Design & Fabrication of a Digital Three-Phase Wattmeter (Custom PCB – KiCad)

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Abstract— This project presents the complete design and fabrication of a digital three-phase wattmeter capable of measuring electrical power in sinusoidal and PWM regimes. The system was architected using a modular multi-board approach (Analog, IHM, and Power Management), combining precision analog signal conditioning, ADC-based acquisition on STM32, and real-time digital processing. Particular attention was given to measurement accuracy (<0.5%), signal integrity, filtering strategy, PCB layout discipline, and system-level architecture coherence.

1 System Objective and Engineering Context

The device is a three-phase digital wattmeter designed to measure phase voltages, phase currents, and derived power quantities (active and apparent power). The typical use case is the characterization of a BLDC motor drive under both sinusoidal and PWM excitation.

The system supports:

- Line voltage amplitudes up to 30 V (21 V_{RMS})
- Phase currents up to 10 A_{RMS}
- Measurement precision better than 0.5%
- Capability to operate from either an external 9V DC supply or an internal battery source
- Dedicated analog conditioning stage delivering filtered phase voltages (VaN, VbN, VcN) and phase currents to the digital acquisition board

The device is inserted between the energy source and the load, enabling non-intrusive power monitoring and optional data logging via UART.

Beyond its initial academic scope, the developed wattmeter is currently deployed as a functional instrumentation tool in an ongoing power electronics project focused on the design and construction of an electric scooter platform.

It is used for real-time performance characterization of the motor drive system, including efficiency evaluation and dynamic power analysis under PWM control.

2 System Architecture and Functional Decomposition

The architecture was deliberately partitioned into three physically separated PCBs:

- **PCB_Analog** — Signal conditioning and reference generation
- **PCB_IHM** — Acquisition, digital processing and UI
- **PCB_Alim** — Power management and source selection

This modular approach simplifies EMC control, improves measurement stability, and allows independent validation of analog and digital domains.

This modular system partitioning is captured in the global functional architecture shown in Figure 1.

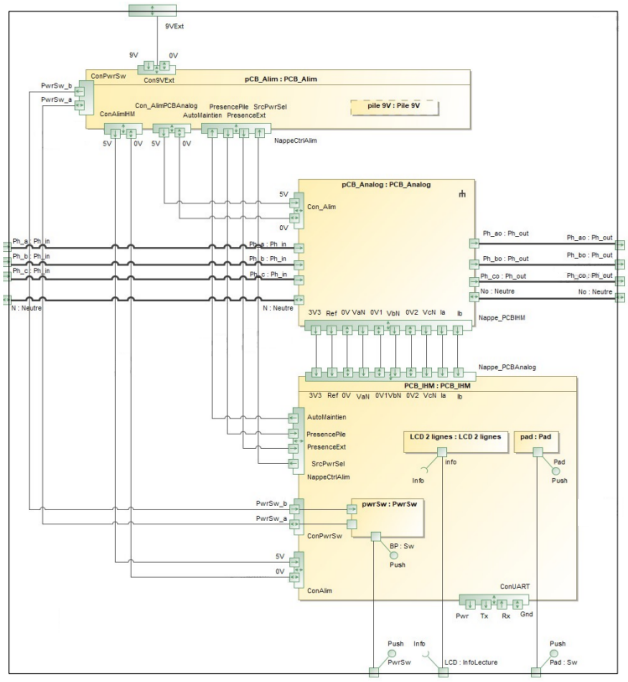

Figure 1: Global functional architecture showing PCB_Analog, PCB_IHM and PCB_Alim interconnections.

3 Analog Front-End Engineering (PCB_Analog)

The analog board is responsible for transforming raw three-phase electrical quantities into ADC-compatible signals.

3.1 Voltage Conditioning Strategy

Each phase voltage is reconstructed relative to neutral (VaN, VbN, VcN) and scaled to match the 3.3 V ADC range. A mid-supply reference (1.65 V) is generated to allow bipolar signal acquisition using a single-supply ADC.

The design rationale:

- Avoid dual supply complexity
- Maximize ADC dynamic range
- Ensure symmetric headroom for positive and negative excursions

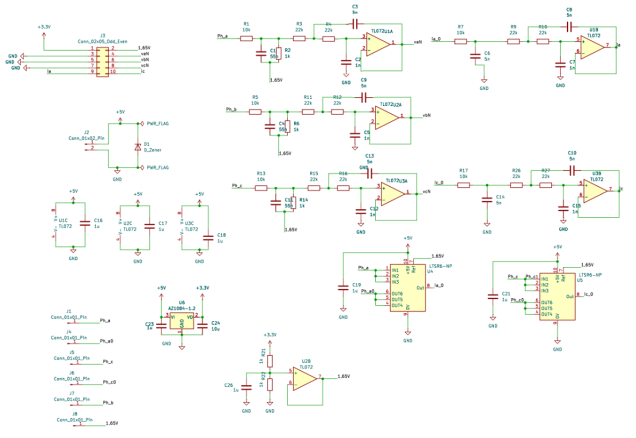

Figure 2: KiCad schematic of PCB_Analog: signal conditioning, filters, LEM current sensors and voltage reference generation.

3.2 Current Measurement Architecture

Phase currents are measured using LEM LTSR-NP Hall-effect sensors. This choice ensures:

- Galvanic isolation
- Low insertion losses
- High linearity over operating range

3.3 Analog Filtering Design

Five analog low-pass filters (3 kHz cutoff) were implemented to attenuate switching components while preserving fundamental content. The cutoff frequency was selected as a compromise between:

- PWM harmonic rejection
- Transient response
- Minimal phase distortion in the power computation band

The complete analog front-end implementation (conditioning, filtering, current sensing, and mid-supply reference generation) is summarized in the KiCad schematic shown in Figure 2.

4 Digital Acquisition and Processing (PCB_IHM)

The PCB_IHM integrates an STM32F103-based module (uC_Stamp), responsible for:

- Multi-channel ADC acquisition
- Digital filtering (15–20 kHz LPF)
- Real-time power computation
- LCD display management
- User input handling
- UART communication

4.1 Reference and ADC Strategy

All analog inputs are centered around the 1.65 V reference, ensuring coherent sampling across voltage and current channels. Care was taken to preserve reference stability and minimize ground noise coupling.

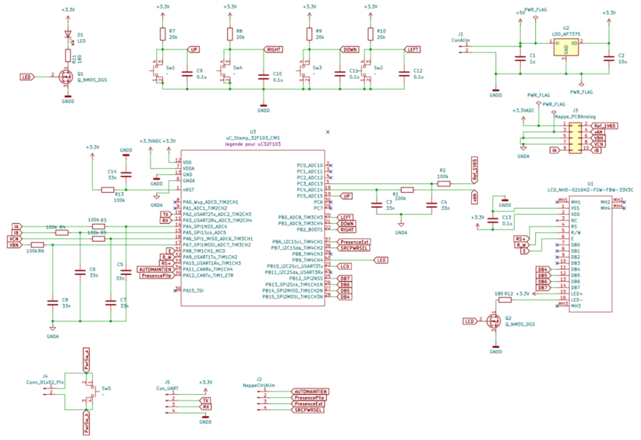

Figure 3: KiCad schematic of PCB_IHM: STM32, LCD interface, buttons and UART communication.

4.2 User Interface Engineering

The interface includes:

- 2x16 LCD display
- Four navigation push-buttons
- Power status LED
- UART connector for PC logging

The digital acquisition, processing and user-interface circuitry implemented on the PCB_IHM is shown in Figure 3.

5 PCB Layout and Signal Integrity Considerations

5.1 Analog Board Layout

The analog PCB was designed to:

- Separate high-current paths from low-level signals
- Minimize loop areas
- Maintain clean ground referencing
- Reduce coupling between channels

Special attention was given to decoupling placement near TL072 op-amps and the LEM sensors.

The resulting placement and routing choices for noise control and channel separation are illustrated in the PCB_Analog layout shown in Figure 4.

5.2 Digital Board Layout

The IHM board was optimized for usability:

- LCD centered and mechanically accessible
- Buttons aligned ergonomically
- Ribbon connectors aligned coherently
- Clean routing between STM32 and LCD

The PCB_IHM placement was optimized for usability and clean digital routing, as shown in Figure 5.

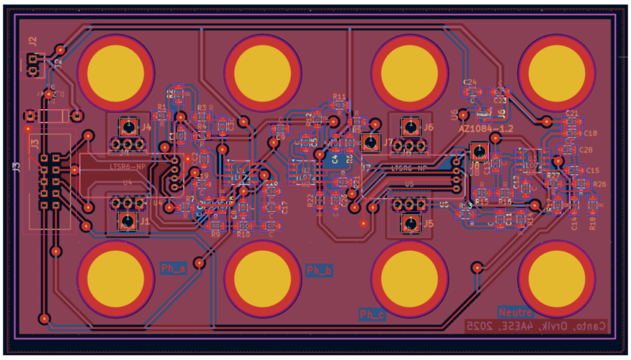

Figure 4: PCB_Analog layout: separation of measurement channels and controlled routing around current sensors.

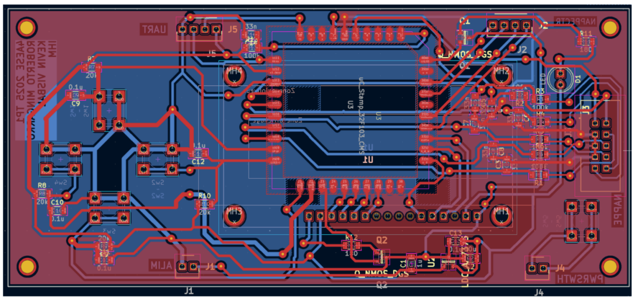

Figure 5: PCB_IHM layout: optimized user access and structured digital routing.

6 In-House PCB Fabrication (LPKF ProtoMat Process)

Unlike outsourced PCB manufacturing, this project was fabricated entirely in-house using an **LPKF ProtoMat S104 PCB milling machine**. This allowed full control over iteration cycles, rapid prototyping, and immediate electrical validation after layout export.

6.1 Manufacturing Workflow

The fabrication process followed these steps:

- DRC verification and final design rule validation in KiCad
- Export of Gerber files (F.Cu, B.Cu, Edge.Cuts) using extended Gerber X2 format
- Generation of drill files in Gerber X2 format with absolute coordinate reference
- Toolpath generation and isolation strategy configuration
- Copper milling (trace isolation)
- Board contour routing
- Manual drilling where required
- Cleaning, debris removal and inspection under magnification

This manufacturing stage was performed using an in-house LPKF ProtoMat milling system, shown in Figure 6.

During milling, trace isolation quality and minimum track spacing were carefully monitored.

The isolation milling phase, where copper is selectively removed to define traces and pads, is illustrated in Figure 7.

Figure 6: LPKF ProtoMat S104 used for in-house PCB milling and rapid prototyping.

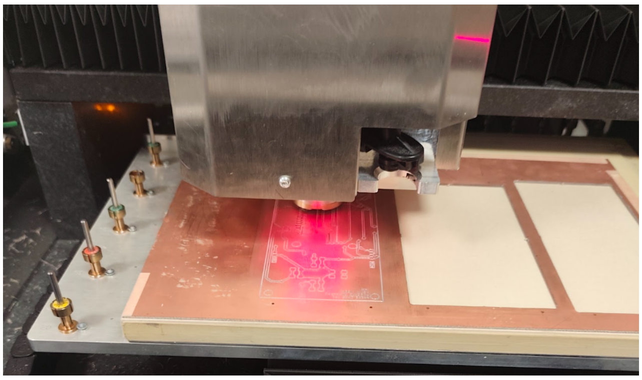

Figure 7: Isolation milling process: copper removal defining traces and pads.

6.2 Manufactured PCB Results

After milling and contour cutting, the raw copper boards were inspected for:

- Trace continuity
- Absence of copper bridges
- Pad integrity
- Mechanical alignment
- Minimum isolation clearance compliance
- Burr formation and edge quality after milling
- Reference plane continuity in critical analog zones

The resulting and final milled boards (prior to component assembly) are shown in Figure 8.

This in-house fabrication approach significantly reduced iteration time and allowed immediate correction of layout-level issues without the delay of external PCB manufacturing.

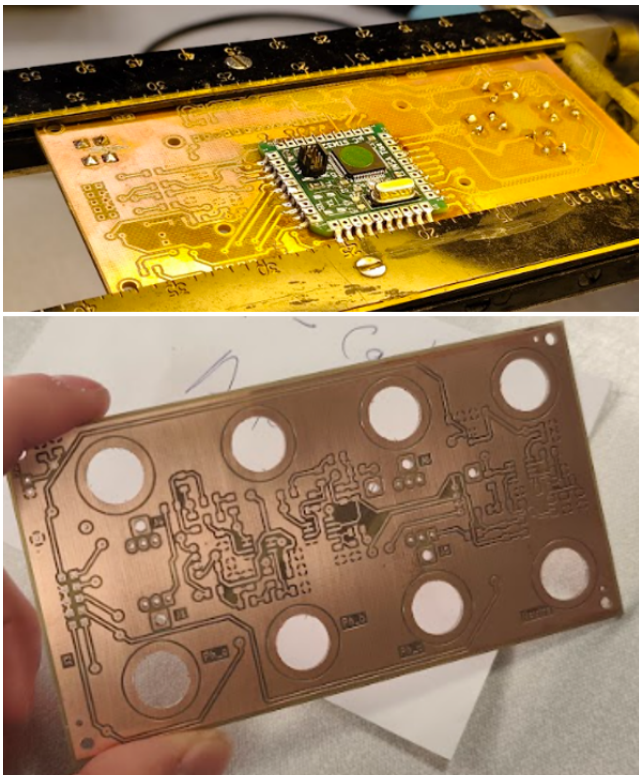

Figure 8: Fabricated PCB boards after in-house LPKF ProtoMat milling. Top: PCB_IHM (digital board) with STM32 module positioned prior to final assembly. Bottom: PCB_Analog (analog signal-conditioning board) immediately after isolation milling and contour routing.

7 Assembly, Soldering and Laboratory Testing

7.1 Component Assembly Strategy

Assembly was performed manually using precision soldering stations. Special attention was given to:

- Thermal control during SOIC soldering (TL072)
- LEM sensor mechanical stability
- STM32 module alignment
- Decoupling capacitor proximity to supply pins

The manual assembly and soldering phase under laboratory conditions is shown in Figure 9.

7.2 Electrical Bring-Up and Validation

Following assembly, a structured bring-up procedure was applied:

- Verification of 5V and 3.3V rails
- Validation of 1.65V analog reference
- Continuity checks across analog channels
- ADC sampling verification
- LCD initialization confirmation

The structured bring-up and validation procedure applied after assembly is illustrated in Figure 10.

This controlled validation sequence ensured that any anomaly could be isolated to layout, soldering, or design-level causes.

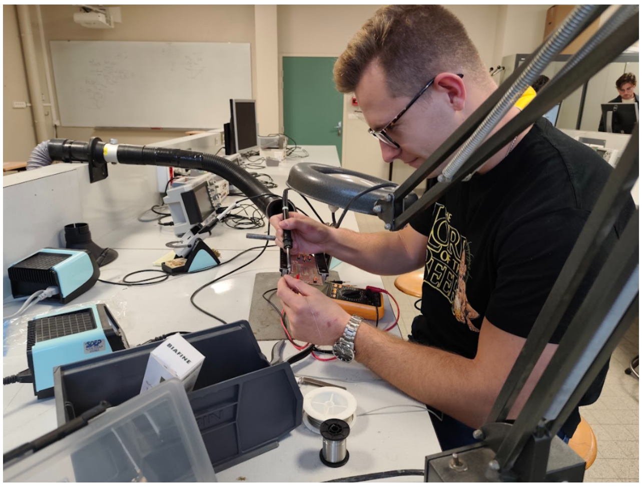

Figure 9: Manual soldering and assembly under laboratory conditions.

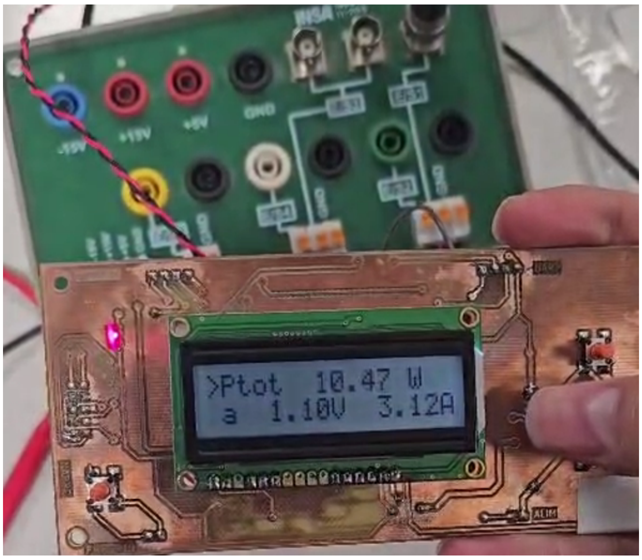

Figure 10: Board bring-up and electrical validation during laboratory testing.

8 Engineering Value of the Manufacturing Phase

Manufacturing the PCB internally provided critical engineering insights:

- Real-world manufacturability constraints
- Minimum trace width and isolation spacing limitations
- Tool wear effects and milling tolerance impact
- Mechanical rigidity and board flatness considerations
- Ground strategy implications in single-layer isolation routing
- Drill positioning accuracy and annular ring integrity

More importantly, the fabrication stage closed the loop between CAD design and physical hardware realization—a step often abstracted away in purely academic projects. The full cycle-schematic, layout, fabrication, assembly, validation-reinforced system-level engineering discipline rather than isolated circuit design.