PRODUCT DESIGN

OF A

DIGITAL PURE SINE WAVE INVERTER (WITH BI-DIRECTIONAL ISOLATED DC-DC CONVERTER AND CHARGING SYSTEM

SUBMITTED BY

PREMAUDA DESIGN AND SYSTEMS LTD

TO

AFRICA DEEP TECH CHALLENGE 2025

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LIST OF FIGURES

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ABBREVIATION

PE – Power Electronics

PFC – Power Factor Correction

DC-DC – Direct Current to Direct Current

DC-AC – Direct Current to Alternating Current

PCB – Printed Circuit Board

PWM – Pulse Width Modulation

HW – Hardware

SW – Software

DSP – Digital Signal Processor

UI – User Interface

I2C – Inter-Integrated Circuit

µC – Microcontroller

PI – Proportional Integral

ADC – Analogue to Digital Converter

FW – Firmware

UV – Under Voltage

OV – Over Voltage

OC – Over Current

GPIO – General Purpose Input and Output

CLA – Control Law Accelerator

WD – Watchdog

TF – Transfer Function

THD – Total Harmonics Distortion

VCL – Voltage Control Loop

CCL – Current Control Loop

DC – Duty Cycle

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CHAPTER ONE

PROBLEM DEFINITION AND CONSTRAINTS

1.1 Introduction

Energy transition from fossil-based energy systems to renewable energy systems is an ongoing generational challenge, and one of the main proposed implementations is the generation of electrical energy in a power electronics (PE) based system. However, PE systems are recently becoming more of complex embedded systems where most device functionalities are achieved in the digital domain. Hence, designers and developers of such systems would not only understand the hardware (HW) design aspect but also the software and embedded technology that the Digital Signal Processor (DSP) brings into the system.

Our product, '*Pure Digital Sine Wave Inverter/Charger',* offers a solution to these challenges. Our product is a high-frequency 3-subsystem PE device consisting of a PFC boost converter at 100kHz, a DC-DC bi-directional converter at 100kHz, and a DC-AC converter at 20kHz, which are ideal in various spectra of power supply systems.

A Texas Instruments TSM32F280049C microcontroller (µC) is at the heart of the device, which is programmed to generate PWM that drives the PE to produce digitally pulsing voltages, sense and measure several AC and DC signals, execute control loops in the digital domain and perform several other background tasks.

1.2 Problem Definition

Some of the problems we try to solve with our product design are below;

i. An energy system that generates electricity as an alternative to fossil fuel.

ii. Efficient and reliable PE power system as an alternative to the traditional analogue-based PE power system.

iii. Embedded Expertise Development: Embedded devices are ubiquitous; however, virtually all in Nigeria are imported because of the lack of embedded system expertise. Our product design contributes to solving this.

iv. Technology: The technology in EV, telecom power supply systems is used in our product, hence giving us a good foundation to diversify into other product lines.

v. Energy/Power crisis and transition to renewable energy.

1.3 Constraints

Several constraints were encountered in the design of the product. Some are listed below:

i. **Resource Limitations in Embedded Systems**
   When compared to desktop-based systems, embedded platforms have limited processing power, constrained memory, and strict timing measurements. This required rigorous code optimization, especially for a fully digital product like ours, with over 15,000 lines of code. The use of lightweight control algorithms, all made under tight real-time constraints, must be factored into the design process.
ii. **Component Sourcing**
   Key hardware components were not locally available and had to be sourced internationally. This was a challenging process. This introduced long lead periods, elevated costs due to exchange fluctuations, which at times result in multiple design revisions so as to accommodate available substitutes while maintaining system integrity.
iii. Implementing precise Digital Control of Power Electronics System in a complex field of control requires more than just theoretical understanding, but an in-depth knowledge to implement the deep expertise needed in control loops, signal conditioning and noise immunity.
iv. Standard design practices in both embedded systems and PE placed structural constraints on architecture selection, thermal management, isolation techniques, and electromagnetic compatibility (EMC). Integrating these diverse requirements into a compact, cost-effective prototype pushed the boundaries of our design flexibility.
v. The final validation of such a system demands high-grade test equipment; oscilloscopes, programmable power sources, load banks, PCB machine, which are expensive for a start-up.

1.4 Project Deliverables

The goal of our project is the design of a high-quality inverter/charger with cutting-edge technology that can be used in homes and offices in Nigeria and beyond, hence our 5 project deliverables below:

i. SW deliverables
   1. Professional SW development process: Software developed in a structured and professional way to enable easy development and debugging.
   2. Firmware: Final SW binary that would be written to the HW
ii. HW deliverable
   3. Standard HW circuit diagram: Well-structured HW circuit diagram
   4. PCB: Final artefact from the HW design
iii. 5. Prototype: sample product for field test or to be sent to the client

CHAPTER TWO

OVERVIEW OF A DIGITAL PURE SINE WAVE INVERTER/CHARGER

An overview of our product is presented below in comparison with traditional and existing PE systems.

2.1 Simplified view of digital and analogue PE system.

Traditional inverters/charging systems are usually low-frequency devices, hence they tend to be noisy, inefficient and bulky. Also, traditional PE systems are heavily analogue devices using little or no firmware for their operation. This leads to most being square wave or modified sine wave devices with high harmonic distortions, reducing accuracy in sensing the ADC signal and limiting the overall system's functionality. Also, recent modern functionality like Battery Management System and advanced protection systems are missing in those systems.

Our device completely differs from traditional analogue-based PE systems as it is high frequency, with its functionalities all achieved in the digital domain using a powerful and efficient microcontroller. A simplified view of both PE systems is presented below

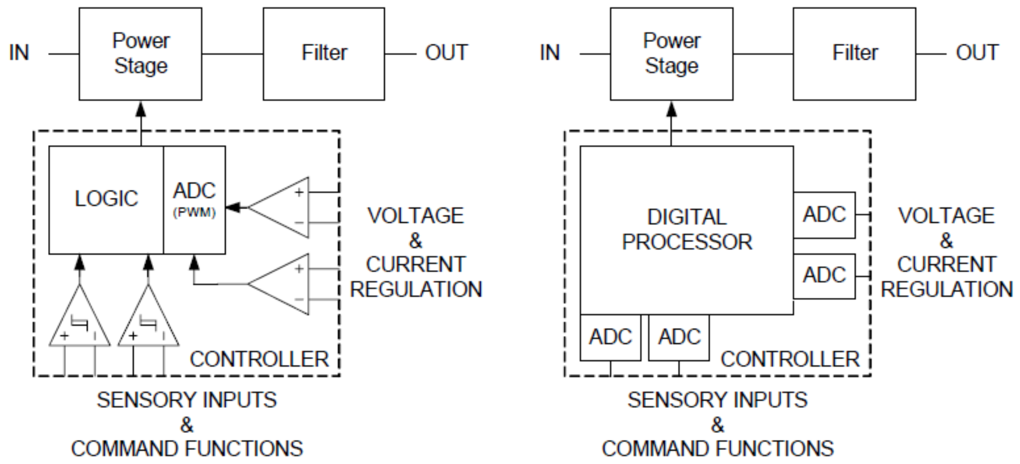

Figure 1: Traditional/analogue (left) and digital (right) based PE systems

2.2 System/Topology Overview of Traditional and Modern PE Inverter Systems.

Modern PE systems radically depart from traditional systems and have several subsystems in their implementation. This introduces enormous complexity but also a more robust system and increased reliability.

The top-view block diagram of the traditional and digital Power Electronic system is presented in Figures 2 and 3

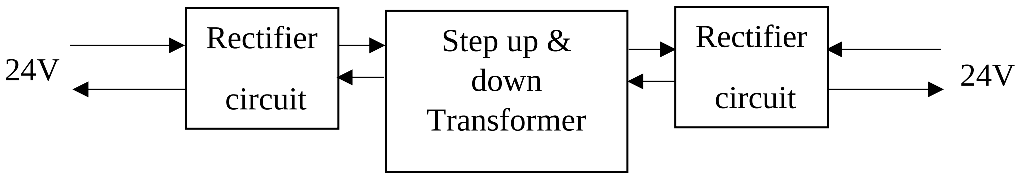

Figure 2: Top view of traditional/analogue based PE systems

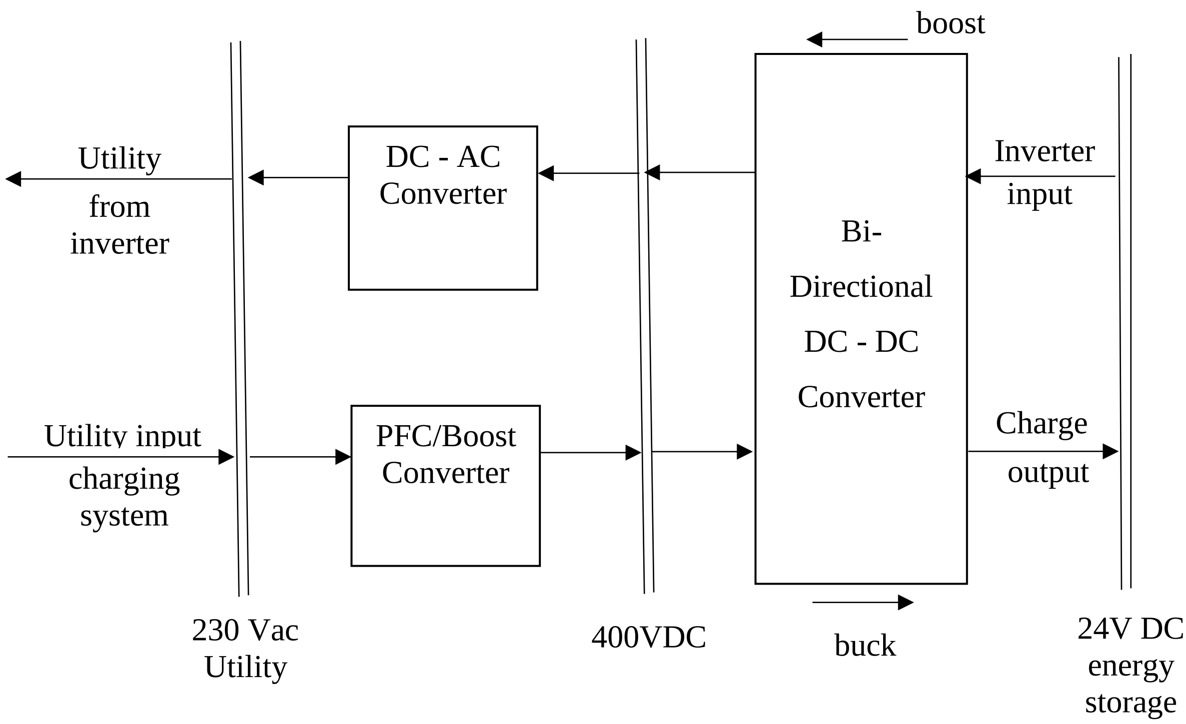

Figure 3: Top view of digital based PE systems

The difference between the systems is enormous; however, the advantages of the digital PE system justify it. This is also a major reason for our product design decision. A list of the advantages is below.

i. The systems based on advanced technology are more reliable and efficient.

ii. Due to the high frequency of operation, the magnetics are lightweight, which affects overall system performance and good form factor.

iii. Control systems in the digital domain do not suffer degradation of performance due to the ageing of components.

iv. Pure sine wave.

v. Suitable for any kind of load; sensitive and insensitive.

vi. It is noise-free.

vii. The radio frequency interference is also eliminated.

2.3 Charger/Inverter Specification

Product and subsystem specifications are listed in Table 1.

Table 1: Charger/Inverter Specification

INVERTER		CHARGER	
General		**General**	
Input (V)	12V/24V DC	**Input (V)**	230V AC
Output (V)	230VAC	**Output (V)**	12V/24V DC
Frequency (Hz)	50Hz		
Current (A)	2.5A	**Current (A)**	20A
Power Rating (W)	600W	**Power Rating (W)**	400W
DC-DC Converter		**DC-DC Converter**	
Topology	Current fed Push Pull	Topology	PSFB
Control	ACMC	Control	PCMC
Input (V)	12V/24V DC	Input (V)	380V – 400V DC
Output	375V–400V DC	Output	12V/24V DC
Switching Freq.	100kHz	Switching Freq.	100kHz
DC-AC Converter		**PFC/Boost Converter**	
Topology	Modified Unipolar Modulation	Topology	Interleaved Boost
Control	PR Controller	Control	ACMC/PI
Input (V)	380V DC	Input (V)	150V- 265V AC
Output	230V AC	Output	150V- 265V AC
Output Freq.	50Hz		
Switching Freq.	20kHz	Switching Freq.	100kHz

Others: 1. Protection – Over current, over voltage, high temperature, short circuit, overload and surge protection at each stage of the device

2. UI – audio, switch, 4 digits 7 segment display and LED

CHAPTER THREE

OUR JOURNEY - PROJECT IMPLEMENTATION

The product design is a very broad and extensive engineering project. It covers a range of activities, including project management, hardware and software design implementation, control system design and testing, subsystem integration, system tests, and supply chain activities, proper documentation, design alternatives and final decisions for both HW and SW tool chain, among others.

Various project implementation stages and activities are enumerated below

3.1 Pre-design Stage

These were activities that preceded the commencement of the actual product design.

i. Research and Selection of PE topology: Extensive research was done into various PE topologies before the final selections were made.
ii. Microcontroller selection and SW design loops: Several microcontrollers from various manufacturers were reviewed before the selection of the TI C2000 platform.
iii. System specification: The system specification is presented in Table 1 of Chapter 2.
iv. Project Management: An extensive project management was involved in the project, including monthly meetings, stand-up scrum, and work allocation.

3.2 Product design phase

This phase encompasses a range of activities, including decisions on the theories as well as the PE topologies to be used, calculations based on these decisions, including HW calculations and SW design, which eventually led to implementations and testing of our developed concepts. Further details are highlighted below:

i. HW

- Design
  - Measurement circuit design
  - PE topology selection including calculations
  - HW unit and sub-system design
  - Simulation of designs
- Implementation
  - Testing of various units of hardware design
  - Breadboarding and breakout boars of design
  - Integration of the HW units with SW

- Testing of hardware sub-modules
- PCB design

ii. **Control system**

- Design
    - Selection of control system
    - Design calculation of selected control system
    - Control system integration with PW topology
    - Simulation of control system
- Implementation
    - SW implementation for the control algorithm
    - Control Integration and testing control system with the hardware design.

iii. **Software**

- Design
    - Software architecture and structure
    - SW Data structure
- Implementation and testing
    - Programming of microcontroller peripheral
    - SW unit implementation and testing
    - SW module implementation and testing
    - Subsystem and system integration and testing

iv. **Testing and System Integration**

v. Other

- Mechanical design
- Supply chain activities.

This report will mainly focus on the design stage of the engineering process.

3.3 List of tools used for development

Table 2: List of both SW and HW tools used for the product development

HW Tools		
S/N	**HW tool name**	**Usage**
1	Logic analyzer	For viewing/inspecting microcontroller signals and serial bus communication (I2C, UART)
2	Oscilloscope	To monitor and analyse analogue and digital signals for stability and noise.
3	Electronic Load	Used to simulate real world load conditions for testing.
4	Eagle CAD	Drafting of HW circuit, and design of custom PCB
5	LT Spice	Simulation of electronics HW designs
SW Tools		
1.	GIT	Version control for SW development
2	MATLAB/Simulation	Testing and simulation of control loop designs and PE topology
3	TI Code Composer Studio	IDE for SW development and debugging of Firmware
4	TI Proprietary tools	For the simulation of the designed PE topology

CHAPTER FOUR

DESIGN DETAILS

4.1 HW design

This entails all the steps and design decisions that relate to the HW design of the product and the final 9-page circuit diagram. Some important HW design details are included in this section.

4.1.1 Microcontroller /DSP selection

At the heart of all embedded and Digital PE devices are µcs. The Texas Instruments TMS320F280049 32-bit µc was selected. The µc has advanced features that make it ideal for digital PE products. One of the first steps in the HW design is the pin allocation of the µc. This essentially connects the chip to the entire HW circuitry of the product. Each pin is further configured in the HW layer of the SW design. The Pin mapping of the µc is in Figure 4 below:

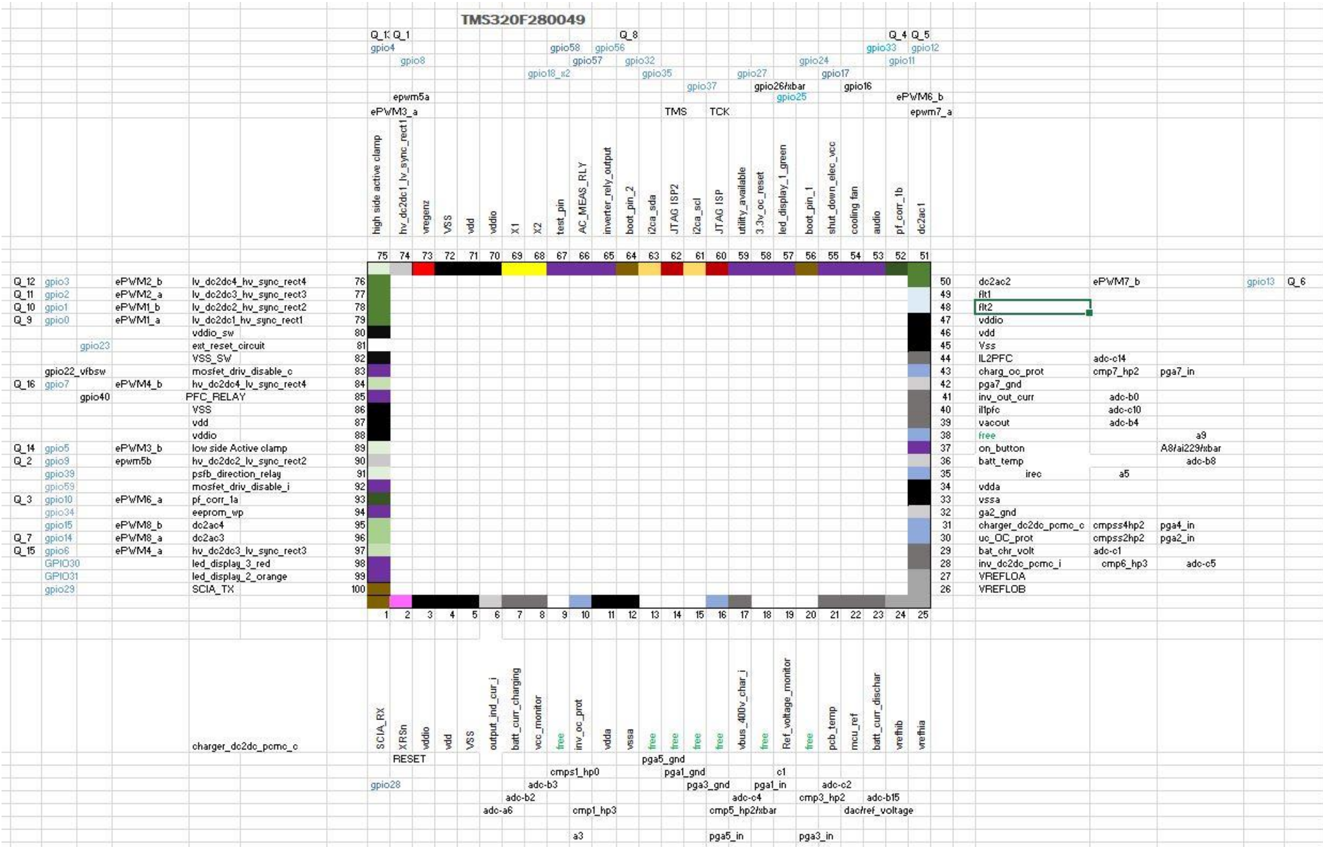

Figure 4: Full Pin Mapping for the µc

a. Signal measurements circuitry design.

Accurate and real-time signal measurements using the µc ADC and comparator block and the HW signal measurement circuits are needed to monitor the power stage plant and the system, and the measurements are used for calculation in the control loops, among others. Several signals are measured. The list of measured signals is given in Table 3. A generalised representation of the signal measurement is below:

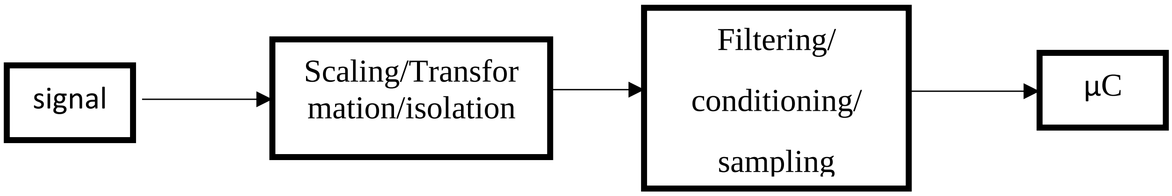

Figure 5:A generalized diagram of the signal measurement using the ADC peripheral

The µC Formula for ADC Measurement

$$\text{ADC result} = 4096 \times \frac{Measured\ voltage - V_{ref\ low}}{V_{ref\ high} - V_{ref\ low}} \qquad (1)$$

This result is what is further processed in the µc for various usages.

Example Signal measurement implementation

The 400V bus voltage measurement implementation is given below:

i. A circuit diagram for measurement was designed. This design fulfils the generalised model for the signal measurement above: The snapshot of the circuit diagram is below:

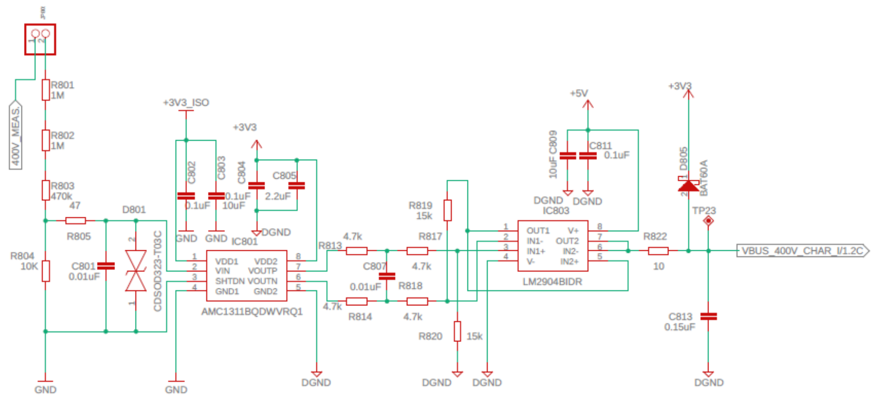

Figure 6: Circuit diagram for 400V DC bus voltage

ii. The circuit diagram is represented as a macro in the SW. The macros are basically the formula for calculating the measured variable and are given below:

```
//Where resistor divider
#define R_K_BUS_400VOLT        ((float32_t)(1000000u+1000000u+470000u+10000u)/10000u)
#define PFC_BUS_VOLT_ISOLATION_GAIN            (float32_t)
#define PFC_BUS_VOLT_OP_AMP_GAIN            (float32_t)1.596
//macro converts bus voltage value to adc equivalent value
#define ADC_400_VOLT(value)
((value*ADC_MAX_VALUE)/(R_K_BUS_400VOLT))*(PFC_BUS_VOLT_ISOLATION_GAIN*PFC_BUS_VOLT_OP_AMP_GAIN/ADC_REF)
//calculate actual measured values and to convert adc measurement to real measured value
#define CAL_BUS_400VOLT(ADC_MEASU)
(((MEASUR_ADC_VOLT(ADC_MEASU))*R_K_BUS_400VOLT)/(PFC_BUS_VOLT_ISOLATION_GAIN*PFC_BUS_VOLT_OP_AMP_GAIN*0.9
```

Table 3: List of measured signals.

S/N	µ channel	Signal	Method	Isolation	Nominal Value	Usage
1	Adc-a5	Charger current /dc	Op Amp	No	1.0A/2.0A DC	Charger load current/ ACMC computation/OC µC silicon trip.
2	adc-a6	Inver Inductor current /ac	CT/Op Amp	Yes	3.0A AC	Inverter Unipolar modulation control computation/OC µC silicon trip
3	adc-a9	Inverter Inductor current /ac	CT/Op Amp	Yes	3.0A AC	Uses above to operate
4	adc-b0	Inverter output current. /ac	CT/Op Amp	Yes	3.0A AC	Measures inverter output current/inverter control
5	adc-b2	Battery current/dc	Op Amp	No	25.0 A/50.0A DC	Measure batt charging current/OC µC silicon trip.
6	adc-b3	VCC monitor/dc	Volt divider	No	12V DC	Measures the biasing voltage
7	adc-b4	AC Volt/ac	Op Amp	No	230V AC	Measures utility & inverter AC volt & frequency/inverter control
8	adc-b8	Battery temp/dc	Volt divider	No	35.0 °C	Measures battery temperature
9	adc-b14	µc temperature	internal	NO	33.0 °C	Internally measures µC temperature.
10	adc-b15	Batt discharge current	Op Amp	No	5.8A/12.0A DC	Measure battery discharge current/OC µC silicon trip.
11	adc-c0	Ref. volt monitor/dc	Volt divider	No	1.65V DC	Measure reference voltage ADC circuit/OV and UV µC silicon trip.
12	adc-c1	Battery voltage/DC	Volt divider	No	14.0V/30.0V DC	Measure batt volt & charging volt/OV and UV µC silicon trip/control.
13	adc-c2	PCB temp. /dc	Volt divider	No	35.0 °C	Monitor PCB and ambient temperature.
14	adc-c4	Bus voltage/DC	Volt divider/OP Amp	yes	400V DC	Measure 400V of DC – DC /charge control/OV and UV µC silicon trip
15	adc-c10	Boost Channel 1 current/ac	CT/Op Amp	Yes	5.0A DC	Measure the current in the boost channel.
16	adc-c14	Boost Channel 2 current/ac	CT/Op Amp	Yes	5.0A DC	Measure the current in the boost channel.
17	CMP4	Charger DC-DC current/ac	CT/Op Amp	Yes	1.8A AC	Monitors current for PCMC/ OC HW PWM trip
18	CMP6	Inverter DC-DC current /AC	CT/Op Amp	Yes	28.0A AC	Monitors current for PCMC/ OC HW PWM trip

Sampling Rate: ADC a – 100KHz or MOSFET triggered | ADC b 50KHz | ADC c – 5KHz

Where value = µc measured value, ADC_REF = µc reference voltage is 3.3v, CAL_BUS_400VOLT(ADC_MEASU) = calculate measured voltage, ADC_400_Volt_(value) = converter's voltage to µc adc equivalent, with the first 3 macros from the code

iii. The macro is finally used in the code to perform a variety of assignments, including OV, OC and UV protection.

```
//convert the bus voltage value to ADC value for OV and UV
ADC_setPPBTripLimits (ADCC_BASE, ADC_PPB_NUMBER4,
(int32_t)ADC_400_VOLT(INV_DC2DC_BUS_VOLT_OV),(int32_t)ADC_400_VOLT(INV_DC2DC_BUS_VOLT_UV));

//Calculate the measured bus voltage
s_inv_ccl_var.vbus_out_inst = CAL_BUS_400VOLT(AdccResultRegs.ADCRESULT3);
```

b. PE & PWM GENERATION.

Crucial to digital PE systems is the PWM, which drives the plant to generate the output voltage. A generalized view of a digital converter is presented in Figure 7.

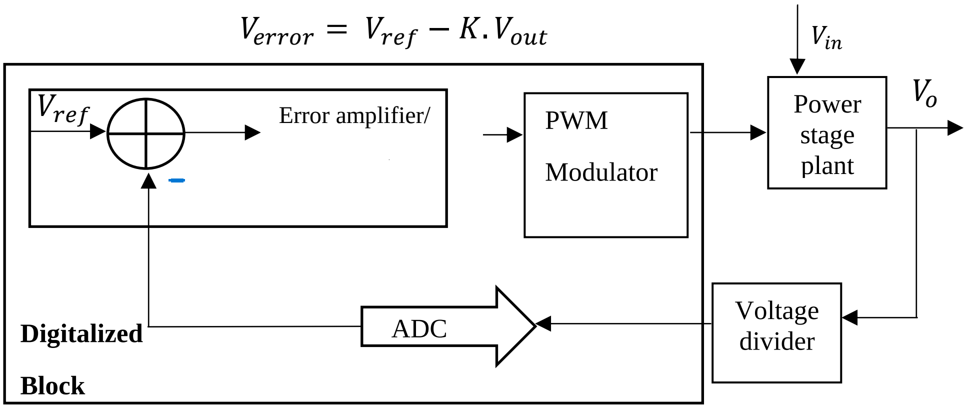

Figure 7: General operation of the PE PWM

Table 4: This table shows the implemented PWMs

S/N	Subsystem	PWM channel	Frequency	Control	HW topology
1	Charger PFC/boost	PWM 6 a & b	100KHz	ACMC	Interleaved
2	DC – DC buck	PWM 1 and 2; a and b	100KHz	PCMC	H- topology
3	DC – DC boost	PWM 4 and 5; a and b	100KHz	PCMC	H- topology
4	DC – AC converter	PWM 7 and 8; a and b	50Hz / 20KHz	Unipolar Mod.	H- topology
5	Synchronous rectifier	PWM 1 and 2, 4 and 5; a and b	100KHz		

The PWM is generated by the µc, and **<u>the output of the control effort is the duty cycle</u>** that the µc uses to generate the PWM that drives the PE to generate the required voltage.

The µc formula for generated PWM is below:

$$\mathrm{TBPRD}.\,{}^{1}\!/_{2}\cdot\frac{F_{TBCK}}{F_{PWM}} \qquad (2)$$

$$\mathrm{CMPA} = (1 - \mathrm{DC}) \times \mathrm{TBPRD}$$

Where F_{TBCL} – PWM peripheral clock frequency, F_{PWM} = PWM Frequency, CMPA – Comparator value fed to µc to generate PWM, TBPRD – Time-based period of PWM

4.1.2 Components Selection

HW design consists of several HW units that make up the system. The final design consists of hundreds of components which has specific functions. The major considerations for component selection are:

i. Device rating
ii. Topology used
iii. Norms and device save operation

PE PWM has been at the heart of inverters, and renewable energy is briefly presented. The components assembly block diagram for the PE PWM is presented below.

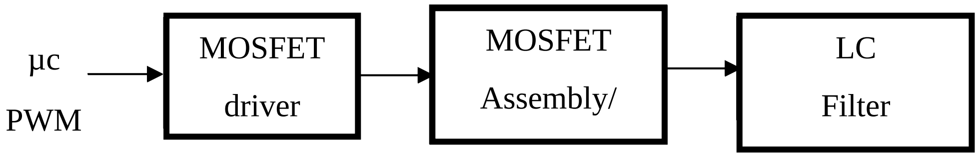

Figure 8: PE component assembly overview

The diagram is similar and applicable to each converter subsystem. The table below for the main components for PE of the DC-AC converter is presented below.

Table 5: List of selected components for the DC-AC Power Electronics

S/N	Component	Selected components	Function
1	MOSFET driver	UCC21540	Interface µc to PE; isolate µc from high voltage; source current
2	MOSFET	IRF840	Inversion of DC to AC voltage based on unipolar topology.
3	LC filter	Capacitor/ indicator	Extraction of carrier signal to get the sinusoidal AC voltage

Similar steps were taken for the component selection of the other power converters. The calculation of some of the HW unit designs is presented in the calculation section.

The LC (which represents the control plant) filter values are presented in the calculation section.

4.1.3 Calculations

Some calculations are presented below:

a. AC Voltage and Current measurement. Measurement is demonstrated in the SW implementation video

$$V_{sum} = \frac{V_1 + V_2 + V_3 + \ldots\ldots\ldots + V_n}{n} \qquad (1)$$

$$V_{rms} = Form\ Factor \times {}^{V_{sum}}\!/_{n}) \qquad \text{(For the current, the same is applicable)}$$

At 5kHz sampling and 50Hz signal

n = number of samples taken = $\frac{5000}{50} = 100$, Frequency calculation = $\frac{no\ of\ samples\ in\ 50Hz}{2}$

b. Unipolar modulation calculation

i. Open Loop PWM calculation

$$d_k = \frac{\pi}{P}\ MSin(\alpha_{in})\ (0\ to\ 1) \quad (2)$$

Where K_{th} pulse

Modulation index (M), $\propto_{in}$= generatted internally/digitally

$\propto_{in}$= generatted internally/digitally; d_k = duty cycle

ii. Close Loop PWM calculation

$$d_k = \frac{(ind\_ref\ \_insta - inv\ \_inst) \times G_2 + V_{inst}}{V_{bus\ inst}} \quad (3)$$

Where ind ref instate. Inductor current Instantaneous reference inv. inst. – inductor current instantaneous

G = Compensator gain, V_{inst} = inverter output instantaneous

4.2 SW design

4.2.1 Embedded SW

The embedded SW was presented based on the layered architecture Figure 10. Based on this SW architectural view, the SW overview is presented below.

i. Application Layer: The top layer contains the codes that perform a top-layer operation, control and monitoring of the device subsystems. This includes the following code classes for inverter, battery, charger, UI, etc.

ii. Control layer: This layer handles the control loop, which runs at a fast speed to drive the MOSFETs based on the selected control method. Examples are PI control and type II compensator.

iii. Utilities: SW code that performs several functionalities and support functions to the app layer. This includes system class, I2C class, GPIO, etc.

iv. C2000 libraries: These are static libraries that support the programming of the µc peripherals.

v. HW layer: Contains a class of codes that configures the µc peripherals to operate correctly and to interface and control the HW circuit. This includes PWM, ADC, Timer, and DAC.

4.2.2 SW implementation structure

The complexity of digital PE systems dictates that the SW implementation be well-structured. This will enhance a robust SW design and simplify future updates.

4.2.3 SW design class overview

The layered view of SW design is presented in Figure 10. Each layer is further decomposed into several classes that perform a specific set of functionalities. A summary of the layers has been presented in Chapter 2.

4.2.4 System State Machine

The state machine shows the different states of how the device transitions from one state to another. The state machine is central to the embedded SW.

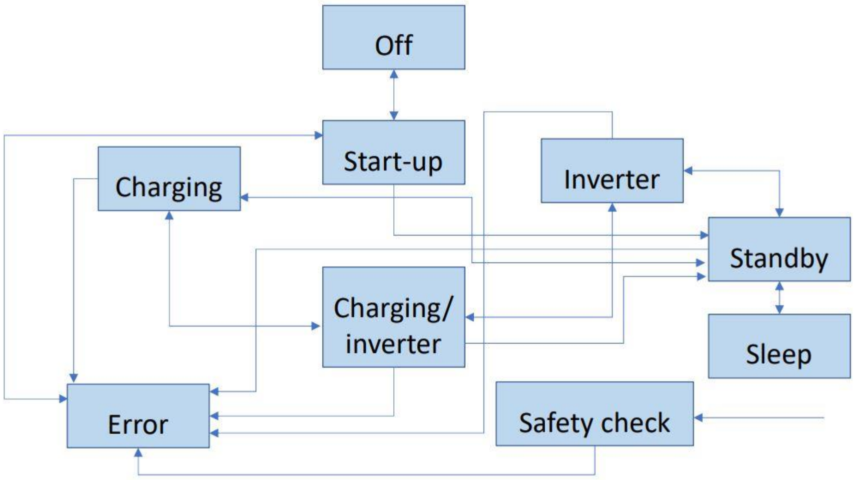

Figure 9: Diagram of the State Machine

4.2.5 SW Logical View

The SW is presented in the logical view of the SW architecture. This view decomposes the SW into units and modules subsystem with each responsible for specific functionality. This view is directly replicated in the SW and helps the SW development process and future upgrades.

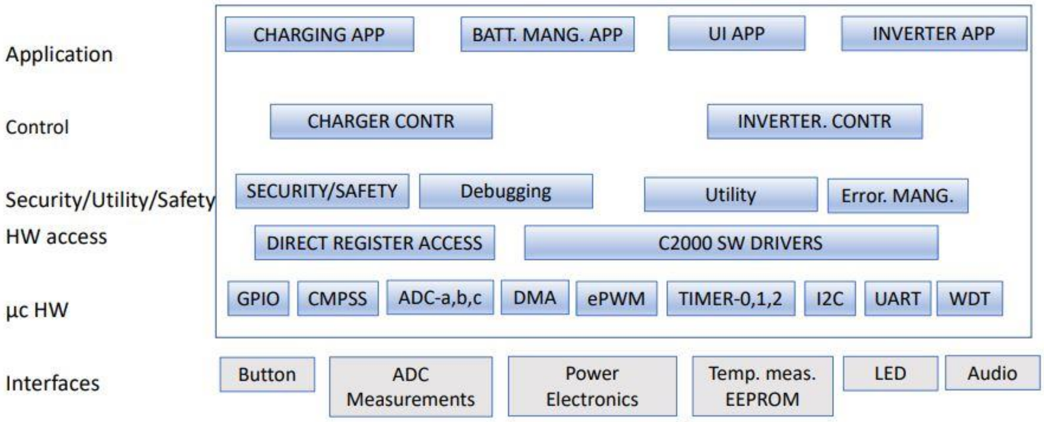

Figure 10: Diagram of the SW Logical View

4.3 Control

A brief and summarized overview of the control and some calculations is presented below:

4.3.1 Overview

Traditional control systems have always been implemented in the analogue domain (i.e. pure electronic components without microcontrollers); however, modern controls are entirely actualized in the digital domain and handled by the DSP with electronic components only for signal ADC measurement. An overview of the control system used in the project is presented below:

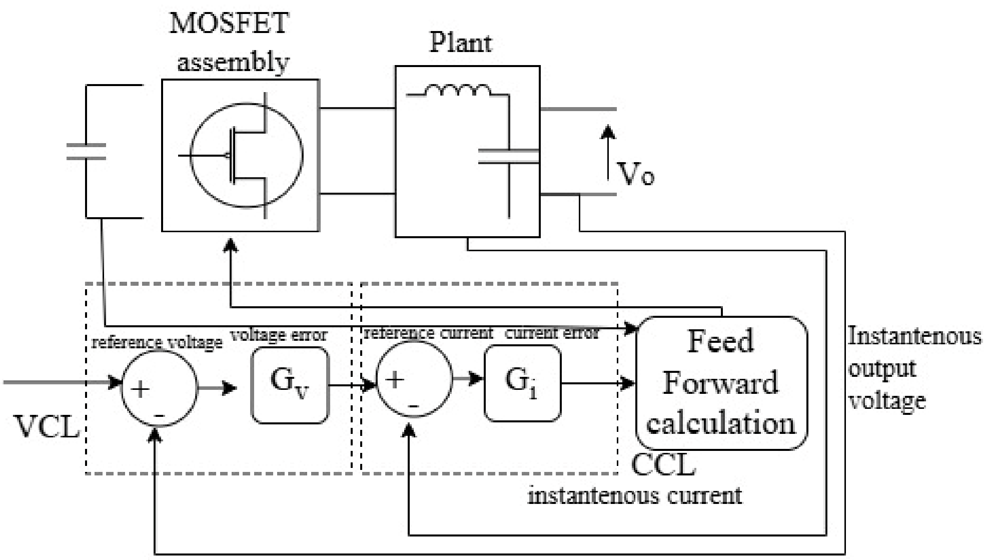

Figure 11: Overview of Implemented Control System

GV/GV are implemented in the control system, PI, PRC, and type II compensator. **Control calculation results are used as variables in control functions in the SW**. A summary of the control calculations is presented below:

4.3.2 PFC/Boost converter

The control uses a PI controller and an Average Current Mode Control (ACMC). The PI is used to reduce the steady-state error, while the ACMC is used for the PFC correction.

Calculations

VCL

$V_{CL} = (V_{ref} - V_{out})\, pi\ output$ where V_{ref} = 400V, V_{out} = generated bus voltage

Pi output has two parts. Proportional G_p and Integral G_i

$$Gp = 2.\pi.C\ BW_{loop} \times R_{main} \tag{16}$$

$$Gi = \frac{2\pi\ Gp\ Bw}{f_{vloop}}$$

The output of the V_{CL} Pi controller

$$I_{cref} = (V_{err} \times Gp) + (V_{err} \times Gi)$$

The ACMC is part of the VCL and the $Sin\ factor = \frac{V_{ac}}{\pi V_{arg}}$ of the pfc_boost

CCL

The reference for the CCL is the above control effort, combined with and below

$$I_{acref} = I_{\ cref} \times \sin factor \tag{17}$$

CCL = $\left(I_{acref} - I_o\right) Pi_{output}$

$$Gp_i = 2\ \pi L P_{BW} d_{mav}$$

$$Gp_i = \frac{2\ \pi\ GP_i I_{BW}}{F_{iloop}}$$

The control is implemented in the code with the CCL at 100KHz and VCL at 2KHz.

4.3.3 DC-AC Converter

The inverter output voltage is obtained from the DC-2-AC converter using a modified unipolar modulation topology and a PR controller. A snapshot of the test setup and some of the readings are shown in Figure 12.

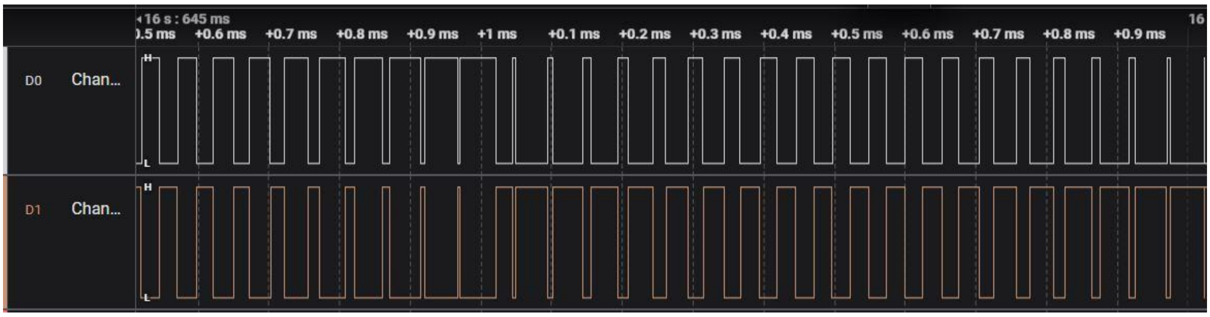

Figure 12: Unipolar modulation PWM Waveform Duty Cycle of DC – AC Converter

The control model in Figure 8 was the control reference signal for the CCL. It is the output of the VCL. This VCL consists of PR controllers to be able to zero the AC voltage tracking over, and for errors due to harmonics. Lead-lag compensator is also used to improve the system's performance.

CCL

The CCL was implemented as a discrete form in a PI controller. The equation for a discrete PI controller is represented below:

$$G_{(2)} = \frac{b_o Z^2 + b_1 Z + b_2}{Z^2 - Z}$$

(18)

Where,

$\boldsymbol{b_0} = kp^1 + Ki^1 + K_0{}^1$; $\boldsymbol{b_1} = -Kp^1 + Ki^1 - 2K_D$; $\boldsymbol{b_2} = K_D^1$;

where $\mathrm{K}_{\mathrm{p1}}^1$, $\mathrm{K}_{\mathrm{I}}^1$, $\mathrm{K}_{\mathrm{D}}^1$ are derived from the PI controller gains.

VCL

The PR controller is represented in the digital domain by the equation below:

$$G_{cR}(z) = \frac{Y(z)}{E(z)} = \frac{a(1-2^{-2})}{b_o + b_1 Z^{-1} + b_2 Z^{-2}}$$

(19)

Where, $\boldsymbol{a_1} = 4K_1T_sW_c$, $\boldsymbol{b_0} = T_1^2W_0^2 + 4T_sW_c + 4$, $\boldsymbol{b_1} = 2T_s^2W_s^2 - 8$, $\boldsymbol{b_2} = T_s^2W_0^2 - 4T_sW_c + 4$

$\mathbf{T_s} = \text{Sampling Frequency}, \mathbf{Wc} = \text{cutoff frequency}; \mathbf{W}$
$= \text{fundermental and harmonics frequencies}$

4.4 Printed Circuit Board (PCB)

A circuit diagram was drafted and PCB design for the final product and end result of the HW design.

4.5 Casing

The Mechanical engineer designed the casing for the product.

CHAPTER 5

RESULTS

IMPLEMENTATION TEST RESULTS

Several SW and HW units make up the entire device. Some of the implementations are given below:

i. Snapshot of setup as shown in Figure 13

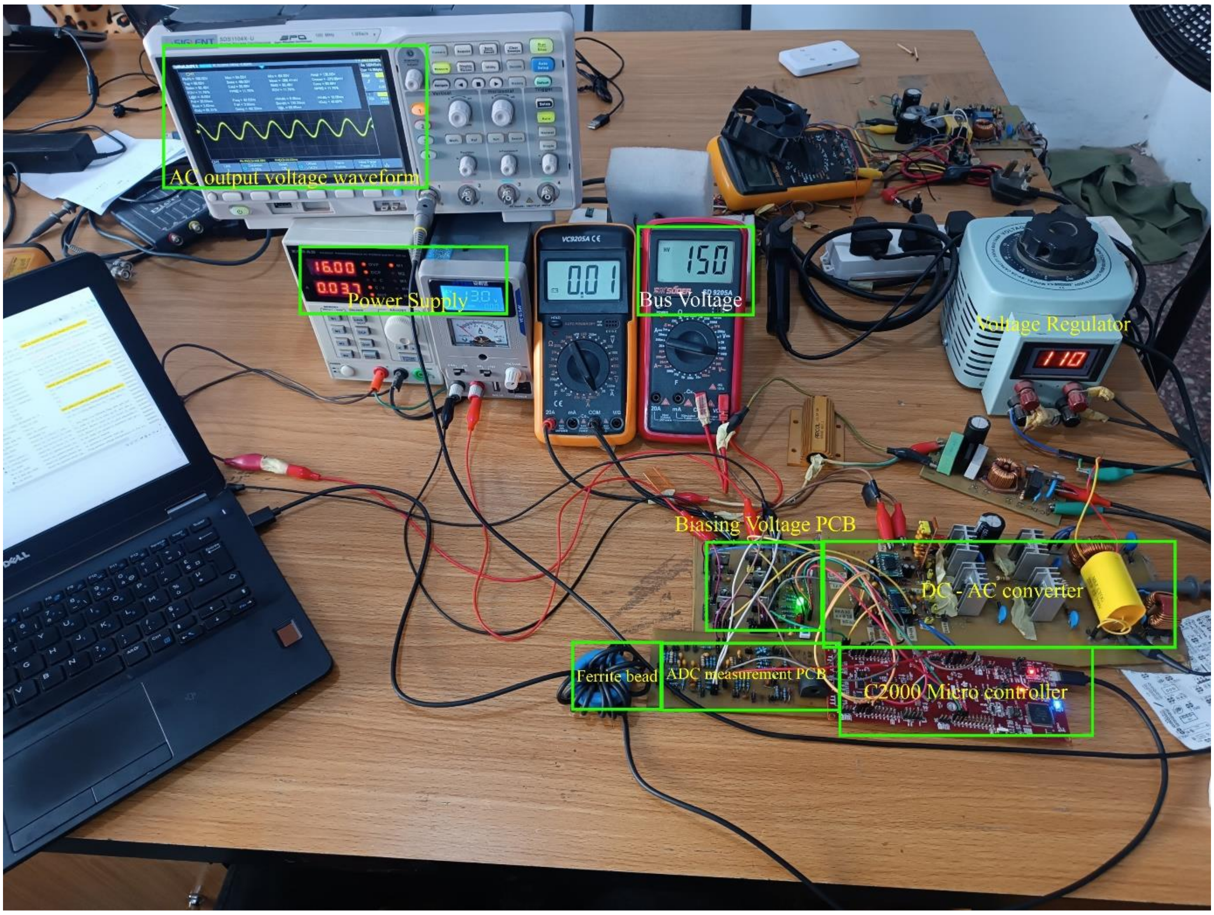

Figure 13: Snapshot of full PFC setup featuring the ADC measurement PCB, PFC, PCB and µc

ii. Several breakout boards were made to be used for test purposes before the final PCB is ready. The snapshot of one is below:

Snapshot measurement board as shown in Figures 14 and 15

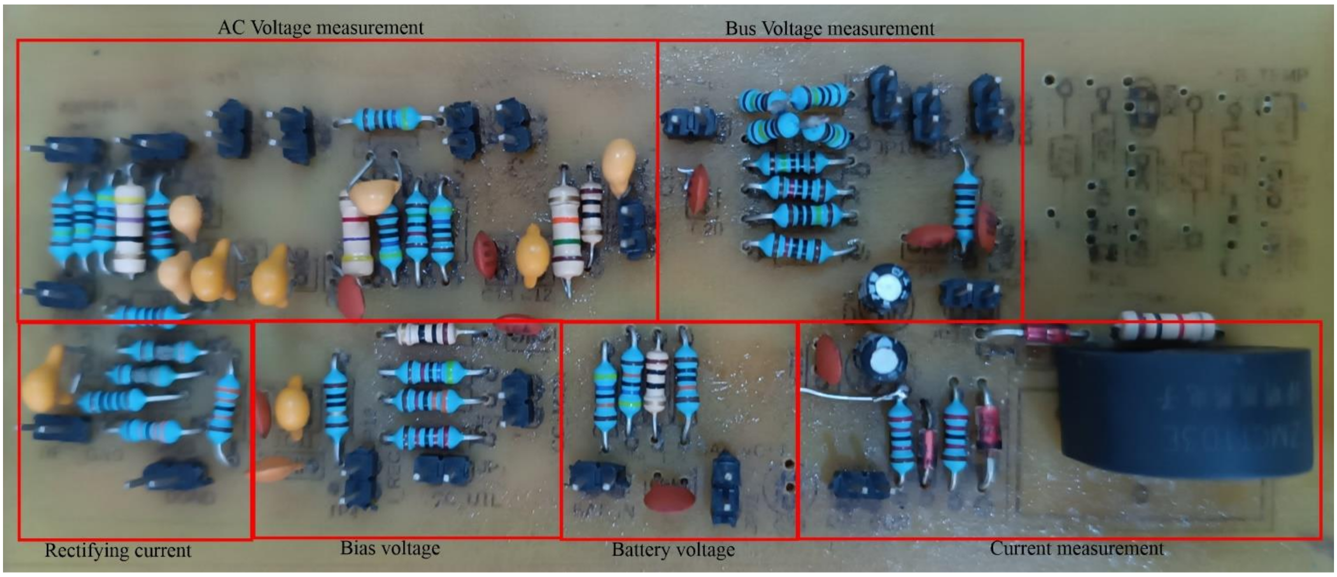

Figure 14: Snapshot of measurement board - front view

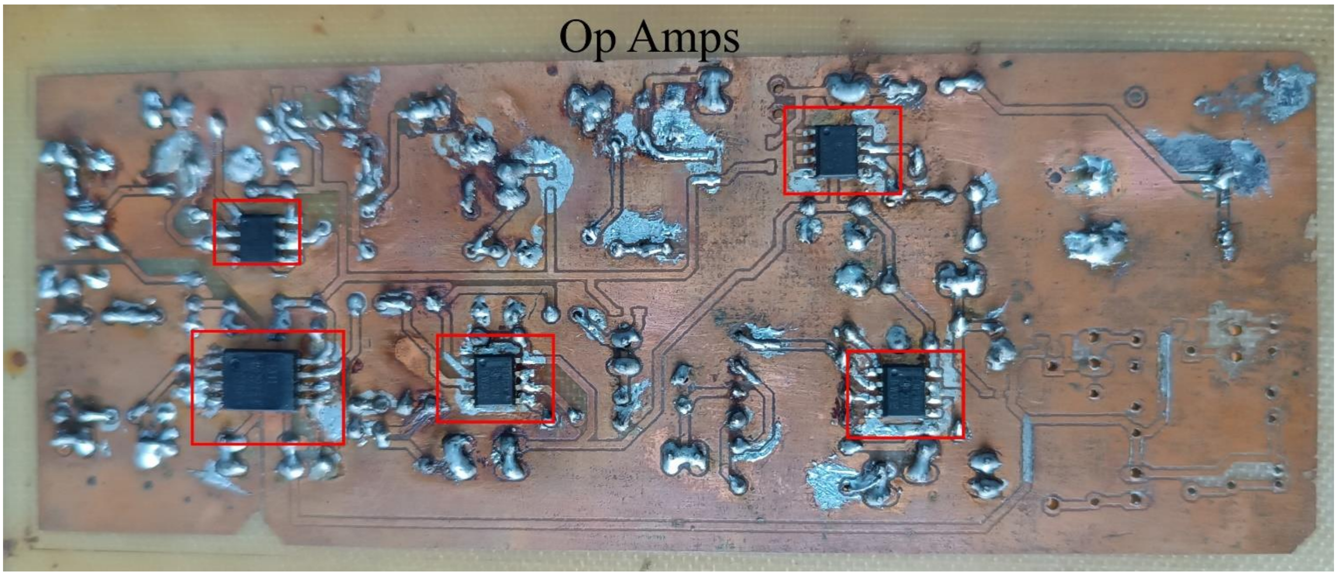

Figure 15: Snapshot of measurement board - back view

iii. Sample serial terminal output for debugging purposes to display device internal values for monitoring purposes

```
sys_s = C        bus_v = 363.27  batt_v = 24.20  uti_v = 203.16  intern_temp = 31.00     batt_c = 0.19   v_ref = 1.53    new_dc = 0.00   pfc_c = 0.000    bais_v = 10.05
batt_c_discha = 0.054   up_tim =  1312
bms_param:       bat soc = 4.82  batt_v = 24.19  batt_temp 31.00
sys_s = C        bus_v = 364.16  batt_v = 24.13  uti_v = 206.77  intern_temp = 31.00     batt_c = 0.19   v_ref = 1.53    new_dc = 0.00   pfc_c = 0.000    bais_v = 10.05
batt_c_discha = 0.000   up_tim =  1314
bms_param:       bat soc = 4.82  batt_v = 23.81  batt_temp 32.00
sys_s = C        bus_v = 360.46  batt_v = 23.79  uti_v = 197.89  intern_temp = 31.00     batt_c = 0.19   v_ref = 1.52    new_dc = 0.00   pfc_c = 0.005    bais_v = 9.93
batt_c_discha = 0.000   up_tim =  1316
bms_param:       bat soc = 4.82  batt_v = 23.73  batt_temp 31.00
sys_s = C        bus_v = 365.06  batt_v = 24.08  uti_v = 204.36  intern_temp = 32.00     batt_c = 0.21   v_ref = 1.53    new_dc = 0.00   pfc_c = 0.000    bais_v = 10.02
batt_c_discha = 0.027   up_tim =  1318
bms_param:       bat soc = 4.82  batt_v = 24.19  batt_temp 31.00
sys_s = C        bus_v = 364.16  batt_v = 24.11  uti_v = 205.35  intern_temp = 31.00     batt_c = 0.21   v_ref = 1.53    new_dc = 0.00   pfc_c = 0.000    bais_v = 10.01
batt_c_discha = 0.054   up_tim =  1320
bms_param:       bat soc = 4.82  batt_v = 23.79  batt_temp 32.00
```

Figure 16: Serial Terminal debug output

Legend
Sys_s - system state; **C –** charging; **bus_v –** bus voltage; **util_v –** utility voltage; **batt_c –** battery current; **v_ref –** voltage reference; **pfc_c –** power factor correction current; **bias_v –** bias voltage; **batt_c_discharge –** battery current discharge; **up_tim** -up time, **batt soc** – battery state of charge

iv. User Interface Design

The user interface design sub-system is a combination of HW & SW to enable the user to operate and receive feedback from the device.

The block diagram of the user interface is shown in Figure 17

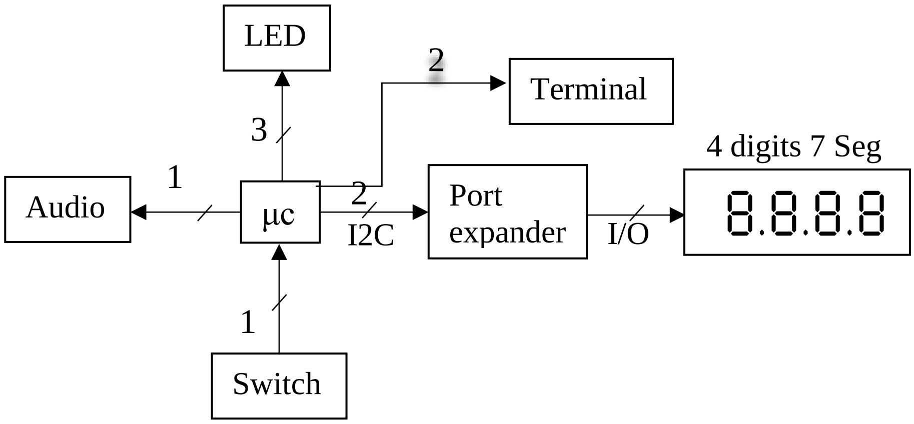

Figure 17: Diagram of the whole User's Interface