Cooker DC Conversion kit – the Conficio approach

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Working Paper for Comment

1 Executive Summary

This working paper was produced mainly by Conficio, a design agency. Conficio were commissioned to investigate the possibility of making a DC conversion Kit for AC electric pressure cookers. Working alongside Gamos, Conficio undertook a Stage 1 and 2 investigation of the constraints of commercial EPCs, and what this might mean for designing such a DC conversion kit.

This report discusses the main design aspects of the switch mode power supply created to run the heating element of an Amazon Basics pressure cooker. The requirements listed below necessitated that the design to achieve a maximum of 200V DC to achieve 800W of heating power through the fixed resistance of the heating element.

The desire was to make as few changes as possible to the existing pressure cooker layout and only change the control PCBA andthe input wiring and connector. This would then reuse the existing connectors and wiring and therefore the 'upgrade' to a DC pressure cooker could be completed in minutes rather than hours.

This obviously gave the PCBA design a quite tight space restriction limiting the size of devices used and the number of devices. The input current to the system potentially could exceed 35A therefore the weight of the copper required for some of the tracking would need to be 4oz; this is generally 4 times thicker than a regular construction.

The PCBA generally had all the power devices on one side of the board and the microcontroller and lower power devices on theother. As the weight and therefore thickness of the copper increases so do minimum track sizes, component pads and clearance distances. This means that a maximum of 2oz copper could be used on the underside of the board and, since board construction must be symmetrical, 2oz copper had to be used on the top.

Only 70% to 75% efficiency was achieved, and it was not possible to run for more than a few minutes before damage was caused to the low side MOSFETs. Replacing these devices is a difficult task due to the thickness of the copper and the proximity of other components. It is therefore recommended that a larger PCB is designed with the purpose of performing more experimental observations with slightly differing snubber networks.

The MECS philosophy is about learning so this report will have a more in depth look at the design and the characteristics of the component parts used and their influences on losses and therefore efficiency in the system.

The Conficio reports were intended for discussion with the client (MECS through Gamos) and was not originally intended for publication (although all work within MECS is open source). The information contained could potentially prove useful for partners and collaborators and we now wish to place it on our website for wider use. (June 2021). It is presented as a working paper for comment.

It can be shared as an open resource and any researcher or interested party is welcome to use the ideas as a launch to further explore the resulting conclusions, or to pushback where the existing research fails to address a concern. As well as the official UK Aid disclaimer above we acknowledge that these thoughts are incomplete and any organisations using the following discussion to further their work must rely on their own enquiries and

Contents

Term	Description
UI	User Interface
HV	High Voltage
LV	Low voltage
MCU	Microcontroller
PWM	Pulse Width Modulation
BMI	Boot Mode Index
CPU	Central Processing Unit
ZVS	Zero Volt Switching
PSU	Power Supply Unit
LLC	Inductor, Inductor and Capacitor Filter

2 Introduction

MECS commissioned Conficio Design company to develop a PCB and software that can be released as an Open Source device that is suitable as a Direst Current conversion kit to retrofit into an off the shelf AC pressure cooker. The design should be suitable for off-grid and mini-grid installations where the input voltage and quality will not be guaranteed. Most of these environments will run from 24 or 48 volts DC.

The project was divided into 3 sections, the first Stage 1, will include the teardown of the chosen electric pressure cooker and the validation of the chosen design. This will be performed using an off the shelf power supply to ensure that the interlocks and interfaces are capable of being modified. The second stage will consist of the development of the PCB and software capable of performing the voltage and current control tasks and timing for the design. The final stage will gather the documentation together in a way that outlines the interface methods required to make the PCB work.

Currently, this project is electronics only and does not include any of the industrial design that may be required to modify a pressure cooker to house the PCB and to connect the DC power rather than AC power.

3 Stage 1

An Amazon Basics Pressure Cooker was procured and stripped down to observe the functionality and connectivity of the system to see the feasibility of converting it to run off a DC power source of 24V or 48V.

The main questions identified at the start of the project were:

- Can the heating element accept a DC power rather than an AC power?
- Is it possible to replace the AC circuitry with DC for other system functionality?
- Can the original control system still operate?

The heating element was supplied with a DC voltage of 200V. No power fluctuations or abnormal heating was observed. This equates to approximately 800W of heating power. Water in the pot was observed to be rising in temperature.

The circuitry was inspected, and components identified to gain an understanding of it’s operation and it is feasible to replace the AC circuitry with DC.

It should be possible to maintain the original control system with the creation of a 50Hz signal to supply the control PCB with what is believed to be a timing input from the mains 50Hz. The best outcome would be to provide a drop in replacement PCB for the existing one with the only wiring changes to the mains connector, preserving the original wiring and connectors where possible. This may come down to availability of such PCB connectors.

The DC voltage level provided by the solar battery banks will have an impact on the current level required by the cooker and 48V should be considered.

Therefore, this report recommends the continuation of the project into Stage 2. Stage 2 Tasks:

- Electronic Design Documentation
- Software Design Documentation
- Electronic Cable Assembly Drawing

3.1 Teardown

The underside cover was removed by releasing just a single screw and rotating the cover to reveal the main electrical connections and electronics as shown in Figure 1.

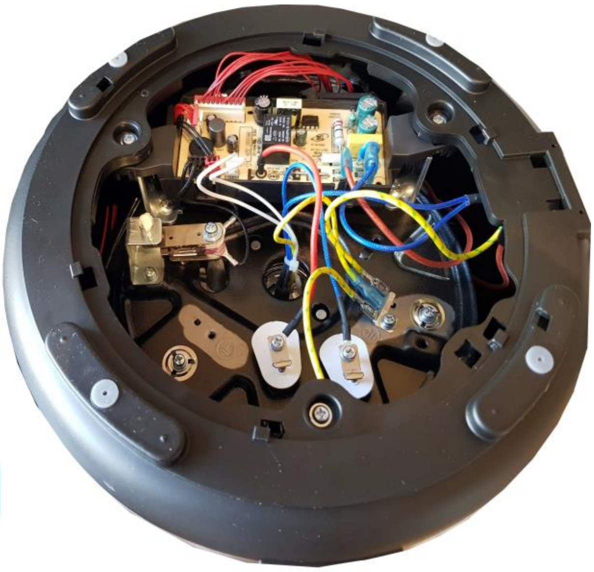

Figure 1 Exposed base of an Amazon Basics EPC

The removal of a further three screws releases the outer cover, this shows the rear of the electronic control panel that houses the control PCB assembly in Figure 2. The red cable is shown in Figure 1 in its mating connector.

Figure 2 Exposed wiring of PCB control board of Amazons Basic EPC

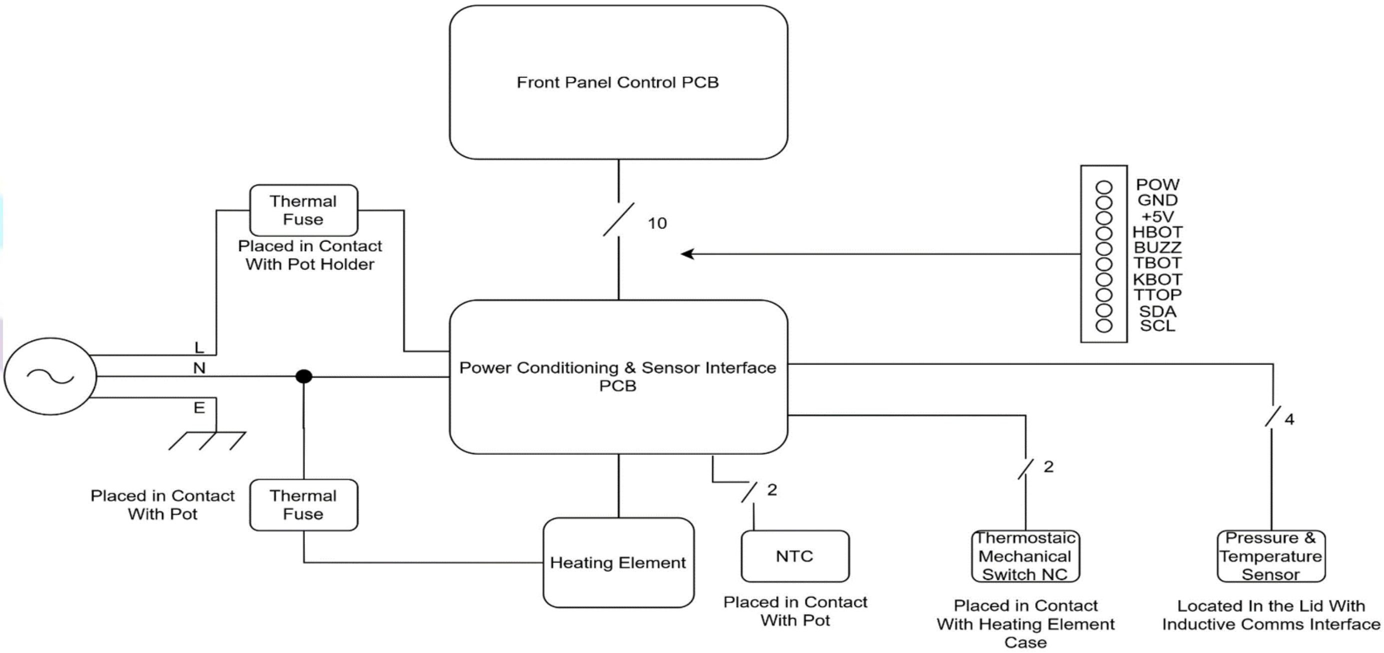

Figure 3 Amazon Basics Pressure Cooker System Architecture

Figure 3 identifies the system blocks and their interconnects. The mains power supply enters the system via an IEC connector that has no power switch. All metallic and conducting elements of the system are connected to earth form a single point; this is not shown in the diagram for simplicity.

Thermal fuses are used on both the Live and Neutral supplies. There are two PCBs with an interconnect cable;

- One is mounted in the base of the unit for power conditioning, interfacing of the sensors and switching of the power to the heating element
- The second PCB is mounted in the front panel for HMI and microcontroller control of the system.

The heating element has a measured resistance at an ambient temperature of 20°C of 55Ω. A 200V DC power supply was connected to the element and a voltage was applied starting at a low voltage rising to the maximum of 200V. This equated to a approximately 800W of heating power. The pressure cooker in its original form is stated as providing 1000W, MECS require this to be in the 600-800W region from the initial brief. The final stage of the voltage provided to the heating element will control the final power delivered.

The DC voltage level provided by the solar battery banks will have an impact on the current level required by the cooker and 48V should be considered. To achieve 800W of cooking power from a nominal 24V source would require the system to draw approximately 33A. A 48V supply would reduce this by half to approximately 16.5A. This is assuming 100% system efficiency; in reality this should be 90-95%.

4 Product Design Summary

Modern Energy Cooking Services (MECS) approached Conficio Product Design Ltd to design a drop in replacement power board for an Amazon Basics pressure cooker. The purpose of the replacement power board is to drive the pressure cooker from a solar battery where the input DC supply is expected to be between 22VDC – 60VDC. MECS have requested the output cooking power for the heating element should be between 600W – 800W and all original safety controls shall be maintained.

4.1 Requirements

- Run from a 22VDC – 60VDC solar battery input voltage
- Have a suitable DC connector to interface to the external power supply cable
- Have a minimum and maximum output power of 600W – 800W respectively
- The boost topology should have a minimum of 90% efficiency
- The main control program and UI shall be preserved

4.2 Replacement Power PCB Architecture

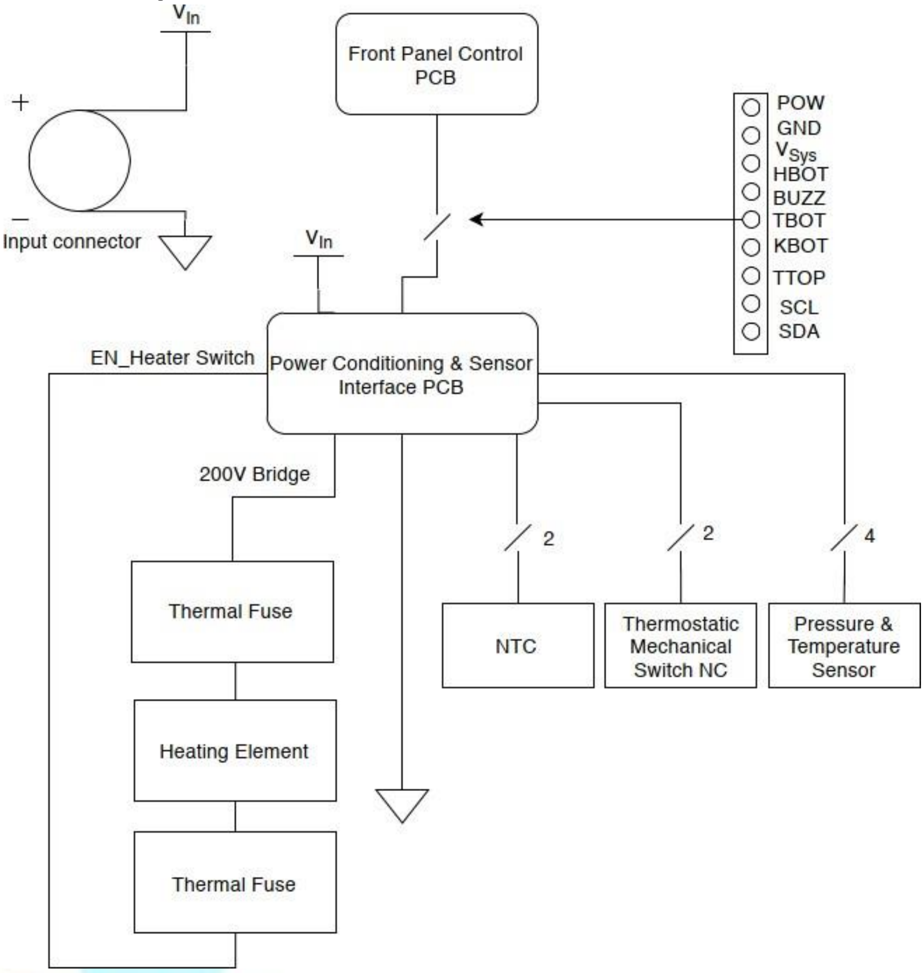

Figure 4 DC System Architecture

4.3 Boost Topography

The application requires a driving voltage of 200V(V_{Boost}) to operate a 55ohm heating element for the pressure-cooking process, as a result a boost converter is required to step up the input voltage of the system to this value. Due to the hazardous voltage as well as current considerations a full bridge and transformer is deemed most suitable as it isolates the HV supply from the rest of the system.

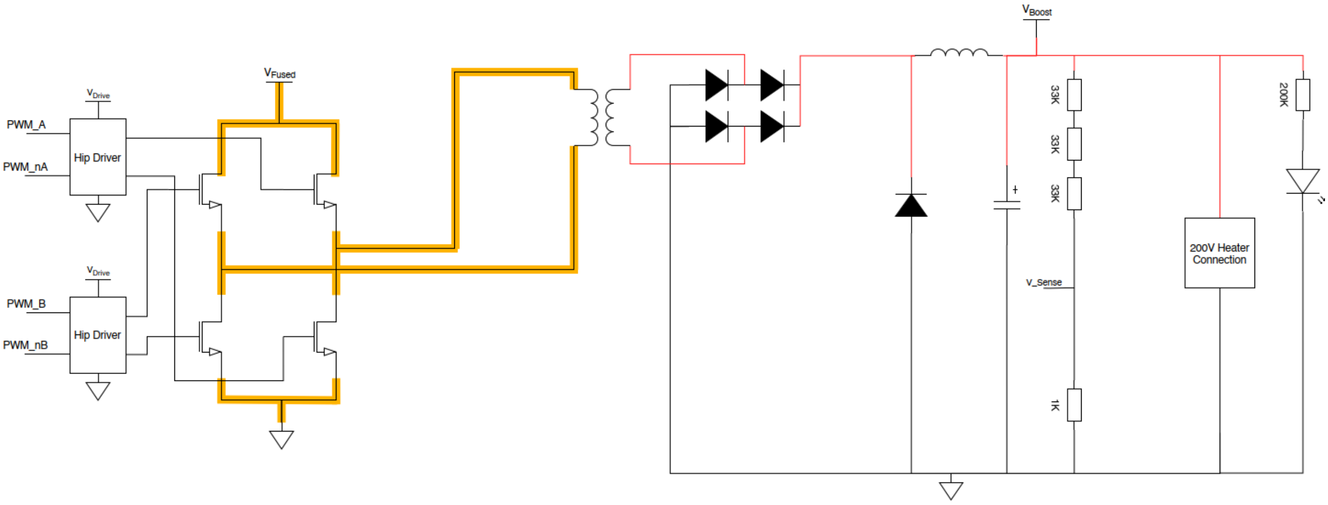

Figure 5 V_{Boost} Topography

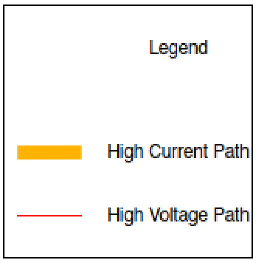

Figure 6 V_{Boost} Topography Legend

4.4 Transformer

Due to the isolation requirements and current considerations for the V_{Boost} supply, the use of a boost transformer is identified. The Boost transformer is required to boost an input voltage of a minimum 20V to 170V and therefore will need to be a 1:8.3 transformer. The output of the transformer will be controlled by the current through the V_{Boost} H-Bridge.

For an output of 200V the system needs to maintain 3.63A through the heating element.

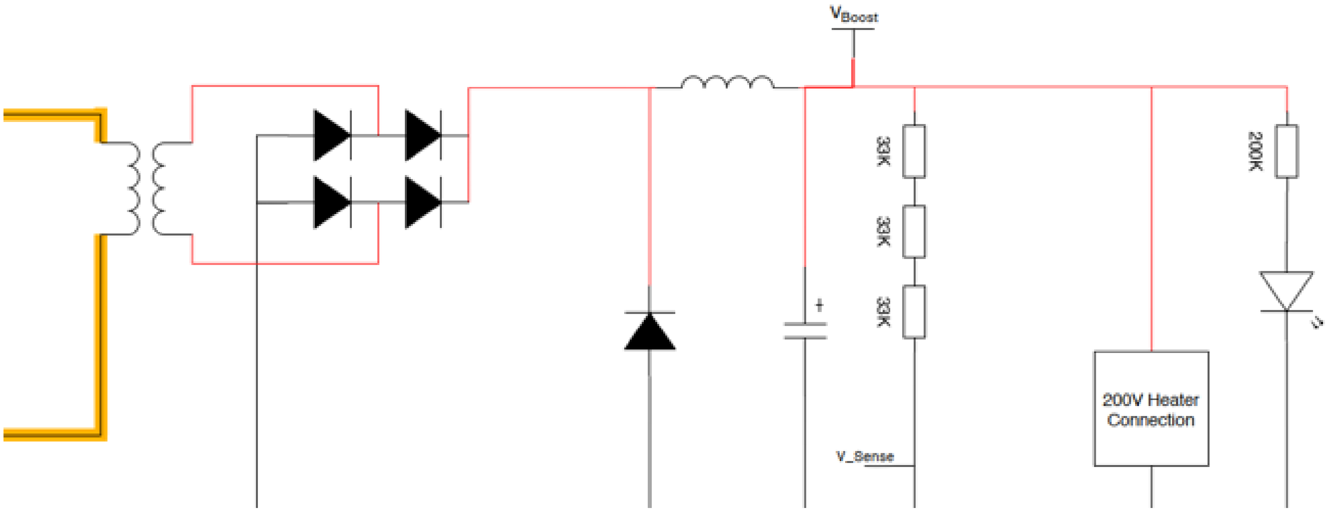

Figure 7 V_{Boost} Transformer

4.5 Microcontroller

XMC1300 has been selected over the XMC1200 due to the Math Coprocessor which will as sist in the control of PWM driving signals for bridge drivers. The 32-bit ARM Cortex-M0 CPU supplies sufficient processing capabilities within the package, supported by an assortment of peripherals key to the application.

The package includes an ADC peripheral which can be coupled to a timer (Such as an PWM generator) which can be used to quickly shut down high powered parts of the system in the event of a fault.

In addition to the critical ADC peripheral the device has a suitable onboard memory capacity of ROM and SRAM as well as on chip flash memory as well as a suitable number of pins to interface the required number of ADCs and Drive signals.

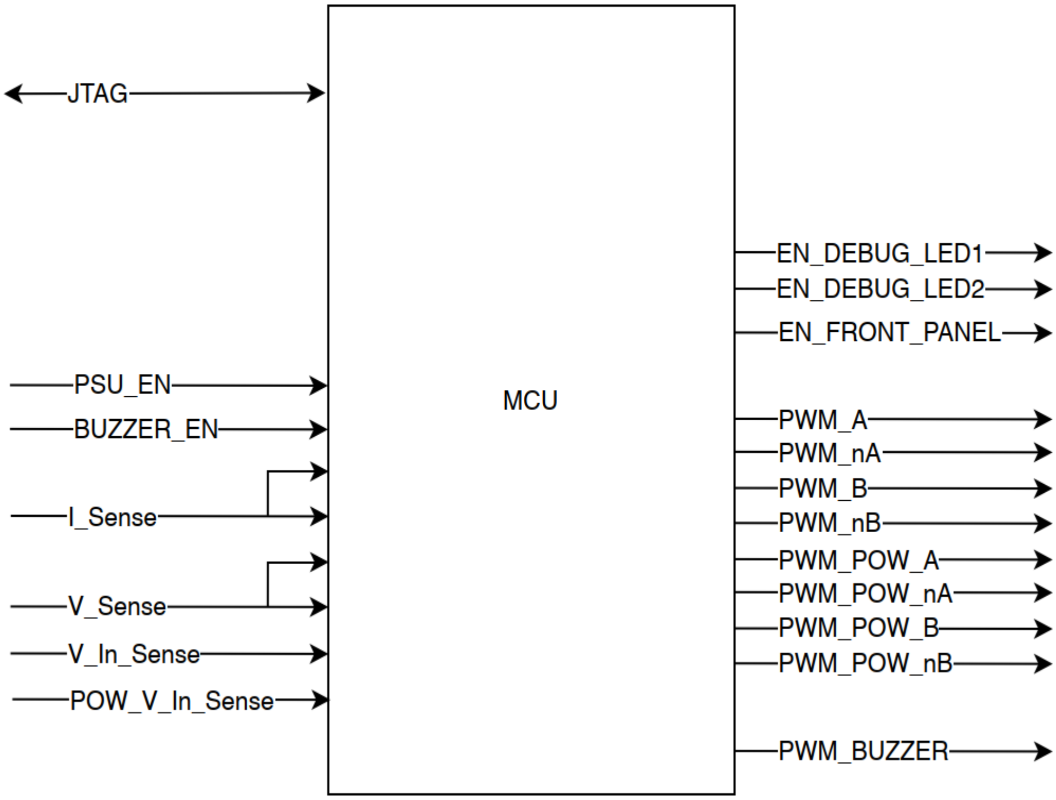

Figure 8 Power PCB MCU

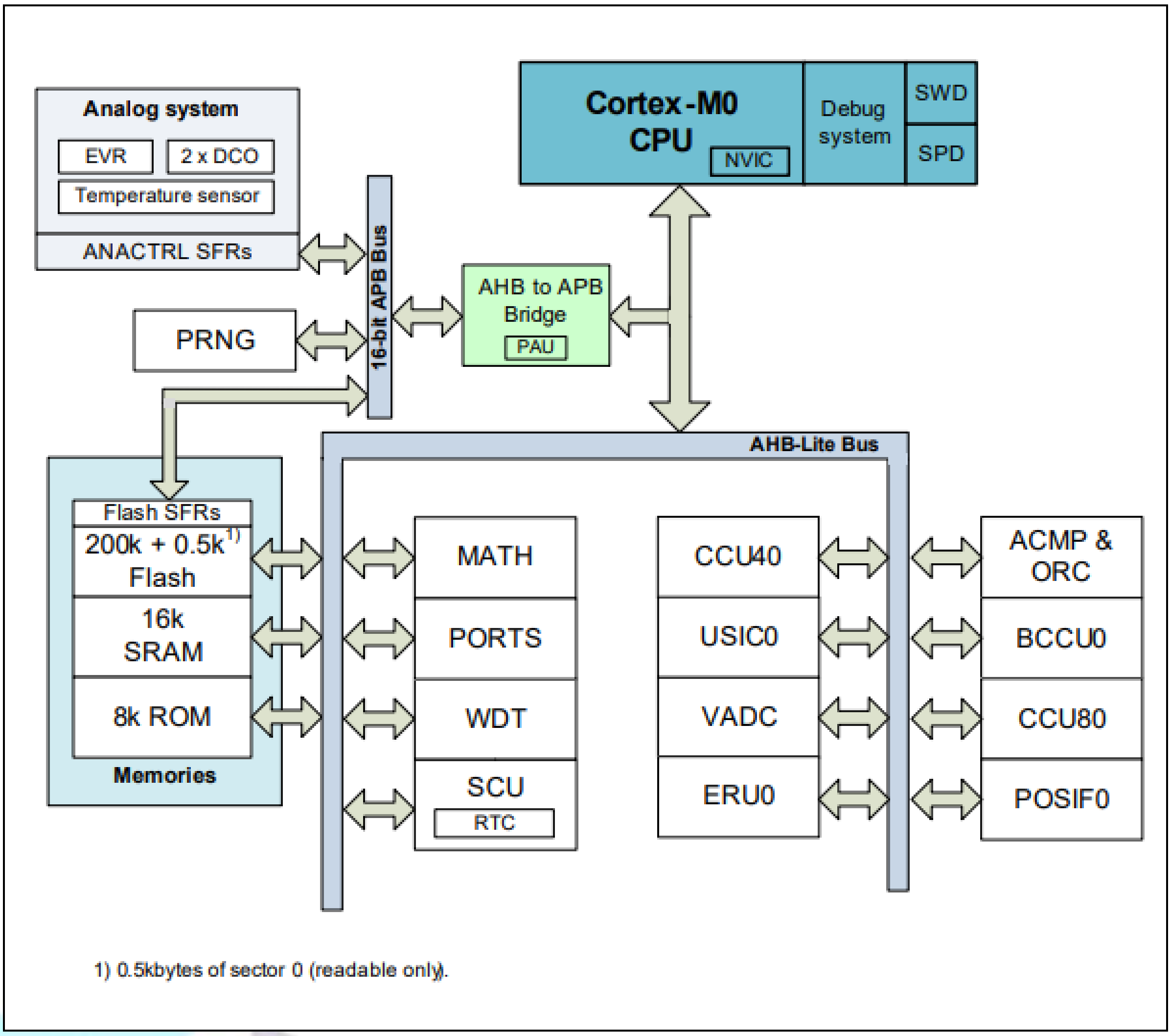

Figure 9 XMC1300 Architecture Diagram

4.5.1 Programming interface

- (JTAG) SWD/SPD
- BMI SERIAL LINK

It should be noted that to be able to program the device the Boot Mode Index (BMI) needs to be configured for J-Link as this is not the default for this MCU.

4.5.2 Incoming Signals

Signal Name	Signal Description	Pin	Pin mode
SWDI0_0	Programming/Debug	P0.14	
SWDCLK_0	Programming/Debug	P0.15	
PSU EN	Signal required to drive the heatingelement	P1.2	GPIO
BUZZER_EN	Signal required to drive buzzer	P1.3	GPIO
I_Sense1	Current feedback from V_{Boost} bridge	P2.0	VADC0.G0CH5
I_Sense2	Fast stop current feedback from V_{Boost} bridge	P2.1	VADC0.G0CH6
V_Sense1	Voltage feedback from V_{Boost} bridge	P2.2	VADC0.G0CH7
V_Sense2	Fast stop voltage feedback from V_{Boost} bridge	P2.6	VADC0.G0CH0
V_In_Sense	Input voltage ADC	P2.7	VADC0.G1CH1

4.5.3 Outgoing Signals

Signal Name	Signal Description	Pin	Pin mode
EN_DEBUG_LED1	Debug LED indicator fordevelopment purposes	P0.0	GPIO
EN_DEBUG_LED2	Debug LED indicator fordevelopment purposes	P1.1	GPIO
EN_FRONT_PANEL	Enable signal for control PCB (front panel)	P2.9	GPIO
EN_HEATER	Enable signal for heating element	P1.0a	GPIO
PWM_BUZZER	Drive signal for Buzzer	P0.5	ALT5 CCU80.OUT12
PWM_A	Drive signal to right side hip of V_{Boost} H-Bridge for High FET	P0.6	ALT5 CCU80.OUT11
PWM_nA	Complementary drive signal to right side hip of V_{Boost} H-Bridge forlow FET	P0.7	ALT5 CCU80.OUT10
PWM_B	Drive signal to left side hip of V_{Boost} H-Bridge for High FET	P0.8	ALT5 CCU80.OUT20

PWM_nB	Complementary drive signal to left side hip of V_{Boost} H-Bridge forlow FET	P0.9	ALT5 CCU80.OUT21
PWM_POW_A	Drive signal to right side hip of POW H-Bridge for High FET	P0.12	ALT5 CCU80.OUT33
PWM_POW_nA	Complementary drive signal to right side hip of POW H-Bridge forlow FET	P0.13	ALT5 CCU80.OUT32
PWM_POW_B	Drive signal to left side hip of POW H-Bridge for High FET	P2.11	ALT5 CCU80.OUT31
PWM_POW_nB	Complementary drive signal to left side hip of POW H-Bridge for low FET	P2.10	ALT5 CCU80.OUT30

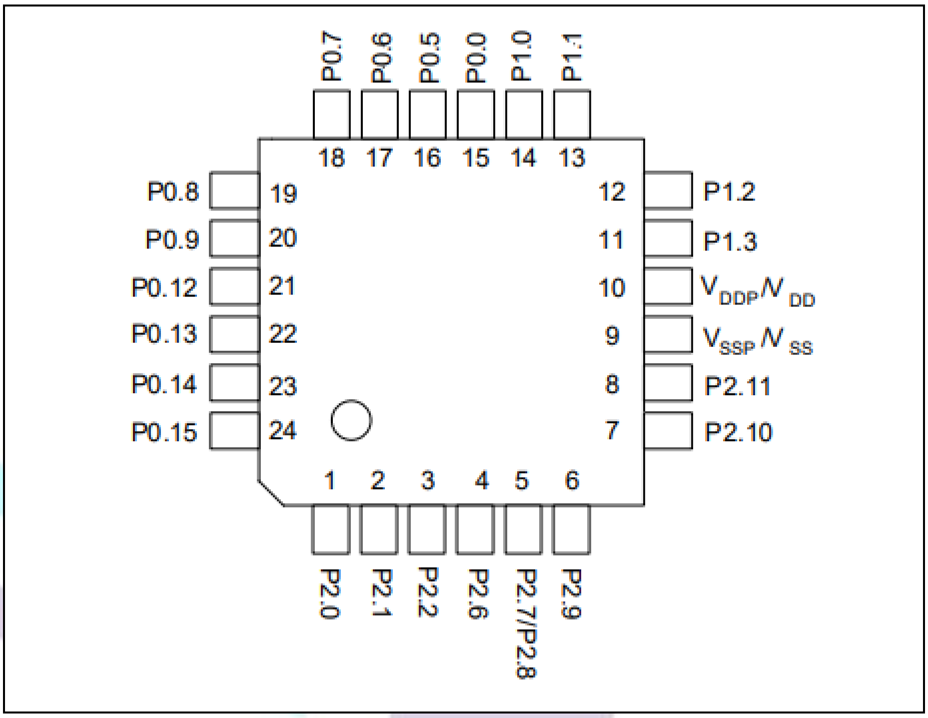

Figure 10 XMC1300 PG-VQFN-24 Pin Configuration

5 Software Design

The software is required to monitor the input voltage and the half bridge boost supply to ensure safe operation. The system is to enable the heating element while PSU_EN is high from the Pressure Cookers control PCB

5.1 Timing/clock considerations

The application will require a master clock (MCLK) frequency suitable for the CCU8 peripheral prescaler

5.2 ADC considerations

An ADC is required to sense the following signals from the hardware:

$V_{\_In\_Sense}$

This signal is used to identify a suitable input voltage is present and inhibit the system if the input value is out of range.

$V_{\_Sense}$

This signal is interfaced to two different pins on the MCU, one is responsible for the feedback and used to calculate the drive signals for the V_{Boost} H-bridge. The other is responsible for triggering and ERU for fast shutdown of the power supply in the event of a fault. The ERU is explained in its own section.

$I_{\_Sense}$

This signal operates identically to $V_{\_Sense}$ with respect to current.

5.3 PWM considerations

Within this application the system is required to control 8 PWM drive signals to bridge hip drive rs which are responsible for the isolation and drive of bridge FETs. There are 2 H-bridges within the system, 1 for the VBoost circuit, which is used to power the heating element at 200V, 1 for the generation of the POW signal required by the control PCB on the front panel. Capture/Compare Unit 8 (CCU8) will be used for this application as the peripheral has the capacity to drive 8 independent signals.

5.4 V_{Boost} H-Bridge

4 drive signals are driven by this peripheral for V_{Boost}:

- PWM_A
- PWM_nA
- PWM_B
- PWM_nB

Where PWM_A, PWM_nA provide drive signals to one side of the bridge (hip driver) and PWM_B and PWM_nB drive the other side(hip). The V_{Sense} value calculated by the ADC peripheral provides a feedback for a PWM drive control algorithm which keeps the V_{Boost} within range.

The drive signal to the hip drivers are controlled using the phase angle between the high and low side signals for a hip. The control algorithm reduces the phase angle if the feedback is greater than the desired voltage and increases the phase angle if the feedback is less than the target voltage. The greater the phase angle the greater the current through the transformer.

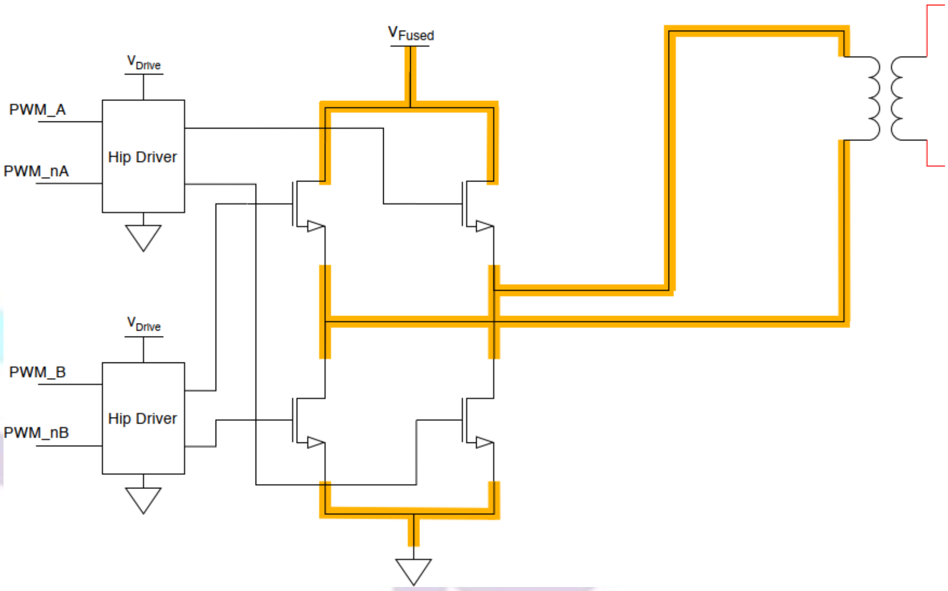

Figure 11 V_{Boost} H-Bridge

5.5 POW H-Bridge

The POW output it based on the input voltage signal $V_{\_In\_Sense}$. Figure 9 shows a charge pump circuit where the output is regulated to 48V from the V_{Fused} input voltage

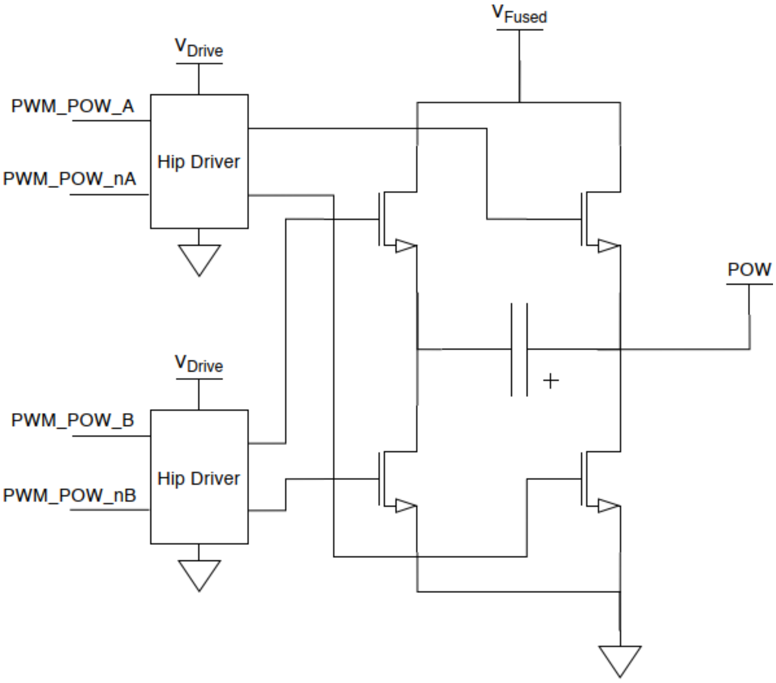

Figure 12 POW H-Bridge

5.6 PWM Phase Control

The output of the H-Bridge is controlled by the phase angle between the A & B channels. This is used to control the output current for instance within the V_{Boost} output to the Tx transformer.

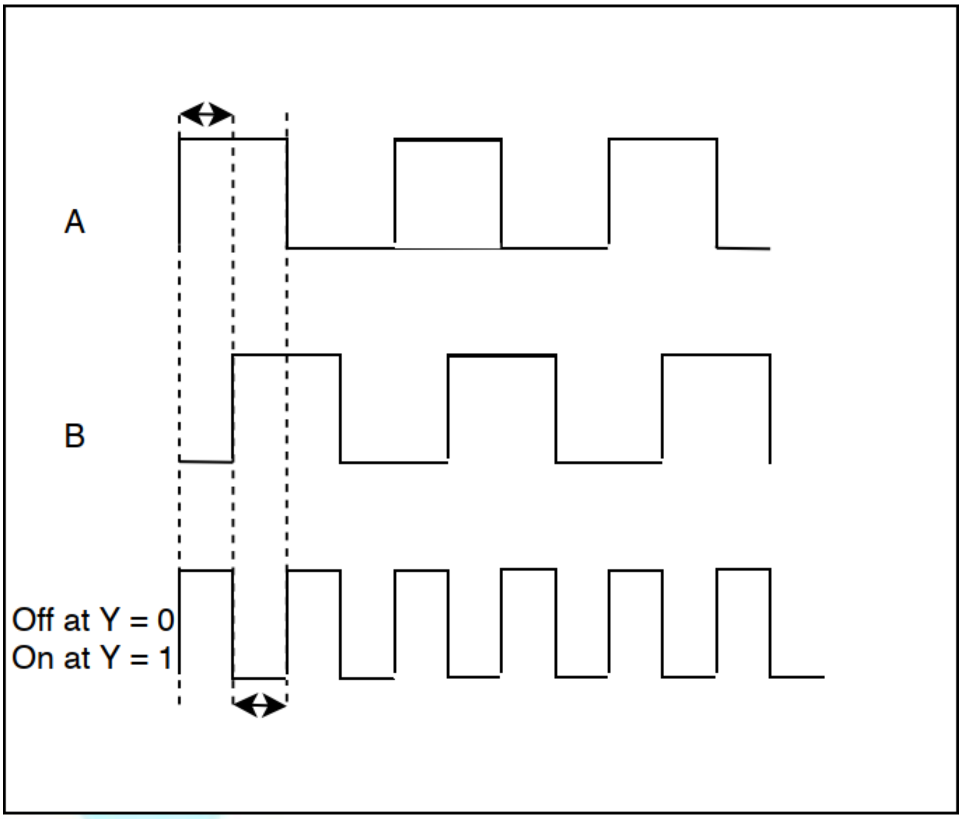

Figure 13 PWM Phase Control Diagram

5.7 Event Request Unit (ERU) considerations

This peripheral is used by the system to tie the ADC peripheral input (I_{Sense2} & V_{Sense2}) and CCU8 timer blocks together so that in the event of a critical failure the H-bridges can be shutdown as soon as possible. This is required due to how quickly a power supply such as a boost converter can 'run away' and build up dangerous voltages which have the potential to damage the system as well as cause harm.

5.8 Fault

In the event of a fault the system is to stop: V_{Boost}, V_{Sys} Switched and POW signals and reset on a power restart.

6 Software Diagram

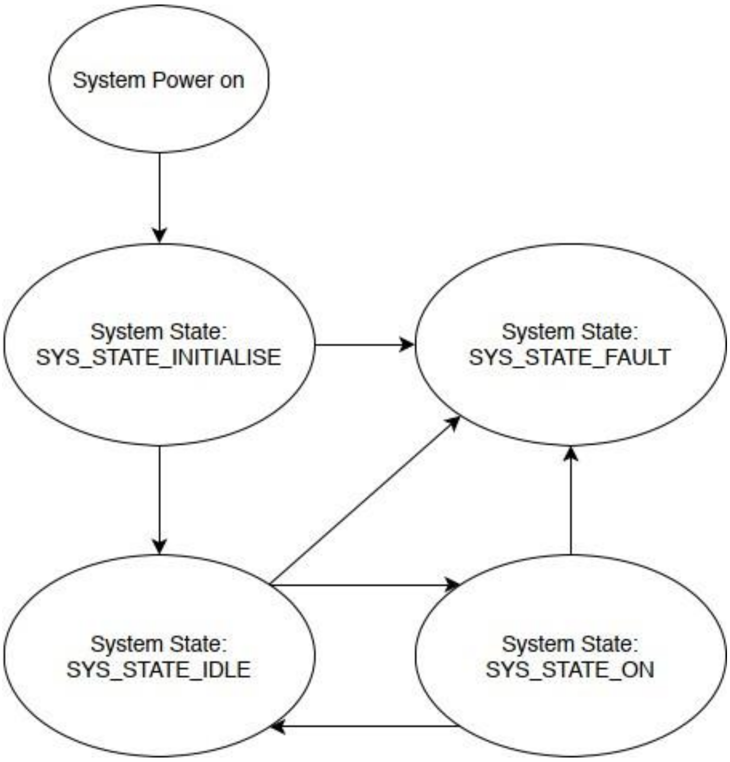

Figure 14 Power PCB MCU Software Diagram

7 Supplies

- V_{In}
- V_{Fused}
- V_{Drive}
- V_{Sys}
- V_{Sys} Switched

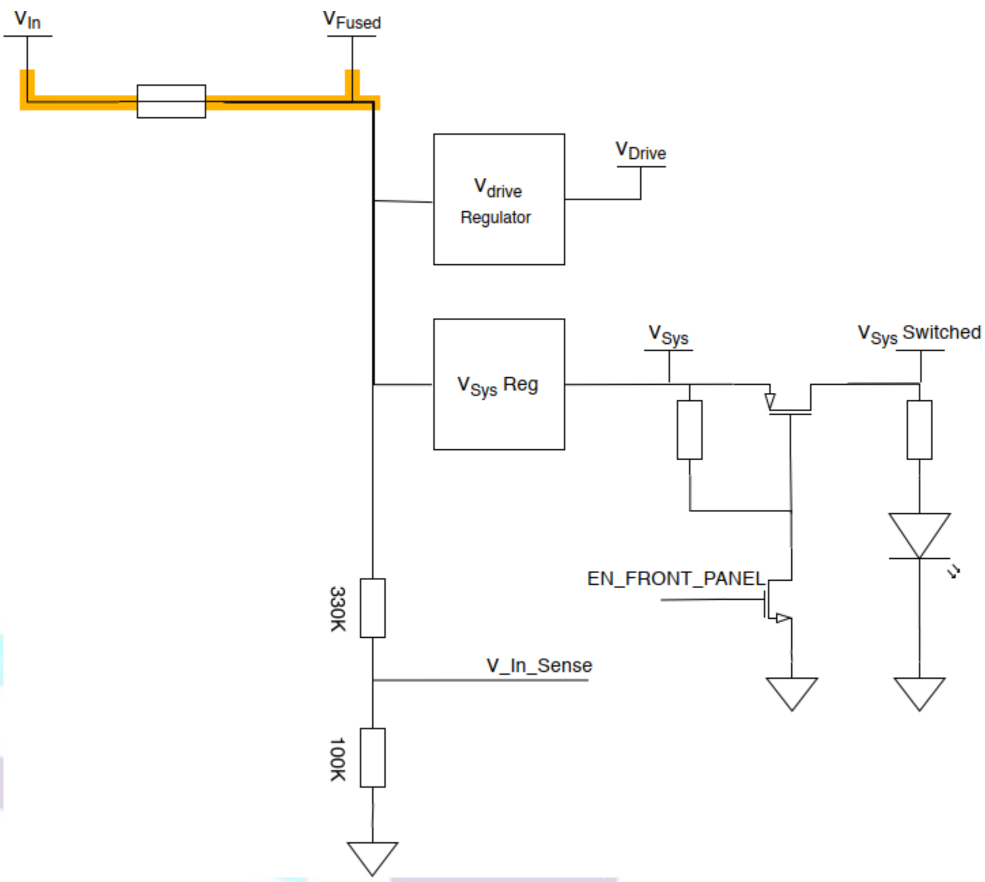

Figure 15 Power PCB Supply Rail's

7.1 V_{In} -> V_{Fused}

V_{in} is likely to be between 22VDC - 60VDC, this supplied form solar batteries.

For safety reasons it is critical to fuse the input to protect both the system as well as the supply source for unexpected current drain. This generates the V_{Fused} Supply rail for the system.

The maximum current the system should draw is approximately 37A, based the below calculations the input fuse for the system should be 40A slow blow. This allows for a 10% tolerance on the nominal 24VDC input and accounts for expected shoot through current.

$$\frac{800W}{22VDC} = 36.3A$$

$$\frac{800W}{48VDC} = 16.6A$$

$$\frac{800W}{40A} = 20VDC$$

$$\frac{800W}{35A} = 22.8VDC$$

7.2 V_{Drive}

V_{Drive} is a supply rail for the purpose of supplying bridge hip drivers. The V_{Drive} regulator is required to support the current of up to 4 hip drivers.

7.3 V_{Sys}

The V_{Sys} rail supply is required to support:

- MCU
- Debug LED's
- Buzzer

7.4 V_{Sys} Switched

5V switched is controlled by a gate driven by the MCU and provides control of a required 5VDC signal to the control PCB on the front panel.

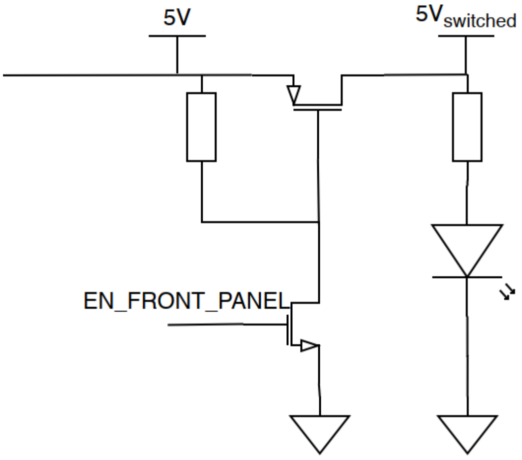

Figure 16 5V Switched Signal Control Circuit

8 Size Considerations

Due to the nature of the application, it is required that the developed PCB fit within the existing housing of the Amazon basic pressure cooker hardware.

	Dimensions	Top side height	Underside height
Power PCB	111.5mm x 50mm	18mm	3mm

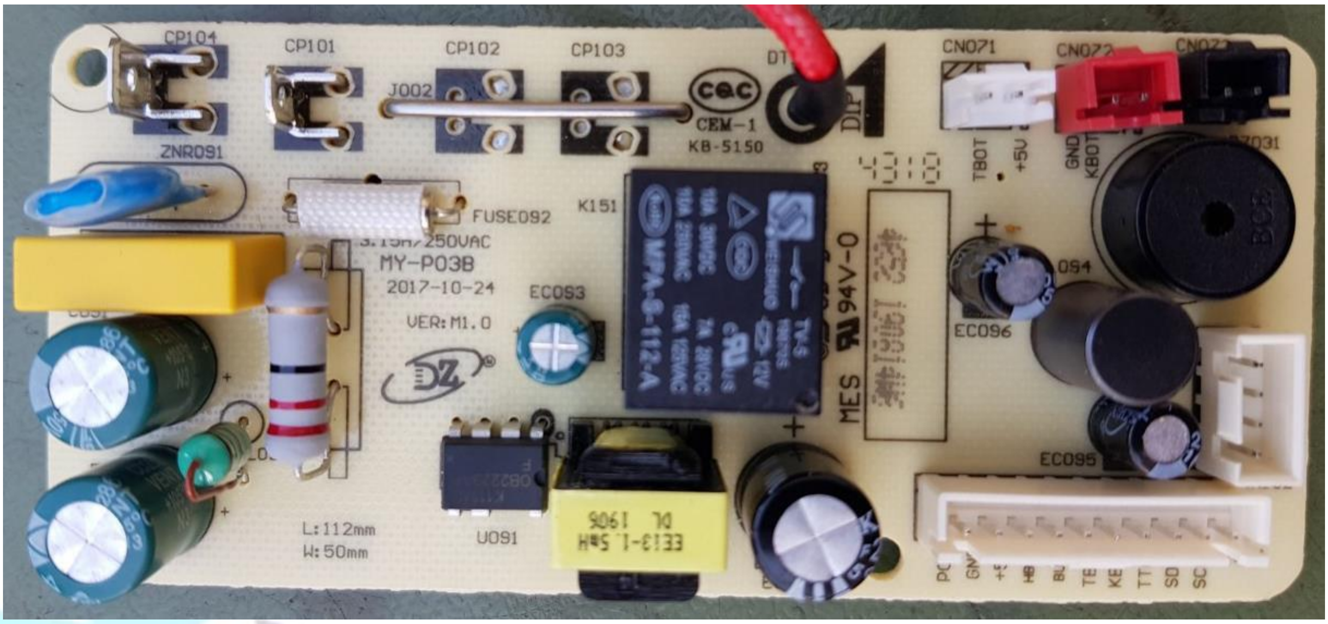

Figure 17 Amazon Basic Pressure Power PCB

9 Inter PCB connections

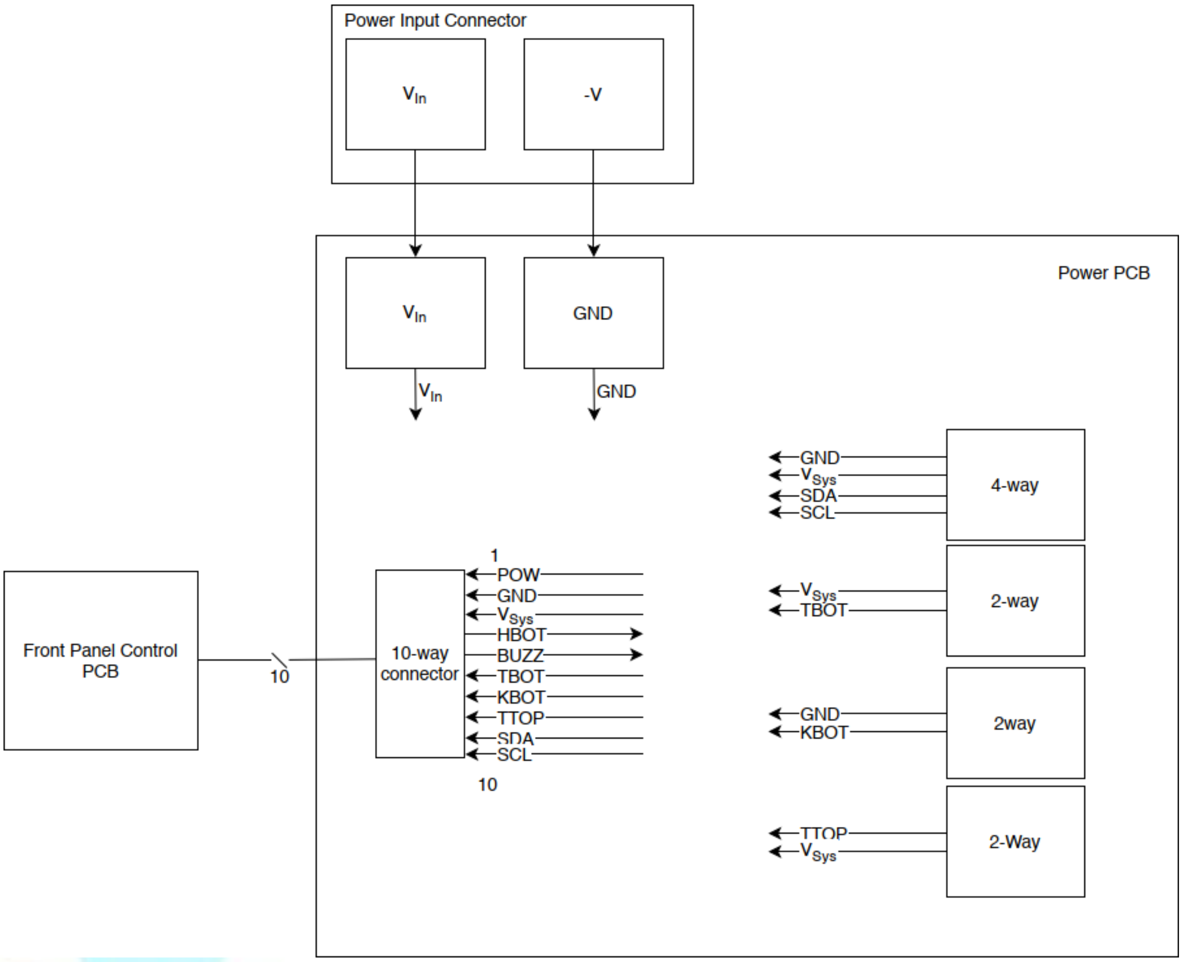

Figure 18 Power PCB Connections and Wiring

Input Power Connectors

Signal	Description	Pin
V +		1

Signal	Description	Pin
Neutral		1

2-way

Signal	Description	Pin
V_{Sys}		1
TBOT		2

2-way

Signal	Description	Pin
KBOT		1
GND		2

2-way

Signal	Description	Pin
TTOP		1
V_{Sys}		2

4-way Pressure & Thermal Sensor

Signal	Description	Pin
GND		
V_{Sys}		
SDA		
SCL		

10-way

Signal	Description	Pin
POW		1
GND		2
V_{Sys}		3
PSU_EN		4
BUZZER_EN		5
TBOT		6
KBOT		7
TTOP		8
SDA		9
SCL		10

10 Stage 2

10.1 Boost Topology

The application requires a driving voltage (V_{Boost}) of 200V to operate a 55Ω heating element for the pressure-cooking process, as a result a boost converter is required to step up the input voltage of the system. Due to the hazardous voltage as well as current considerations a full bridge and transformer is deemed most suitable as it isolates the HV supply from the rest of the system as well as being more efficient that a typical boost converter based on an inductor and switching FETs.

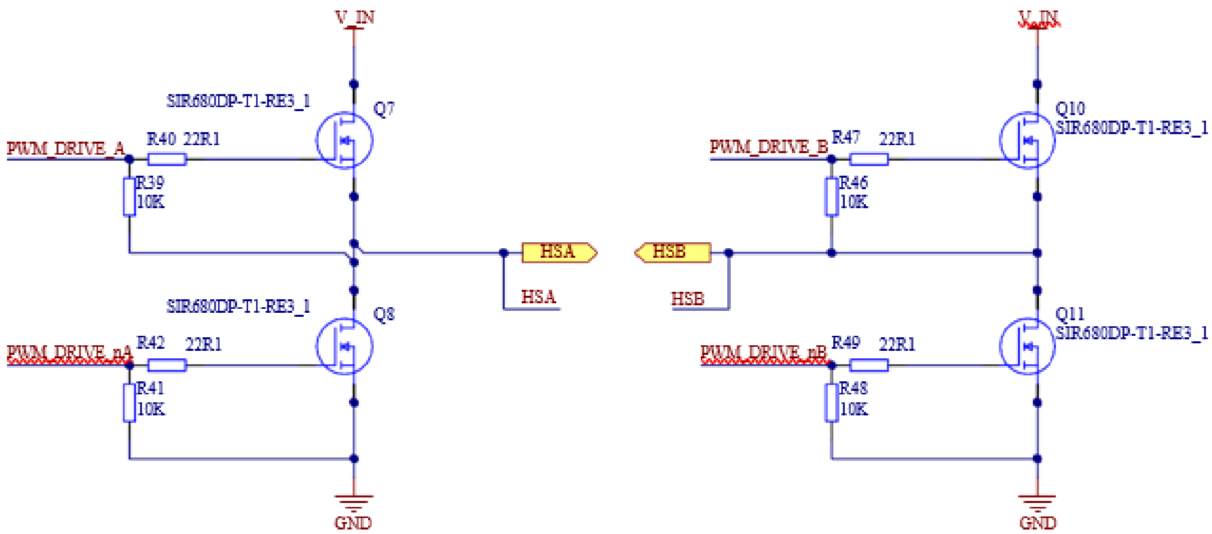

Figure 19 H-Bridge Circuit

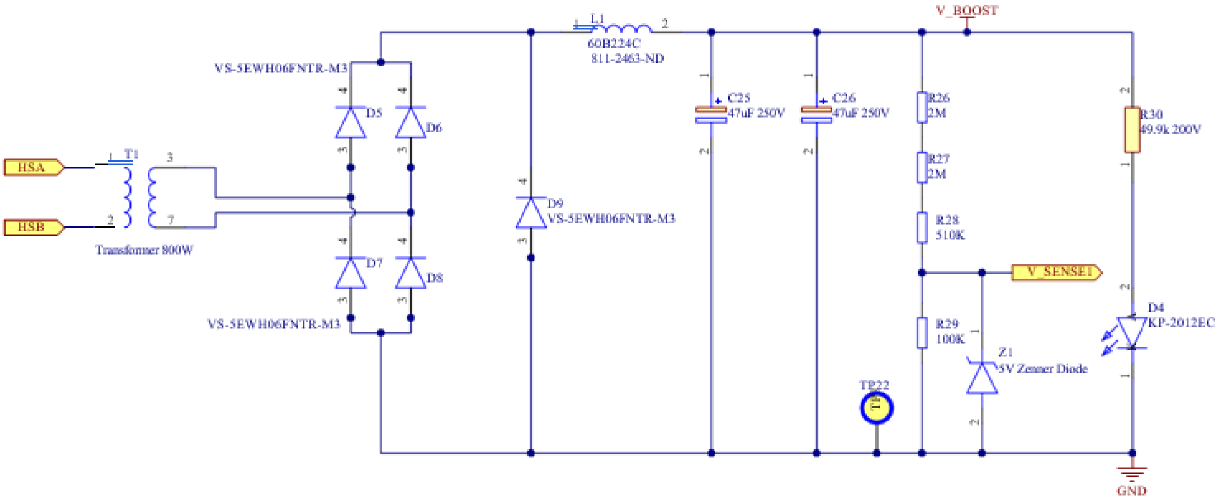

Figure 20 Transformer with Full-Wave Rectification

10.2 Transformer

For this design, a Planar transformer was used. The name planar implies that the geometry of the transformer is more of a two- dimensional component, rather than the traditional three-dimensional wire would equivalents. Planar technology comprises two major design features that distinguish it from the traditional wire would transformers. The windings are replaced by flat copper foil lead frames and can even be embedded into a printed circuit board. These flat windings are then mounted between thin & very lightweight ferrite cores.

Planar transformers also provide performance benefits through being electrically closer to an ideal component than their counterparts. All practical magnetic components introduce detrimental effects into the circuit in which they operate, which an ideal component would not. Planar components being closer to an ideal component remove the limiting factors in the performance of such circuits. They can often also save on additional components that may otherwise be required to overcome such problems.

The main pros and cons of the use of planar transformers are :

Pros

- Precise manufacturing due to the use of PCB substrate makes them more repeatable and hence keeping to the desired design criteria and calculations.
- Potentially a smaller PCB footprint but much improved height due to the flat nature of the PCB plates.
- Better heat dissipation due to the shape offering the ability to add heatsinks and although not in this case the use of fans to move the heat away. The frame is also open so air can move freely through it.
- Higher switching frequency which reduces the overall size of the magnetics used. The magnetics are the transformer and the output inductor. Doubling the frequency from say 100kHz to 200kHz will half the size of the output inductor and the transformer itself.
- Reduced skin effect due to the small cross-sectional area of the PCB copper foil used as opposed to the wound wire in a conventional transformer.
- Overall lower inductance in the transformer therefore reducing the overall losses increasing design efficiency.
- Much reduced weight, in some instances 25% of the weight of its counterpart.
- Higher current carrying capacity per winding due to increased surface to area ratio compared to wire.

Cons

- More expensive to manufacture due to
- A more complex design process which may have to be repeated because other design constraints.
- Although a simpler build process the cost of the component parts is more expensive.
- Longer lead time to first prototype. Although in this instance Himag Planar, the supplier of the transformer, delivered three prototype units in a matter of weeks.

10.3 Soft Start Mechanism

The power supply has a soft start control system shown in Figure 3 - Soft Start Mechanism. Since the system has a high current DC input supply, labelled V_IN, it is important to limit the input current to avoid sparking and degradation of the connectors when the power is connected. The capacitors, C27 & C29, initially have a very low impedance path to ground and hence look like a short circuit causing the large current inrush. By placing resistors on the ground side of capacitors the inrush can be set. In this instance, it is limited to between 25-70mA depending on the voltage level of V_IN. Once the voltage on the capacitors has stabilized a software controlled low on resistance N-FET is activated to bypass the resistor and return the direct ground path for the capacitors.

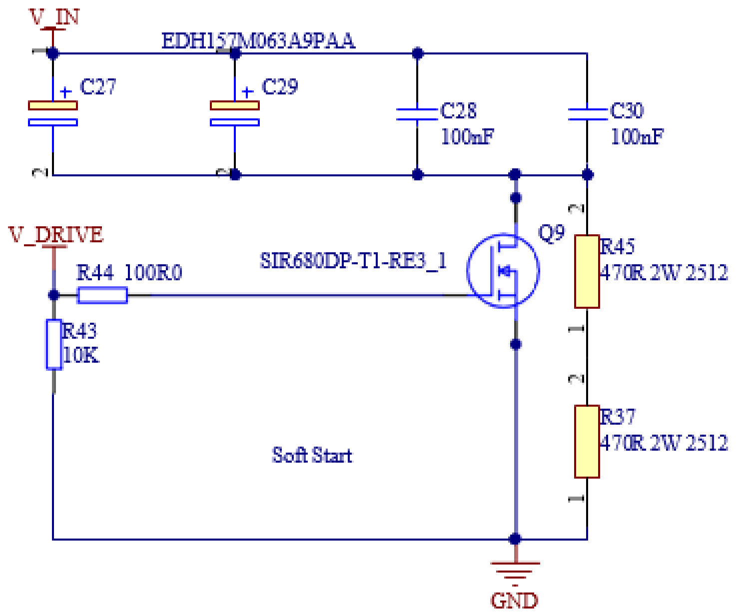

Figure 21 Soft Start Mechanism

11 PCB Construction

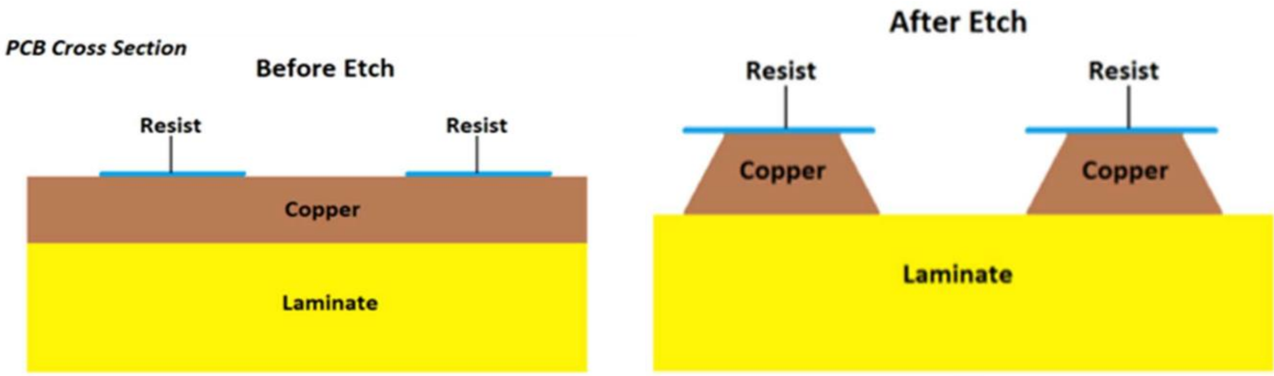

Figure 22 PCB Cross Section Before and After Etching

The laminate is generally FR-4, which is a woven glass and epoxy, and has copper bonded to its surface. The copper surface is etched with ammonium persulfate or ferric chloride. Figure 4 shows the board before the etching process that will remove any exposed copper that is not covered by a surface film; shown here as resist. Since the upper part of the copper is exposed to the chemical etch for a longer period, the cooper trace has a trapezoidal shape. The thicker the copper the longer the exposure and therefore the wasting becomes more pronounced. This causes the limitations in minimum track size and spacing.

In the case of the MECS PCB construction, due to the very tight tracking for the high current input it was calculated that 4oz copper was required to carry the current with a 10°C temperature rise of the traces at an ambient temperature of 25°C. This might not sound very much, but when the ambient temperature inside the unit could be 80°C the heating is more pronounced.

PCB construction must be symmetrical i.e., 4oz copper on the top layer requires 4oz copper on the bottom layer. If this is not followed the PCB can warp when heated in the reflow process to solder the devices to the board. Due to the trapezoidal effectof the etching and the small copper pads for the microcontroller and other components, only 2oz copper could be used on the bottom layer which dictates the top layer also being 2oz.

After consultation with our chosen manufacturer, Garner Osborne Circuits Ltd., it was learnt that a process of electro plating thetop surface could add an additional ounce of copper, but this still led to additional heating of the high current paths.

12 Losses

There are two main sources of power loss in a switch mode transformer-based power supply. The first is the switching losses in the MOSFET devices, the second is leakage inductance in the transformer. It is important to balance these losses to create a high efficiency power supply. Higher losses are generated by switching the MOSFETs at a higher frequency. Generally, for planar transformers where the losses are primarily transformer-based, the frequency range of 200kHz to 1MHz. The design frequency for the MECS PSU is 200kHz.

12.1 Conductance Losses

There are conductance losses in the MOSFETs, Transformer, Rectifier Diodes, and Inductor. The inductor losses will be relatively small. The transformer maximum loss is 4W.

12.1.1 MOSFET Conductance Losses

Each time the MOSFET switches power is lost in the MOSFET these are denoted by:

$P_{MOSFET\ Loss} = I_{in}{}^2 \times R_{DS(on)} \times D$

$P_{MOSFET\ Loss} = 35^2\ x0.003\ \times\ 0.5$

$P_{MOSFET\ Loss} =\ 1.84W$

Where:

$P_{MOSFET\ Loss}$	= MOSFET Conductance Loss in Watts
I_{in}	= Current (A)
$R_{DS(on)}$	= Resistance of the MOSFET whilst on between the drain and the source
D	= Duty cycle

There are four MOSFETs therefore, the total MOSFET conduction losses total *7.36W*

12.1.2 Rectifier Diode Conduction Losses

The power lost by each of the rectifier diodes at full power is given by:

$I_{AV} = (1 - D) \times I_{out} = 0.5 \times 4 = 2A$
$P_{Diode\ Loss} = I_{AV} \times V_{fwd}$
$P_{Diode\ Loss} = 2 \times 1.5 = 3W$

Where:

I_{AV} = Average Diode Current
D = Output Duty Cycle
$P_{Diode\ Loss}$ = Power Loss per Diode
I_{out} = Output current from the transformer

There are four diodes therefore the total rectifier diode conduction losses total 12W.

The sum of the conductance losses = 4W + 7.36W + 12W = 23.36W.

12.2 Switching Losses

MOSFETs have a finite switching time, therefore, switching losses come from the dynamic voltages and currents the MOSFETs must handle during the time it takes to turn on or off. Gate-drive losses are also switching losses because they are required to turn the FETs on and off.

12.2.1 MOSFET Turn On

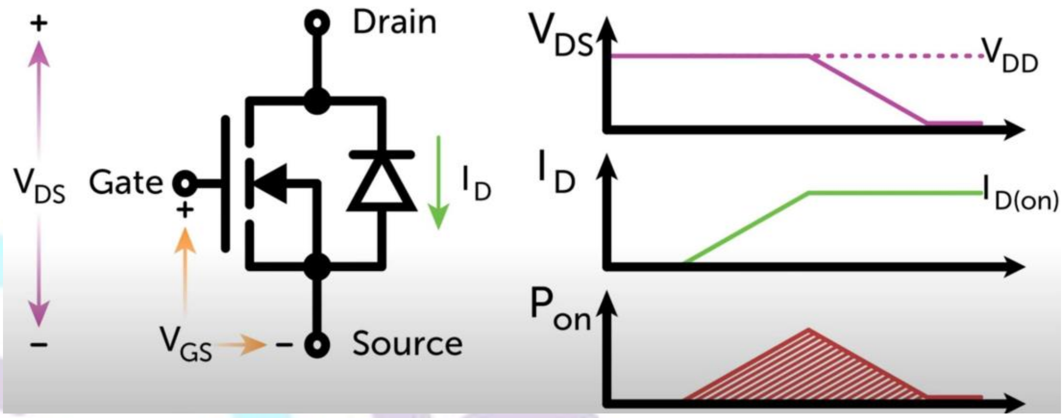

Figure 23 MOSFET Turn on Power Loss

Figure 23 shows the typical turn on cycle of a MOSFET and how V_{DS} and I_D change as it opens which results in the P_{on} switching loss. At t_0 the gate voltage is applied starting the cycle. The turn on delay is approximately the time it takes for current to start flowing in the drain. The current will rise until it reaches the operational point and at the point the V_{DS} voltage starts to fall until it reaches zero, and this is the turn on or t_{on} time.

The MOSFET switching loss is calculated by the following formula:

$P_{Turn On} = E_{Turn On} \times f_{sw}$

$P_{Turn On} = (I \times V \times t_{on} \times ½) x\ f_{sw}$

$P_{Turn On} = (800W \times 36ns \times ½) \times 200kHz$

$P_{Turn On} = 2.88W$

The MOSFET turn on capacitance loss is calculated by the following formula:

$P_{OCL} = (C_{oss} + C_p) \times V^2 \times f_{sw}$
$P_{OCL} = 470pF \times 3,136 \times 200kHz = 0.295W$

Where:

P_{OCL} = MOSFET output capacitance loss
C_{oss} = MOSFET output capacitance = 440pF
C_p = Parasitic capacitance = 30pF (approximated)
V = Drain voltage = 56V
f_{sw} = switching frequency = 200kHz.

The total MOSFET turn on loss = *3.175W*

There are four MOSFETs so the total turn on losses = *12.7W.*

12.2.2 MOSFET Turn Off

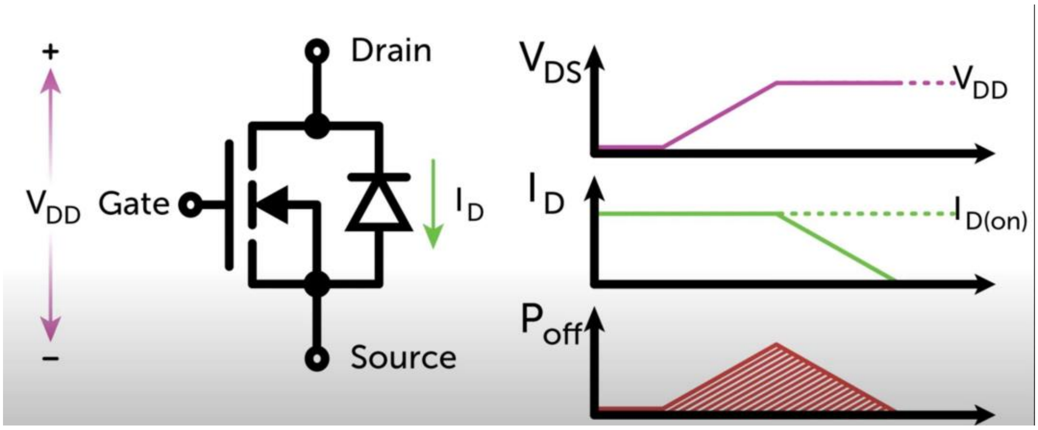

Figure 24 MOSFET Turn off Power Loss

The turn off or $P_{Turn\ Off}$ losses are calculated in much the same way, however, the fall time is generally faster. At t0 there is a turn off delay before the VDS voltage starts to rise and the current stays constant. Once VDS reaches full potential the current starts to fall to zero. The start in rise of VDS to the fall of ID to zero is the toff time.

Using the same formula for $P_{Turn\ On}$, $P_{Turn\ Off}$ is calculated to be 1.32W.

There are four MOSFETs therefore, the total MOSFET turn off losses = 5.28W.

12.3 Diode Recovery Losses

12.3.1 Rectifier Diode Recovery Loss

Diode recovery losses are extremely difficult to calculate because of the wide variations with temperature and current to name a few. There are forward recovery losses as well as reverse recovery losses. The forward losses are not normally calculated, and the reverse recovery loss is an approximation; real world testing is the only true way to understand this.

A diode recovery loss is when the diode stops conducting in the forward direction generating a reverse current to flow that is much higher than the forward current but only for a brief period in the nanoseconds.

To estimate this the following formula is used:

$P_{DRecLoss} = Q_{RR} \times V_{IN} \times f_{SW} / 2$
$P_{DRecLoss} = Q_{RR\_Spec} (I_F / I_{F\_Spec})^{0.5} \times V_{IN} \times f_{SW} / 2$
$P_{DRecLoss} = 93nc \times (4A / 5A)^{0.5} \times 200V \times 200kHz / 2$
$P_{DRecLoss} = 1.66W$

Where:

$Q_{RR} = Q_{RR\_Spec} (I_F / I_{F\_Spec})^{0.5}$ = *Stored charge in the diode*

Q_{RR_Spec} = Q_{RR} *found in the datasheet and is derived from maximum forward current and can double with temperature. Use the worst-case figure = 93nc @ T_J 125°C (51nc @ T_J 25°C)*
T_J = *Diode Junction Temperature*

I_F = *Forward current in the circuit*
I_{F_Spec} = *The diodes maximum forward current from which Q_{RR_Spec} was derived.*

12.3.2 MOSFET Recovery Loss & Freewheeling

So far conductance losses and turn on and turn off switching losses have been examined but there are also losses associated with the off state of the H-Bridge after the MOSFETs have provided an on cycle of current to the transformer. The calculated losses have indicated that an efficiency of over 90% should be theoretically achievable, however, the actual efficiency was measured as being 70% to 75%.

It is believed that these losses are in the H-Bridge and calculation of these losses is a complex procedure requiring a good knowledge of physics and electronics.

The links below are to some technical papers that explain how these losses are created and the design process to follow to minimise these losses by implementing an LLC tank design with ZVS or Zero Volt Switching.

Reverse Recovery Operation

Zero-Voltage Switching Full-Bridge Converter

Resonant LLC Converter : Operation and Design

12.4 Software Implementation

Since the load for the MECS boost converter will only ever be a resistive load it is possible to use an integral only control loop. The first stage of the control loop determines if the PSU should be enabled or not. When a transition to off occurs, the PSU will undertake a soft stop action, this decrements the phase angle of the output by 0.05%. When the PSU is running, the battery level is checked to ensure that there is capacity in the battery to run at the required power. The system will back off by 0.01% if the battery is considered low. Otherwise, the normal integral control loop runs. This alters the phase angle depending on whether the output voltage is too high or too low.

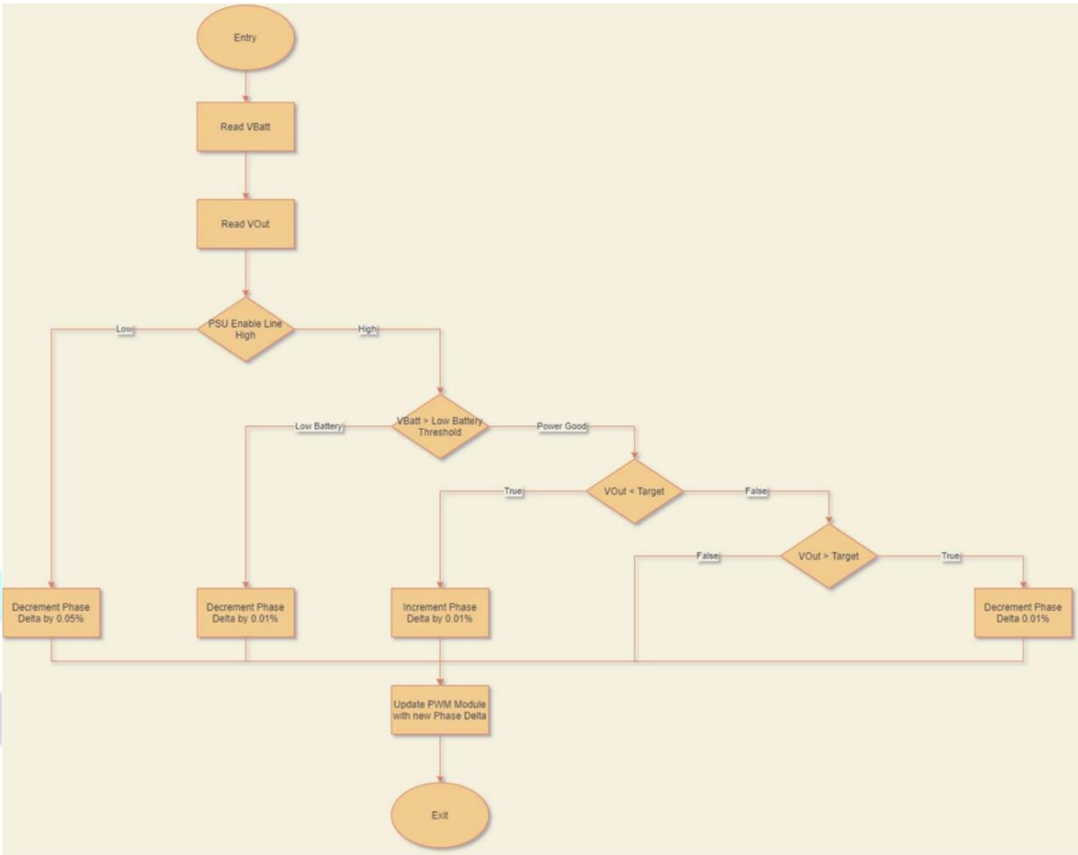

Figure 25 Software Flow Diagram

12.5 Phase Angle Control

The control method for a transformer-based switch mode power supply uses the difference in phase angle between the two sides of the H-bridge. When the PWM outputs are in phase, both sides of the transformer are at the same potential and therefore nocurrent will flow. At the point where the PWMs are 180 degrees out of phase the sides of the transformer are always pulled oppositely. The transformer is therefore energised for 100% of the time. The intermediate states of phase angle are a hybrid of these two extremities. As the phase angle increases from 0 degrees the time that the primary transformer winding is exposed to a voltage differential is increased.

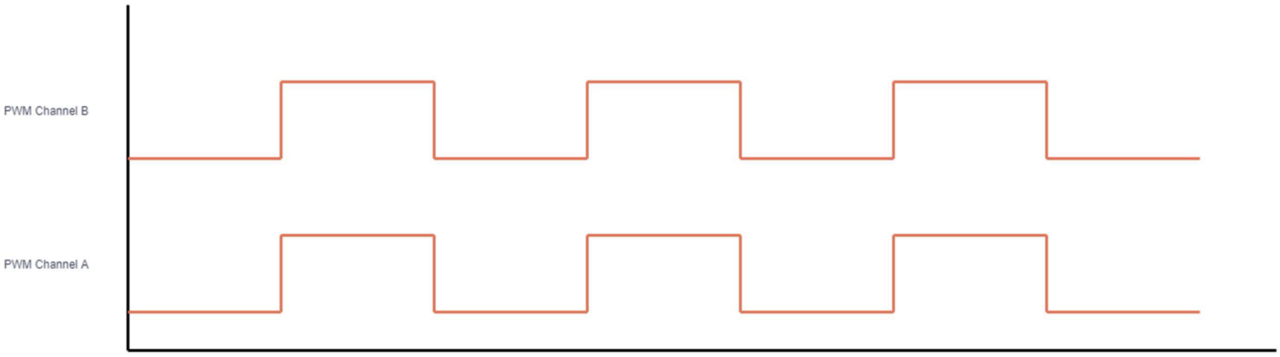

Figure 26 0 Degrees or In Phase

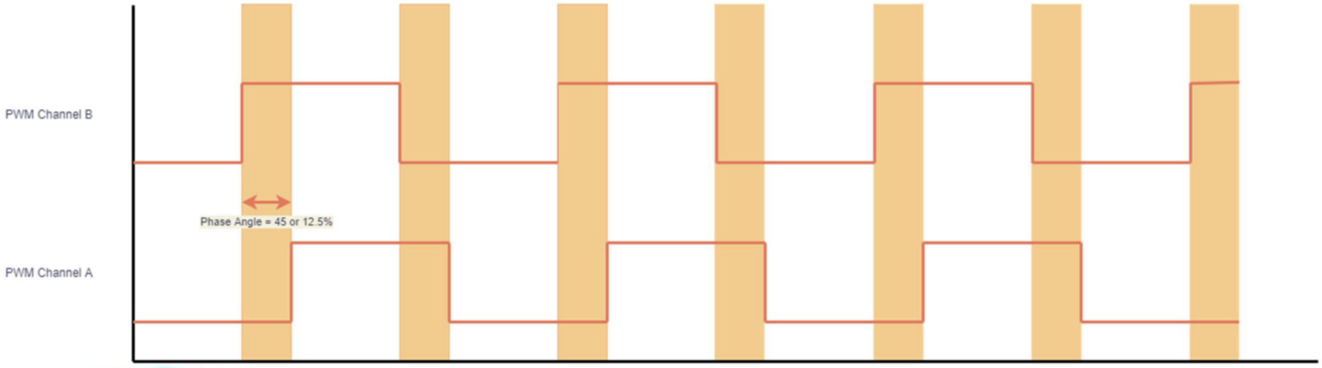

Figure 27 45 Degree Phase Angle 25% Power

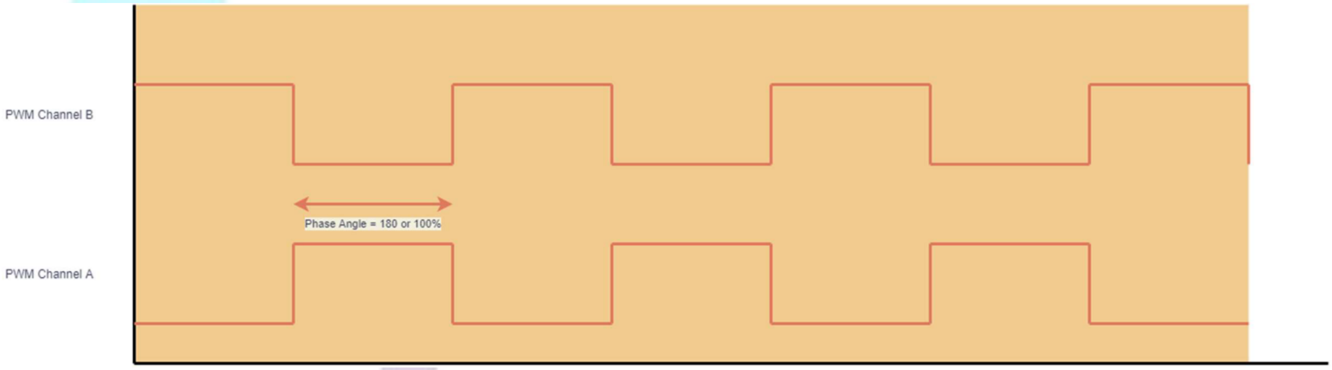

Figure 28 180 Degrees Phase Angle 100% Power

13 Testing

The initial set to work of the MECS power supply involved checking each of the power rails. Once this process was done the processor was connected to the debug probe and the software programmed into the device. This allowed features such as the soft start and FET drivers to be tested. Initially, the PWM channels and drive circuit was tested without a transformer on the PCB. Using this process, the phasing of the PWMs was able to be confirmed without risking damage to any components.

After connecting the transformer, initial tests were performed with a lower resistance load (16 ohms) to start putting power through the transformer. During the first run up tests it was noticed that the switching process for the FETs was relatively long causing a shoot through issue. By replacing the inline current resistors with 0 ohm links the shoot through was removed.

As the testing continued, it was noticed that the switching of the FETs was not quite receiving the correct switching signals causing the transformer to have a floating winding at higher loads. Research into the components identified that the selected bridge driver was forcing a longer deadtime. Changing the component led to a cleaner drive signal. The low side MOSFETs were damaged by the shoot through and therefore replaced.

The full load was then attached to the output. The bench power supply providing the input voltage was set to 24V and the current limited to 15A. The current was limited by the power supply control loop, which performed well. Further testing with this arrangement again ended up causing damage to the hardware despite carefully monitoring the temperature of the bridge. Since the full load is higher than the initial test load the output voltage was also increased.

13.1 Improvements and Next Steps

There are several areas of improvements which will be discussed in this section.

13.1.1 Snubbers

Snubbers are used to suppress the harmful effects that high-speed switching devices can create. The basic snubber is an RC combination that can be placed on both the input and output sides of the transformer. There are also RCD variants employing a diode. Cost, space and efficiency requirements drive the selected method as well as a designer's preferences.

13.1.2 LLC Tank

Figure 11 shows a Full-Bridge LLC converter with Full-Bridge rectifier. The switching bridge generates a square waveform to excite the LLC resonant tank, which will output a resonant sinusoidal current that gets scaled and rectified by the transformer and rectifier circuit, the output capacitor filters the rectified ac current and outputs a DC voltage.

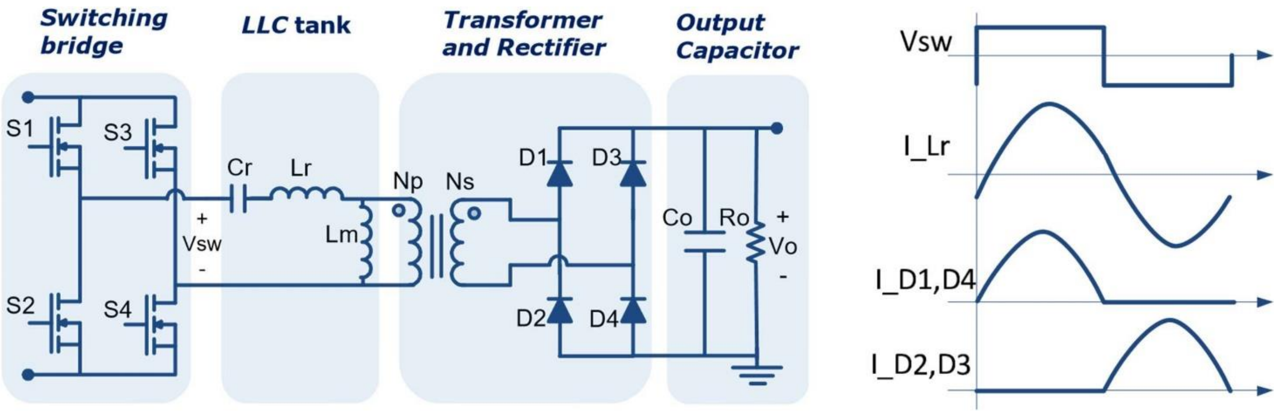

Figure 29 Proposed Topology for Next Iteration

The LLC is regarded as lossless as it redirects the switching power losses back into the primary winding. An LLC tank was thought to not be needed originally as the Planar transformer looks like a near perfect device. However, this should be investigated going forward along with a snubber across the secondary of the transformer.

13.1.3 Heatsinking

Heat is an obvious enemy of any switch mode power supply and the devices need to be kept well below their theoretical maximum operation temperatures. As the MOSFET's temperature increases so does the associated RDs(on) increasing the conductance losses increasing the losses and generating more heat.

13.1.4 Larger PCB

To understand the true losses in the circuit it would be good to take a step back and build a PCBA with a basic circuit with the necessary gate drivers. This would be relatively inexpensive compared to the cost of manufacturing the current PCBA. It may be that the design has to be realised with a larger PCBA to aid heatsinking and also allowing it to be manufactured from 2oz copper.

The PCB should be laid out in such a way that various configurations of filters can be experimented with along with devices that can be more easily replaced if damaged. In this way the circuit operation can be more easily studied and understood.

14 Interim conclusion to Working Paper

The extensive thinking and design work described above plus the limited testing, suggests that constraining the solution to be so small as to fit within any commercial EPC creates overheating problems which are difficult to solve in such a small form factor.

The proposed solution for a DC conversion kit is elegant, but further work needs to be undertaken with a larger PCB.