3- PHASE POWER METERING AND MONITORING SYSTEM DEVELOPMENT.

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Date: February 2025
Version: 1.0

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ABSTRACT

Accurate monitoring of three-phase electrical systems is essential for energy efficiency, operational reliability, and early fault detection in modern power networks. Conventional metering solutions, however, often suffer from high costs, limited scalability, and lack of adaptability for industrial or smart grid environments.

This work presents a compact, real-time monitoring approach that leverages the processing capability of the STM32F411CEU6 microcontroller in combination with low-cost voltage and current sensors. The system continuously acquires measurements from all three phases, computes corresponding power values, and provides instant feedback through an integrated OLED display. Relay-based protection is incorporated to safeguard connected loads by isolating faulty circuits when abnormal conditions are detected.

To validate flexibility in both industrial deployment and academic prototyping, the firmware is implemented in two paths: C (STM32 HAL) for optimized low-level control and C++ (Arduino IDE) for rapid development. The resulting system demonstrates a practical and scalable solution for three-phase power monitoring, with direct applications in energy management, automation, and smart grid integration.

CHAPTER 1: INTRODUCTION

1.1 Background information

Accurate metering and monitoring of three-phase power systems are essential for both industrial and smart grid applications, where real-time data and efficient control strategies are critical for maintaining operational stability and energy efficiency [1]. Traditional electromechanical meters have been widely replaced by embedded electronic systems, which provide higher precision, real-time visualization, and integration with communication networks.

Embedded platforms such as the STM32F4 microcontroller family are increasingly favored for these applications due to their high-speed ADCs, 32-bit processing capability, and versatile communication interfaces (UART, SPI, I²C, CAN) [2]. These features enable precise sampling of voltage and current waveforms, power factor measurement, and effective implementation of monitoring algorithms.

Modern three-phase monitoring systems also incorporate compact OLED displays for user-friendly real-time data visualization and multiple output connectors for flexible power distribution management [3]. Such designs support advanced energy management strategies by continuously monitoring and reporting key parameters including phase voltages, load currents, and active/reactive power. [4].

1.2 Problem Statement

Despite significant advancements in industrial automation, many existing three-phase systems rely on legacy metering equipment that lacks real-time monitoring and control capabilities. These limitations often result in delayed detection of abnormal conditions such as overloads, unbalanced phases, or inefficiencies, leading to potential equipment damage, energy waste, and higher operational costs.

Furthermore, conventional monitoring setups do not provide user-friendly interfaces for on-site operators, nor do they support modular connectivity for multiple outputs. This creates a gap between the growing demand for intelligent energy management systems and the capabilities of currently deployed solutions.

1.3 Problem Justification

The increasing adoption of smart grid technologies and Industry 4.0 automation necessitates advanced monitoring systems that can operate with high accuracy, reliability, and user accessibility. A microcontroller-based approach offers a compact, low-cost, and scalable solution that can be customized for different industrial environments.

The STM32F411CEU6 microcontroller, with its powerful Cortex-M4 core and rich peripheral set, provides an excellent platform for implementing real-time three-phase metering and monitoring. By integrating an OLED display for on-site feedback and supporting multiple connectors for flexible power distribution, the proposed system addresses both technical requirements (precision, speed, reliability) and practical needs (usability, modularity).

This project is therefore justified as it combines academic rigor with direct industrial applicability, offering a design that improves fault detection, energy efficiency, and operator interaction in modern power systems.

1.4 Objectives

The objectives of this project are:

1 To develop a microcontroller-based system for metering, monitoring, and controlling three-phase power outputs.

2 To display real-time power status (voltage, current, power) on a local OLED screen.

3 To support multiple connectors for modular and flexible power output management.

4 To implement the system using a 32-bit STM32F411CEU6 microcontroller, with firmware developed in C/C++ for efficiency and portability.

CHAPTER 2: LITERATURE REVIEW

2.1 Existing technologies

Accurate three-phase power metering systems are fundamental in both industrial and smart grid infrastructures. Conventional digital energy meters typically employ dedicated metering ICs such as the ADE7758 or ATM90E36, which are designed to capture voltage and current waveforms and compute power parameters. While highly accurate, such IC-based systems often lack flexibility for expansion and require additional microcontrollers for advanced functionality like display integration or relay control.

In recent years, microcontroller-based solutions have become popular due to their scalability and programmability. Platforms such as STM32 and ESP32 are widely adopted because of their powerful ADCs, high clock frequencies, and versatile communication interfaces. These systems allow real-time data acquisition, processing, and user interaction via displays or wireless modules, enabling flexible customization for different industrial environments.

The use of microcontroller-based systems with OLED displays and relays provides a cost-effective, adaptable alternative to rigid IC-only solutions. This project builds on those advancements by integrating voltage and current sensors with an STM32F411CEU6 microcontroller, combining metering, monitoring, and relay-based control into one system.

2.2 Components

1. **Microcontroller:** STM32F411CEU6 (Black Pill board)
2. **Display:** OLED display (SSD1306, 128×64, I2C interface)
3. **Voltage Sensors:** ZMPT101B voltage sensor modules (3 units, one for each phase)
4. **Current Sensors:** Three ACS712 modules (3 units) for phases A, B, and C
5. **Relays:** 3-channel relay module (5V control, 250V AC rated)
6. **3-Phase AC Power Source:** 400V RMS (Nominal), connected through terminal blocks for safe testing and operation.

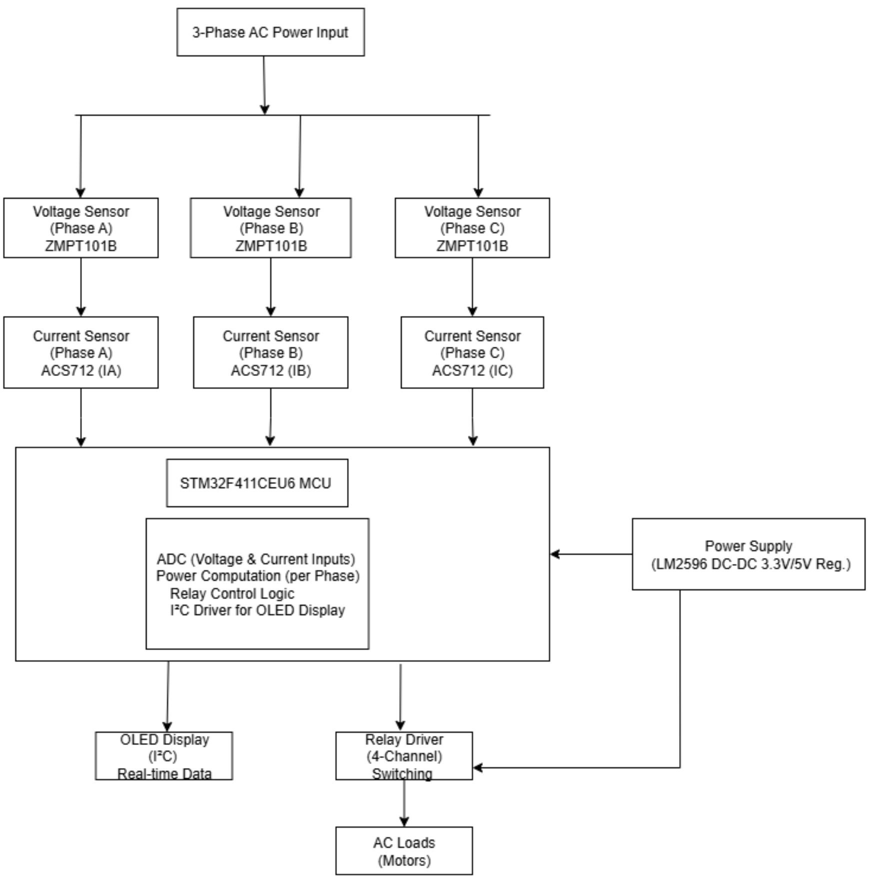
7. **Resistors:** 220Ω resistors for current-limiting in relay control lines
8. **Capacitors:**0.1 µF ceramic capacitor for high-frequency noise filtering near the microcontroller's power pins
9. **Push Buttons:** For system reset and manual control.
10. **Power Supplies:**
    - 12V DC power supply for the relay module
    - Regulated 5 V supply (or 3.3 V as required by the STM32 and OLED) for sensors and microcontroller
11. **Terminal Blocks:** For secure connection to the three-phase power source.

2.3 System overview

The system continuously measures three-phase voltage and current using ZMPT101B and ACS712 modules, digitizes the signals via STM32 ADCs, and calculates instantaneous power for each phase. Results are displayed on a 128×64 OLED over I²C, while relays provide power output control based on thresholds. This design ensures real-time monitoring, user accessibility, and safety, meeting industrial and smart grid monitoring needs.

CHAPTER 3 METHODOLOGY

3.1 Block Diagram

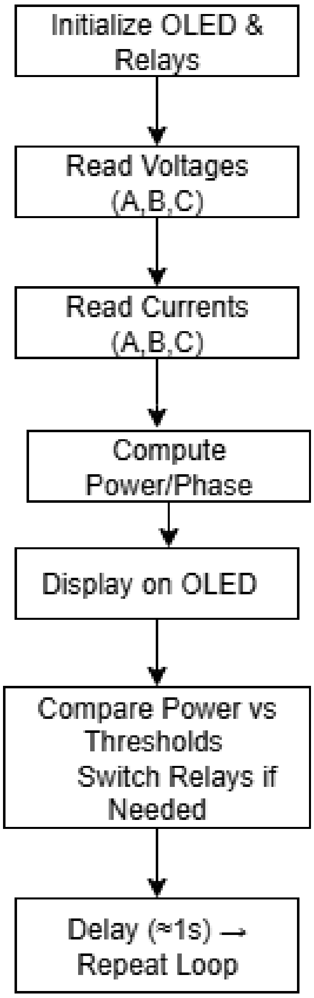


The system comprises a three-phase AC input connected to both voltage sensors (ZMPT101B) and current sensors (ACS712) for each phase (A, B, C). The sensors condition the signals and feed them into the STM32F411CEU6 microcontroller (MCU) through its ADC channels. The

MCU performs signal scaling, calibration, and per-phase power computation. Processed results are sent to an OLED display (128×64, I²C) for real-time monitoring. At the same time, the MCU applies relay control logic to switch loads ON/OFF based on defined protection thresholds. Power for the system is supplied via an LM2596 DC–DC regulator providing stable 5 V and 3.3 V rails. This modular structure ensures measurement, processing, display, and protection functions operate in a closed loop.

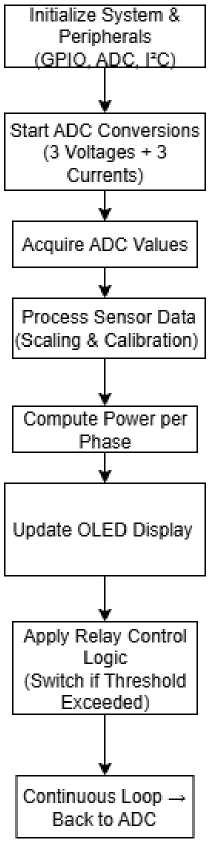
3.2 Software Flowcharts

3.2.1 Code1- C++ (Arduino IDE) Flowchart



The Arduino-based firmware initializes OLED and relay modules, followed by acquisition of phase voltages and currents through analog inputs. The software computes real power per phase and displays the results on the OLED screen. Based on defined thresholds, the MCU decides whether to activate or deactivate relays connected to the loads. The system then waits for 1 second before repeating the measurement–processing–control cycle. This loop provides a simplified but functional monitoring system suitable for prototyping and validation.

3.2.2 Code 2- C HAL Drivers Flowchart



The C-based firmware (STM32CubeIDE) begins with system initialization, configuring GPIOs, ADCs, and I²C peripherals. The program then starts ADC conversions across six channels (3 voltages + 3 currents). Acquired raw data is scaled and calibrated before being used to compute phase voltages, currents, and power values. These values are updated to the OLED display via I²C. The MCU then evaluates relay control thresholds and actuates relays accordingly for load protection. The process runs in a continuous loop, ensuring real-time measurement and control.

3.3 Code structure and Logic

Arduino IDE (C++):

- Uses analogRead() for sensor input.
- Adafruit SSD1306 library for display.
- Simple relay logic based on power threshold.

STM32CubeIDE (C):

- HAL drivers handle ADC and I²C.
- Raw ADC values processed with calibration constants.

- OLED updated with formatted strings for each phase.
- Relays controlled via GPIO outputs.

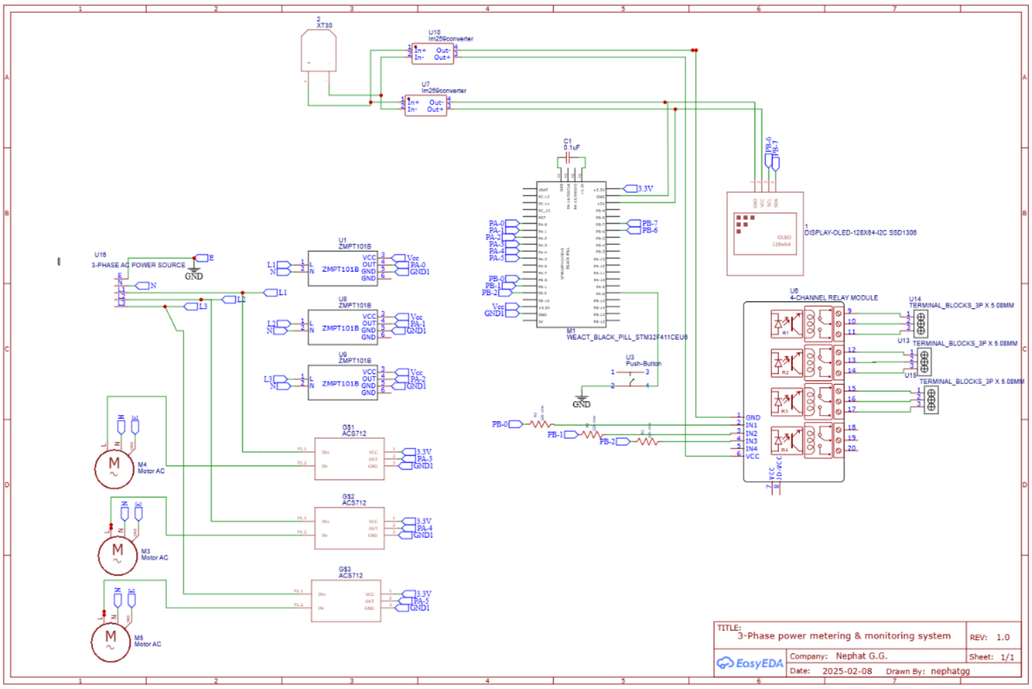
Both implementations follow the same principle: measure → compute → display → control. The STM32 version is lower-level (HAL-driven), while Arduino provides easier coding with high-level libraries.

3.4 Circuit Design

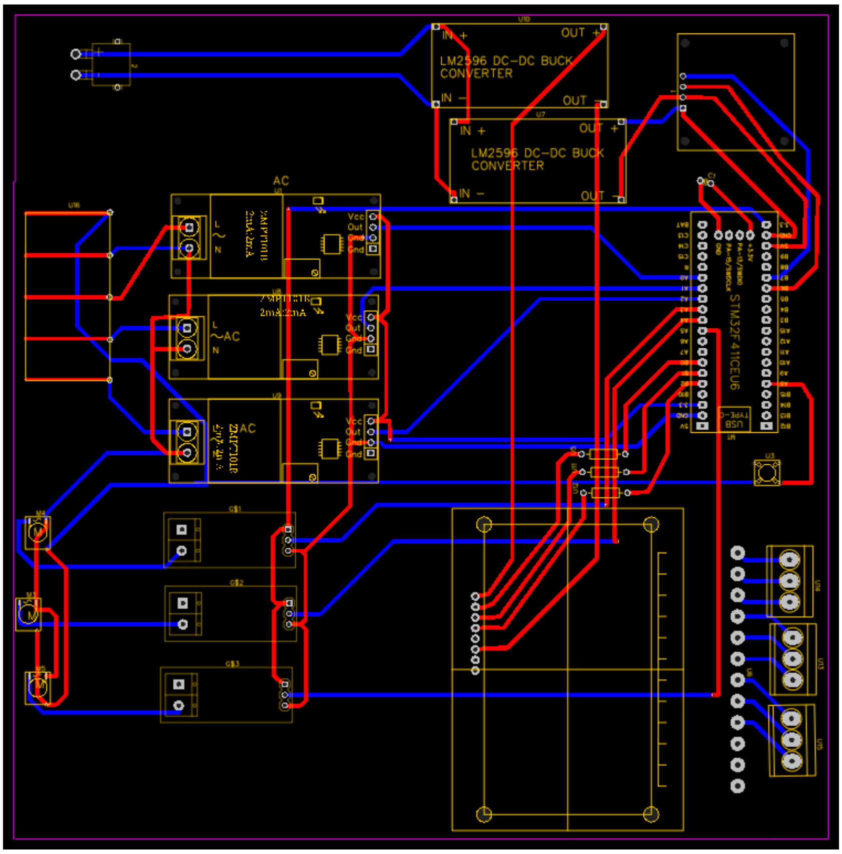
1. **Microcontroller Setup:**
    - Configure the STM32F411CEU6 using STM32CubeMX to initialize GPIO, ADC, and I2C peripherals.
    - Set up I2C for OLED communication and ADC channels for reading voltage and current sensor outputs.
2. **Voltage and Current Measurement:**
    - Connect the ZMPT101B voltage sensors to each phase (Phase A to PA0, Phase B to PA1, Phase C to PA2) with their analog outputs connected to the ADC pins of the microcontroller.
    - Connect the ACS712 current sensors analog outputs to PA3, PA4, and PA5 respectively.
3. **Relay Control:**
    - Connect relay control inputs to digital pins PB0, PB1, and PB2 of the STM32.
    - Use 220Ω resistors in series for current limiting.
4. **Display Integration:**
    - Interface the OLED display with the STM32 via I2C (SCL to PB6, SDA to PB7) to show real-time voltage, current, and power values.
5. **Multiple Power Connectors:**
    - Provide terminal blocks connected to each relay output to support multiple loads.
6. **Power Supply:**
    - Provide a common ground between the microcontroller and sensor modules.
    - Use 0.1µF capacitors across power lines for stability.
7. **3-Phase AC Power Source:**
    - Connect each phase line to its respective voltage and current sensor module.
    - Ensure proper grounding and use protective enclosures to prevent accidental contact with high-voltage lines.
8. **Firmware Development:**
    - Develop code to read ADC values, calculate power parameters, and display them on the screen.
    - Implement relay control logic for load management.

3.5 DIAGRAMS

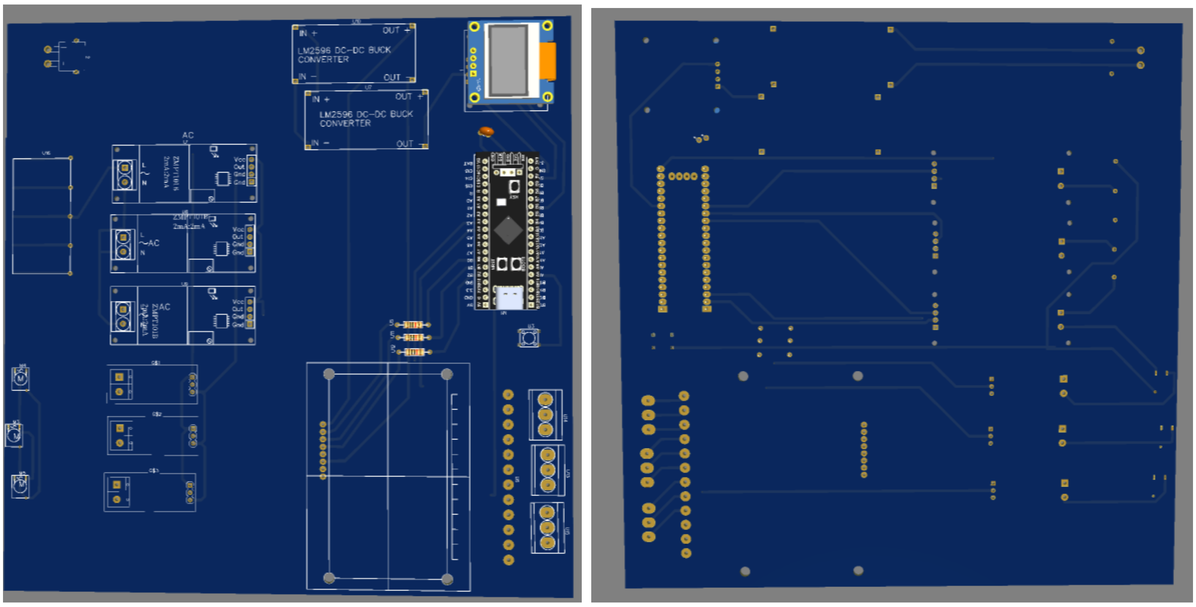
3.5.1 Schematic



3.5.2 PCB Layout



3.5.3 3D view



3.6 CODE

GitHub Link:
https://github.com/NGGithua1/3-Phase_Power_Metering_and_monitoring_sys.git

CHAPTER 4: RESULTS AND DISCUSSION

The developed system successfully measures and displays real-time power parameters (voltage, current, and power) for all three phases. In the firmware implementations:

- Sensor Readings: The ADC channels capture scaled-down voltage and current signals. The calibration factors in software convert these raw values into real-world units.
- Display Functionality: The OLED display (via I2C) continuously shows updated power status for each phase, allowing for real-time monitoring.
- Power Output Control: The relay outputs are controlled based on the computed power, providing a method to disconnect power outputs when the measured power exceeds predefined thresholds.

The STM32CubeIDE version leverages the HAL libraries for precise ADC and I2C handling, whereas the Arduino version benefits from simplified coding and readily available display libraries. Both implementations meet the system objectives and allow for further expansion, such as integrating network connectivity for remote monitoring.

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The 3-phase power metering and monitoring system has been successfully designed and implemented using an STM32F411CEU6 microcontroller. The system accurately reads and computes power parameters for all phases, displays the results in real-time on an OLED screen, and controls power outputs via relays.

Overall, this system provides a robust foundation for advanced power monitoring applications in industrial and smart grid environments.

5.2 Recommendations

Future work could include:

- **Enhanced Calibration:** Improving sensor calibration for more accurate measurements.
- **Network Integration:** Adding Wi-Fi/Ethernet modules for remote monitoring and control.
- **Advanced Protection:** Incorporating overvoltage/overcurrent protection mechanisms for further reliability.
- **Data Logging:** Store historical data in SD card or cloud for trend analysis.

REFERENCES

[1] L. e. a. Zhang, "Smart Grid Monitoring with Embedded Systems.," *IEEE Transactions on Smart Grid.,* 2020.

[2] T. e. a. Lee, "Embedded Solutions for Power Metering.," *IEEE Industrial Electronics Magazine.,* 2019.

[3] M. &. P. R. Garcia, "Advances in Real-Time Power Monitoring Systems.," *IEEE Power Electronics Letters.,* 2021.

[4] S. e. a. Miller, "Fault Detection and Energy Management in 3-Phase Systems.," *IEEE Transactions on Power Delivery.,* 2020.

[5] T. e. a. Lee, "PWM Techniques for DC Motor Efficiency Optimization.," *IEEE Engineering Journal.,* 2019.