Grid Frequency and ROCOF Monitoring System

Implementation using TM4C123GH6PM Microcontroller

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Presentation Outline

Motivation: Grid Stability

Why Monitor Frequency?

- **Nominal Frequency:** 50 Hz (India).
- Deviation indicates mismatch between Power Generation (P_G) and Load (P_L).
- $P_G < P_L \rightarrow$ Frequency Drops.
- $P_G > P_L \rightarrow$ Frequency Rises.

What is ROCOF?

Rate **of** **C**hange **of** **F**requency:

$$\text{ROCOF} = \frac{df}{dt} \quad [Hz/s]$$

High ROCOF is a primary signature of **Islanding** events in renewable grids.

Problem Statement

Grid Instability

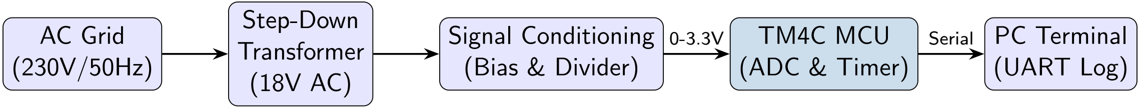
- **Frequency Deviation:** AC Grids must maintain a strict 50 Hz. Deviations indicate a mismatch between generation and load, leading to potential blackouts or equipment damage.
- **Islanding Phenomenon:** In distributed generation (e.g., solar/wind), a generator may accidentally stay connected when the main grid fails. This poses severe safety risks to line workers.

The Measurement Gap

Detecting these events requires monitoring the **Rate of Change of Frequency (ROCOF)**.

- Standard frequency meters are too slow (averaging over seconds).
- Industrial protection relays are expensive and complex.
- **Goal:** Design a low-cost, real-time ROCOF monitor using a standard microcontroller (Tiva C).

System Architecture



- **Isolation:** Transformer provides galvanic isolation.
- **Conditioning:** Attenuation and DC Offset shifting ($0 \rightarrow 3.3V$).
- **Algorithm:** Software-based Zero Crossing Detection (ZCD).

System Specifications

Hardware Parameters

- **Microcontroller:** TM4C123GH6PM (ARM Cortex-M4F)
- **System Clock:** 16 MHz
- **ADC Configuration:**
  - Pin: PE3 (AIN0)
  - Resolution: 12-bit (0 - 4095)
- **Signal Conditioning:**
  - Input: 18V AC (Transformer)
  - Attenuation: 100:1 (Approx)
  - DC Bias: 1.65V ($V_{CC}/2$)
  - Signal Swing: Unipolar (0V - 3.3V)

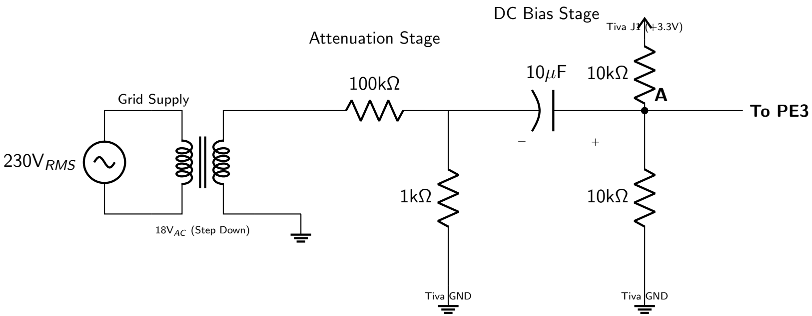
Software & Protection

- **Algorithm:** Zero-Crossing Detection (ZCD) with Hysteresis
- **Hysteresis Band:** $\pm$80 ADC units (approx $\pm$60 mV)
- **Update Interval:** 1000 ms (1 Hz Refresh)
- **Digital Filtering:**
  - Frequency: Moving Avg (Size 5)
  - ROCOF: Moving Avg (Size 10)
- **Protection Thresholds:**
  - Normal Freq: 49.5 – 50.5 Hz
  - Critical ROCOF: $> \pm 1.0$ Hz/s

Design Constraints

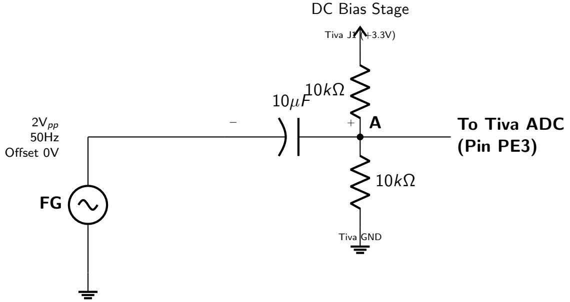
- **ADC Input Limitations**
  - Tiva ADC cannot accept negative voltages.
  - Maximum allowable input is **0–3.3V**, requiring proper signal conditioning.
- **Signal Conditioning Requirements**
  - Transformer secondary produces AC with noise and ripple.
  - AC coupling and DC biasing needed to center waveform safely at 1.65V.
  - Must preserve waveform shape for accurate zero-crossing detection.
- **Timing Accuracy Constraints**
  - Frequency is derived from timer-based period measurement.
  - Timer jitter or noise directly affects frequency and ROCOF accuracy.

Hardware Design with Step Down Transformer



Design Logic:

- **Step-Down Transformer:** Reduces 230V AC mains to 18V AC.
- **Attenuation:** The $100k\Omega/1k\Omega$ divider creates a ratio of $\approx 1:100$.
- **Signal Levels:** 18V input becomes $\approx$ **0.5 V**$_{pp}$ at the ADC.
- **DC Bias:** Sourced from **Tiva J1**, centering the signal at 1.65V.

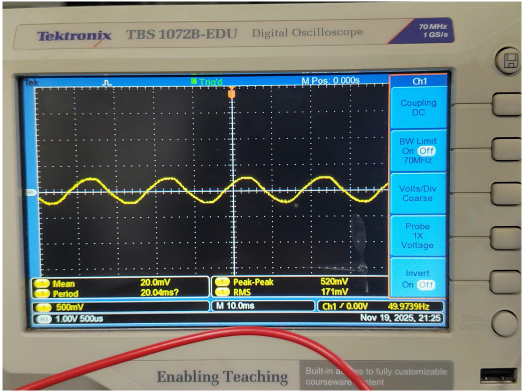


Design Logic:

- **Input Source:** Function Generator set to **50Hz, 2V$_{pp}$, 0V Offset**.
- **Coupling:** Signal is injected at the **negative terminal** of the $10\mu F$ capacitor to block DC.
- **DC Bias: Junction A** is shifted to 1.65V by the divider (sourced from Tiva J1), allowing the unipolar ADC to read the full AC swing.
- **ADC Input:** The conditioned signal is read by Pin **PE3**.

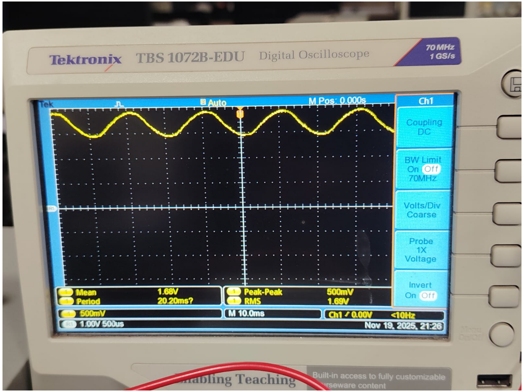
Signal Conditioning Output for Step Down Transformer

Raw AC Input



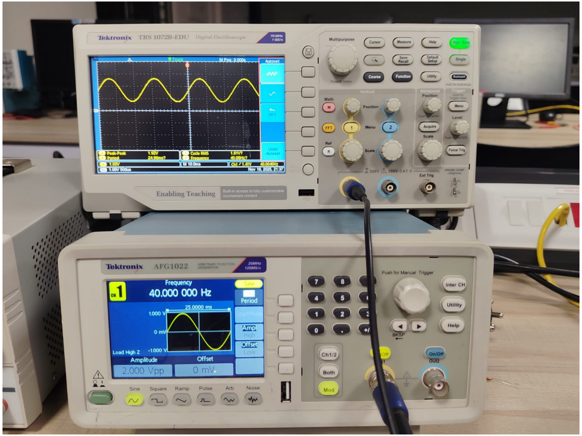
Transformer Output (Bipolar)

Conditioned Signal

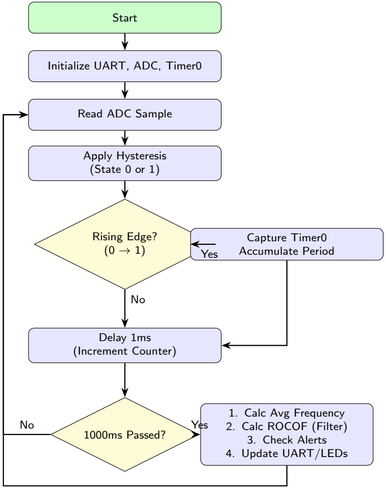


Biased at 1.65V (Unipolar)

Oscilloscope Capture: Bias-Shifted Waveform



Software Flowchart



Software Step 1: Zero-Crossing & Period

Objective: Measure the exact time between AC cycles without hardware interrupts (to minimize jitter).

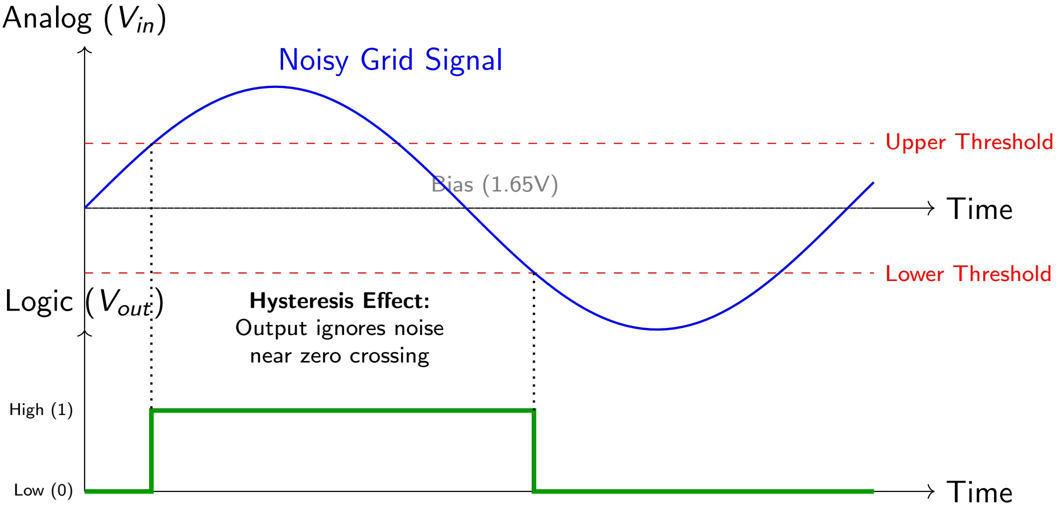
```
// 1. Polling with Hysteresis (Schmitt Trigger)
// Voltage > (2048 + 80) -> High | Voltage < (2048 - 80) -> Low
int state = (v > MID + HYS) ? 1 :
            (v < MID - HYS) ? 0 : lastState;

// 2. Rising Edge Detection (0 -> 1)
if(lastState == 0 && state == 1){
    uint32_t t = TIMER0_TAR_R; // Capture Timer Value

    // 3. Calculate Delta Time (Handling Counter Wrap)
    uint32_t dt = (prev_tick >= t) ? (prev_tick - t) :
                  (prev_tick + (0xFFFFFFFF - t));

    // 4. Calculate Instantaneous Frequency
    float f = (float)SYSCLK / dt;
}
```

Timing Diagram: ZCD with Hysteresis



Software Step 2: Digital Filtering

Raw derivatives are noisy. We implemented **Circular Buffers** to smooth the data.

```
// ROCOF Calculation (1 sec interval)
float rocof_raw = (F - last_freq) / 1.0f;

// Circular Buffer Logic (Moving Average)
rocof_sum -= rocof_buf[idx];      // Subtract old
rocof_buf[idx] = rocof_raw;       // Add new
rocof_sum += rocof_raw;           // Update sum

// Compute Average
filtered_rocof = rocof_sum / 10;
```

Filter Specifications:

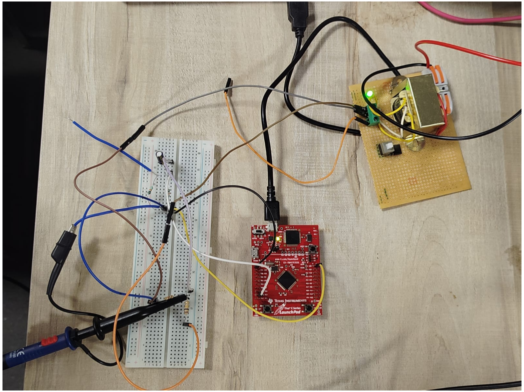
- **Frequency:** 5-sample Moving Average.
- **ROCOF:** 10-sample Moving Average.
- **Result:** Eliminates false triggers from grid transients or quantization error.

The system classifies the grid state based on standard stability thresholds.

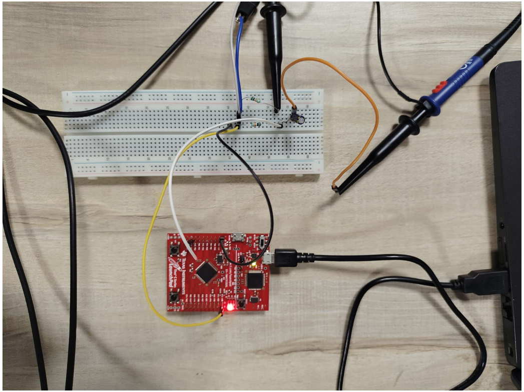
```c
// Threshold Checking
if(filtered_rocof > ROCOF_CRITICAL_HIGH){
    // 1. Serial Alert
    UART_SendString(">>> ALERT: ROCOF POSITIVE CRITICAL");

    // 2. Visual Indication (Red LED)
    GPIO_PORTF_DATA_R = 0x02;
}
else if ( ... ) {
    // Warning State (Yellow/Blue LED)
}
else {
    // Normal State (Green LED)
    UART_SendString("Status: NORMAL");
}
```

Hardware Setup



Setup with Step-Down Transformer



Testing with Function Generator

Terminal Output: Normal Operation

Scenario: Steady Grid Frequency (50 Hz)

```
ROCOF Fast Sampling + Alert Version Running...
Measurement #1 | Freq: 49.98 Hz | ROCOF: -0.00 Hz/s | Status: NORMAL
Measurement #2 | Freq: 49.95 Hz | ROCOF: -0.02 Hz/s | Status: NORMAL
Measurement #3 | Freq: 49.96 Hz | ROCOF: -0.01 Hz/s | Status: NORMAL
Measurement #4 | Freq: 49.94 Hz | ROCOF: -0.02 Hz/s | Status: NORMAL
Measurement #5 | Freq: 49.92 Hz | ROCOF: -0.03 Hz/s | Status: NORMAL
Measurement #6 | Freq: 49.92 Hz | ROCOF: -0.03 Hz/s | Status: NORMAL
Measurement #7 | Freq: 49.92 Hz | ROCOF: -0.03 Hz/s | Status: NORMAL
Measurement #8 | Freq: 49.92 Hz | ROCOF: -0.03 Hz/s | Status: NORMAL
Measurement #9 | Freq: 49.93 Hz | ROCOF: -0.03 Hz/s | Status: NORMAL
Measurement #10 | Freq: 49.93 Hz | ROCOF: -0.03 Hz/s | Status: NORMAL
Measurement #11 | Freq: 49.94 Hz | ROCOF: -0.02 Hz/s | Status: NORMAL
Measurement #12 | Freq: 49.94 Hz | ROCOF: -0.02 Hz/s | Status: NORMAL
Measurement #13 | Freq: 49.90 Hz | ROCOF: -0.04 Hz/s | Status: NORMAL
Measurement #14 | Freq: 49.92 Hz | ROCOF: -0.03 Hz/s | Status: NORMAL
Measurement #15 | Freq: 49.92 Hz | ROCOF: -0.03 Hz/s | Status: NORMAL
Measurement #16 | Freq: 49.91 Hz | ROCOF: -0.04 Hz/s | Status: NORMAL
Measurement #17 | Freq: 49.90 Hz | ROCOF: -0.04 Hz/s | Status: NORMAL
Measurement #18 | Freq: 49.90 Hz | ROCOF: -0.04 Hz/s | Status: NORMAL
Measurement #19 | Freq: 49.91 Hz | ROCOF: -0.04 Hz/s | Status: NORMAL
Measurement #20 | Freq: 49.90 Hz | ROCOF: -0.04 Hz/s | Status: NORMAL
Measurement #21 | Freq: 49.90 Hz | ROCOF: -0.03 Hz/s | Status: NORMAL
Measurement #22 | Freq: 49.91 Hz | ROCOF: -0.02 Hz/s | Status: NORMAL
Measurement #23 | Freq: 49.91 Hz | ROCOF: -0.02 Hz/s | Status: NORMAL
Measurement #24 | Freq: 49.92 Hz | ROCOF: -0.01 Hz/s | Status: NORMAL
Measurement #25 | Freq: 49.93 Hz | ROCOF: 0.00 Hz/s | Status: NORMAL
Measurement #26 | Freq: 49.94 Hz | ROCOF: 0.01 Hz/s | Status: NORMAL
Measurement #27 | Freq: 49.93 Hz | ROCOF: 0.00 Hz/s | Status: NORMAL
Measurement #28 | Freq: 49.93 Hz | ROCOF: 0.00 Hz/s | Status: NORMAL
```

Observation: Frequency is stable at ≈ 49.9 Hz. ROCOF fluctuates near 0.00 Hz/s.

Terminal Output: Fault Detected

Scenario: Sudden Frequency Shift (Simulated)

```
Measurement #4 | Freq: 49.89 Hz | ROCOF: -0.05 Hz/s | Status: NORMAL
Measurement #5 | Freq: 49.87 Hz | ROCOF: -0.06 Hz/s | Status: NORMAL
Measurement #6 | Freq: 49.87 Hz | ROCOF: -0.06 Hz/s | Status: NORMAL
Measurement #7 | Freq: 49.87 Hz | ROCOF: -0.06 Hz/s | Status: NORMAL
Measurement #8 | Freq: 49.87 Hz | ROCOF: -0.06 Hz/s | Status: NORMAL
Measurement #9 | Freq: 49.91 Hz | ROCOF: -0.04 Hz/s | Status: NORMAL
Measurement #10 | Freq: 49.89 Hz | ROCOF: -0.05 Hz/s | Status: NORMAL
Measurement #11 | Freq: 49.89 Hz | ROCOF: -0.05 Hz/s | Status: NORMAL

ROCOF Fast Sampling + Alert Version Running...
Measurement #1 | Freq: 50.01 Hz | ROCOF: 0.00 Hz/s | Status: NORMAL
Measurement #2 | Freq: 49.98 Hz | ROCOF: -0.00 Hz/s | Status: NORMAL
Measurement #3 | Freq: 49.96 Hz | ROCOF: -0.01 Hz/s | Status: NORMAL
Measurement #4 | Freq: 49.92 Hz | ROCOF: -0.03 Hz/s | Status: NORMAL
Measurement #5 | Freq: 49.93 Hz | ROCOF: -0.03 Hz/s | Status: NORMAL
Measurement #6 | Freq: 49.88 Hz | ROCOF: -0.05 Hz/s | Status: NORMAL
Measurement #7 | Freq: 49.88 Hz | ROCOF: -0.05 Hz/s | Status: NORMAL
Measurement #8 | Freq: 51.45 Hz | ROCOF: 0.72 Hz/s | Status: CRITICAL
>>> ALERT: ROCOF POSITIVE CRITICAL
    Value: 2.75 Hz/s
Measurement #9 | Freq: 55.51 Hz | ROCOF: 2.75 Hz/s | Status: CRITICAL
Measurement #10 | Freq: 59.57 Hz | ROCOF: 4.78 Hz/s | Status: CRITICAL
Measurement #11 | Freq: 63.57 Hz | ROCOF: 6.78 Hz/s | Status: CRITICAL
Measurement #12 | Freq: 67.56 Hz | ROCOF: 8.78 Hz/s | Status: CRITICAL
Measurement #13 | Freq: 69.98 Hz | ROCOF: 9.99 Hz/s | Status: CRITICAL
Measurement #14 | Freq: 69.96 Hz | ROCOF: 9.98 Hz/s | Status: CRITICAL
Measurement #15 | Freq: 69.85 Hz | ROCOF: 9.92 Hz/s | Status: CRITICAL
Measurement #16 | Freq: 69.00 Hz | ROCOF: 9.50 Hz/s | Status: CRITICAL
Measurement #17 | Freq: 63.01 Hz | ROCOF: 6.50 Hz/s | Status: CRITICAL
Measurement #18 | Freq: 57.02 Hz | ROCOF: 3.51 Hz/s | Status: CRITICAL
>>> ALERT CLEARED: ROCOF back to normal range
    Current ROCOF: 0.50 Hz/s
Measurement #19 | Freq: 51.00 Hz | ROCOF: 0.50 Hz/s | Status: CRITICAL
>>> ALERT: ROCOF NEGATIVE CRITICAL
    Value: -2.49 Hz/s
Measurement #20 | Freq: 45.01 Hz | ROCOF: -2.49 Hz/s | Status: CRITICAL
Measurement #21 | Freq: 39.87 Hz | ROCOF: -5.07 Hz/s | Status: CRITICAL
Measurement #22 | Freq: 39.87 Hz | ROCOF: -5.05 Hz/s | Status: CRITICAL
```

Observation: Critical Alerts triggered.
ROCOF shows large spikes (Positive & Negative) exceeding ± 1.0 Hz/s.

Project Conclusion

- **Accuracy:** The Tiva C Timer captured frequency with < 0.05 Hz jitter using the Moving Average Filter.
- **Safety:** The resistive bias network successfully protected the microcontroller from high voltage AC.
- **Performance:** The system reliably detects ROCOF events within 1 second, meeting the requirements for basic Grid Protection logic.
- **Future Scope:** Interfacing with a relay to automatically disconnect the load during Critical alerts.

Thank You