Stony Brook University

IoT-enabled Traveling Wave Protection (TWP)

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Outline:

Challenges with Distributed Energy Resources (DERs):
- High variability in fault currents
- Difficulty in maintaining stability across different operational modes

Limitations of Traditional Protection Methods:
- Inadequate response to dynamic and short microgrid topologies
- Prone to false tripping, especially during re-synchronization

Need for Real-time, Low-Cost Solutions:
- Existing systems are computationally expensive and not scalable
- IoT offers potential for enhanced real-time communication and data processing

Fault Detection Complexities:
- Traditional methods struggle with islanding scenarios in some cases
- Low fault current handling is often poor, leading to delayed or missed detections

And many, many more! It was decided to proceed with the development of new vision for microgrid protection!

Methodology overview

Fault distance is determined by analyzing **traveling waves** arriving at the measurement unit (MU) [1].

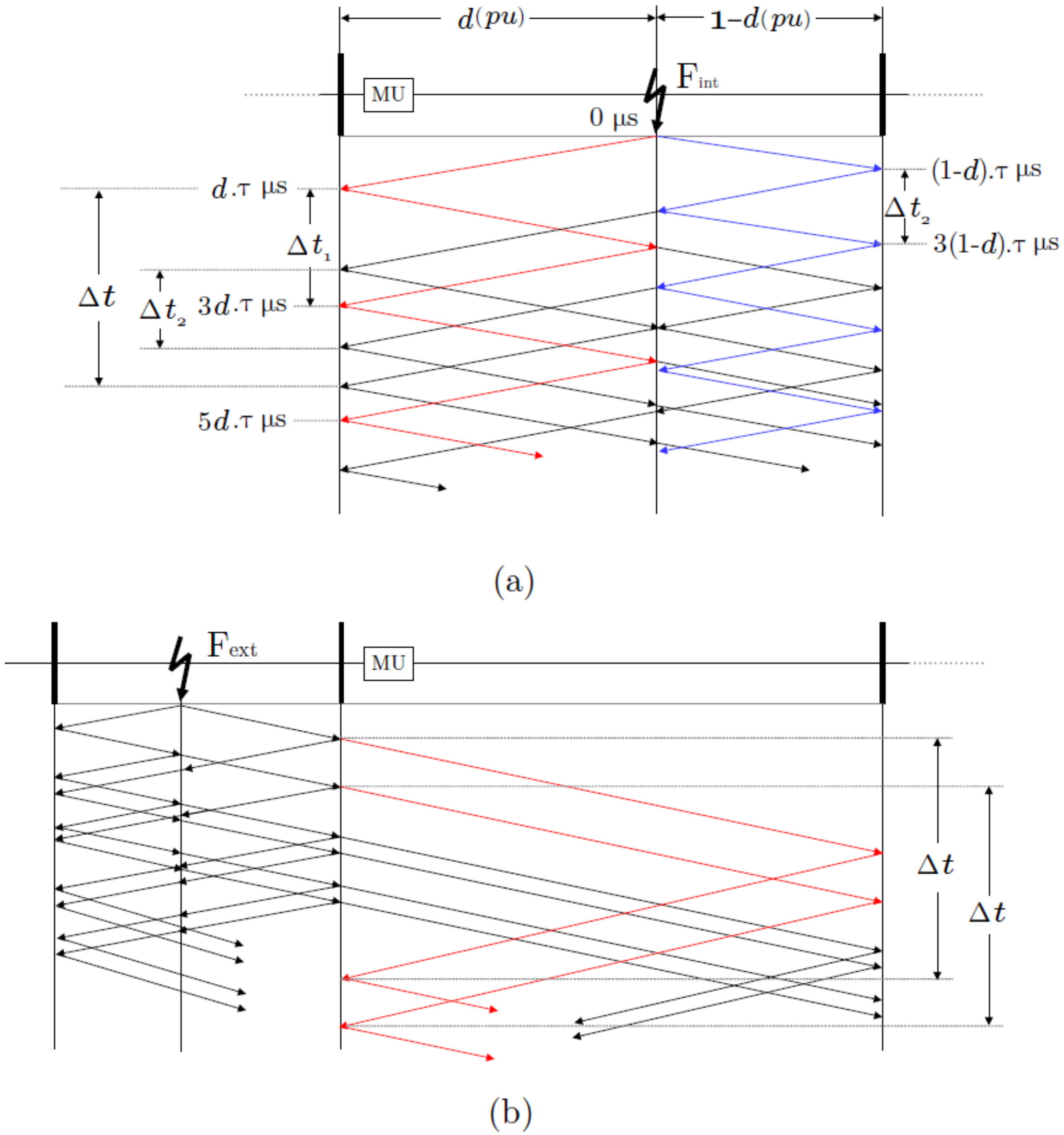
The **time between wave fronts** provides information on fault distance d:

$$\Delta t_1 = 2d \cdot \tau; f_1 = \frac{1}{2d \cdot \tau}$$

Where τ is the **propagation time constant** and d is the fault distance in **per unit (pu)**.

The relationship between **wave fronts** from opposite sides of the fault is:

$$\Delta t_2 = 2(1-d) \cdot \tau;\ f_2 = \frac{1}{2(1-d) \cdot \tau}$$



Time-space diagram and frequency of occurrence of traveling waves: (a) Internal fault; (b) External fault

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Our Lab's Work on development: S. Jena and P. Zhang, "Traveling wave analysis in microgrids," in Microgrids: Theory and Practice, P. Zhang, Ed. Hoboken, New Jersey: Wiley-IEEE Press, 2024.

Methodology overview

Traveling Wave Protection (TWP) leverages real-time fault detection using **IoT** platforms.

The key innovation is using the **Discrete Hilbert Transform (DHT) [2]** for traveling wave analysis, improving detection speed and accuracy.

Why DHT?

Efficiency: Computationally lighter than wavelet-based methods.

Adaptability: Better suited for **dynamic microgrid** environments with varying DERs and loads.

Low computational and power consumption is advantage for less-performance systems as IoTs.

- The **Hilbert Transform** of a real-valued signal f(t) is defined as:

$$H[f(t)] = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{f(\tau)}{t - \tau} d\tau$$

- The **analytic signal** $x_a(t)$ combines the real signal x(t) and its Hilbert transform:

$$x_a(t) = x(t) + jH[x(t)]$$

- The **envelope** E(t) and **instantaneous phase** ϕ(t) are derived as:

$$E(t) = |x_a(t)| = \sqrt{x(t)^2 + H[x(t)]^2}$$

$$\phi(t) = \arg\big(x_a(t)\big) = \arctan\left(\frac{H[x(t)]}{x(t)}\right)$$

The **peak of the envelope** is used to identify the **time of arrival (ToA)** for fault detection.

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[2] S. Biswal, M. Biswal, and O. P. Malik, "Hilbert huang transform based online differential relay algorithm for a shunt-compensated transmission line," IEEE Transactions on Power Delivery, 2018.

Methodology overview

Fault Direction Component

Using the **composite wave impedance** Z_Σ and **conductance** S_Σ, faults are detected and classified as **forward** or **reverse**.

$$Z_\Sigma = \frac{u}{i} = \frac{1+\rho}{1-\rho}(-Z_c)$$

$$S_\Sigma = \frac{i}{u} = \frac{1-\rho}{1+\rho}\frac{1}{-Z_c}$$

Where ρ is the **reflection coefficient**:

$$\rho = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

Fault Conditions:

Forward Fault: $\frac{Z_\Sigma}{(-Z_C)} \geq 1 + \epsilon_1$

Reverse Fault: $\frac{Z_\Sigma}{(-Z_C)} < 1 + \epsilon_2$

ϵ_1 and ϵ_2 are thresholds for reliable detection.

In multi-phase systems, phase-to-mode conversion ensures proper detection across phases using the transformation matrix S.

Fault Distance Component and MHO

- The **MHO characteristic** in fault detection is defined by comparing the **operating quantity** and **polarizing quantity:**

$$\arg(S_{OP}, S_{POL}) \rightarrow \pm 90°$$
$$Re(S_{OP}, S_{POL}^*) > 0$$

- The **apparent impedance** Z_{APP} is calculated as:

$$Z_{APP} = \frac{V_{LOOP}}{I_{LOOP}}$$

- This value is mapped to the **distance-to-fault axis**:

$$m = \frac{Re(V_{LOOP} \cdot S_{POL}^*)}{Re(Z_R \cdot I_{LOOP} \cdot S_{POL}^*)}$$

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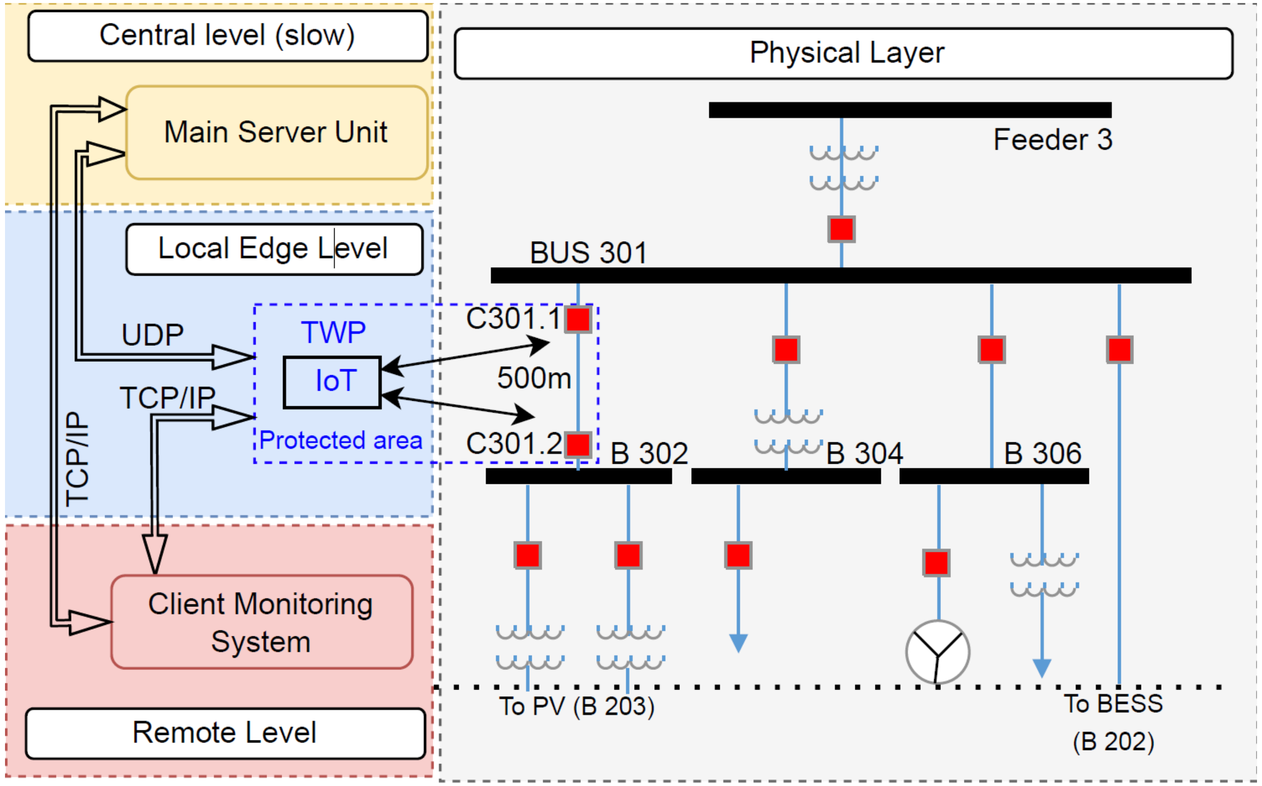
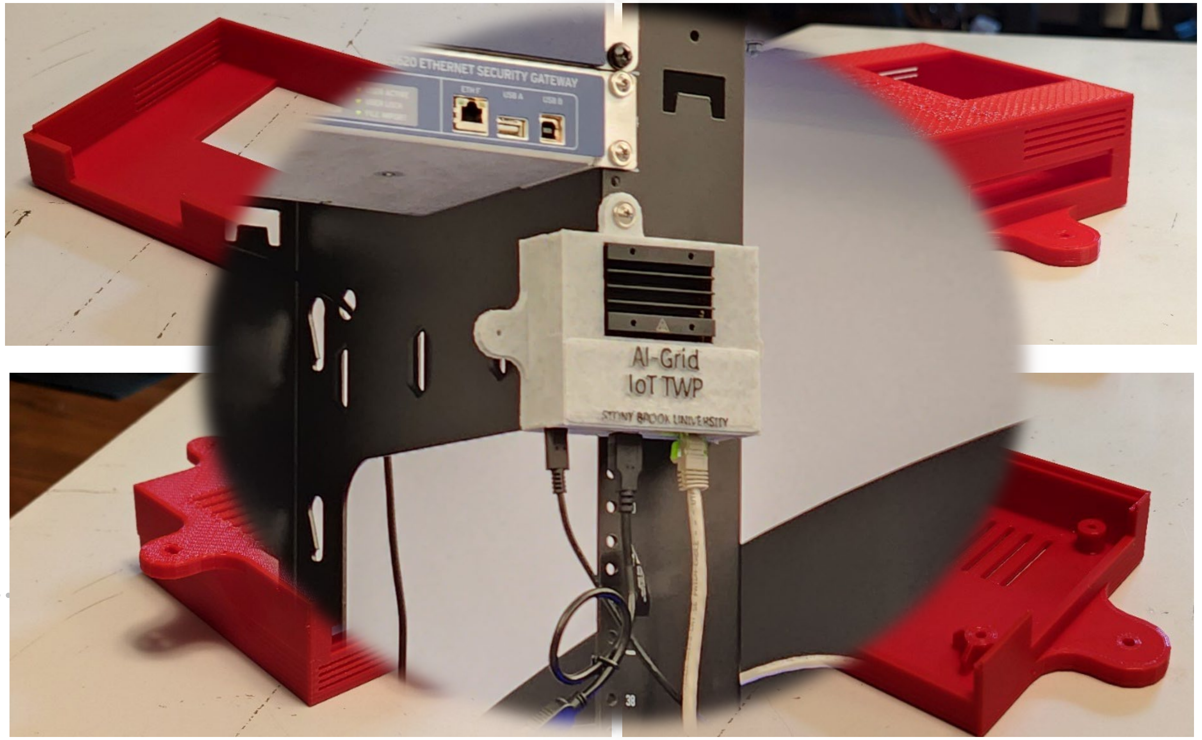
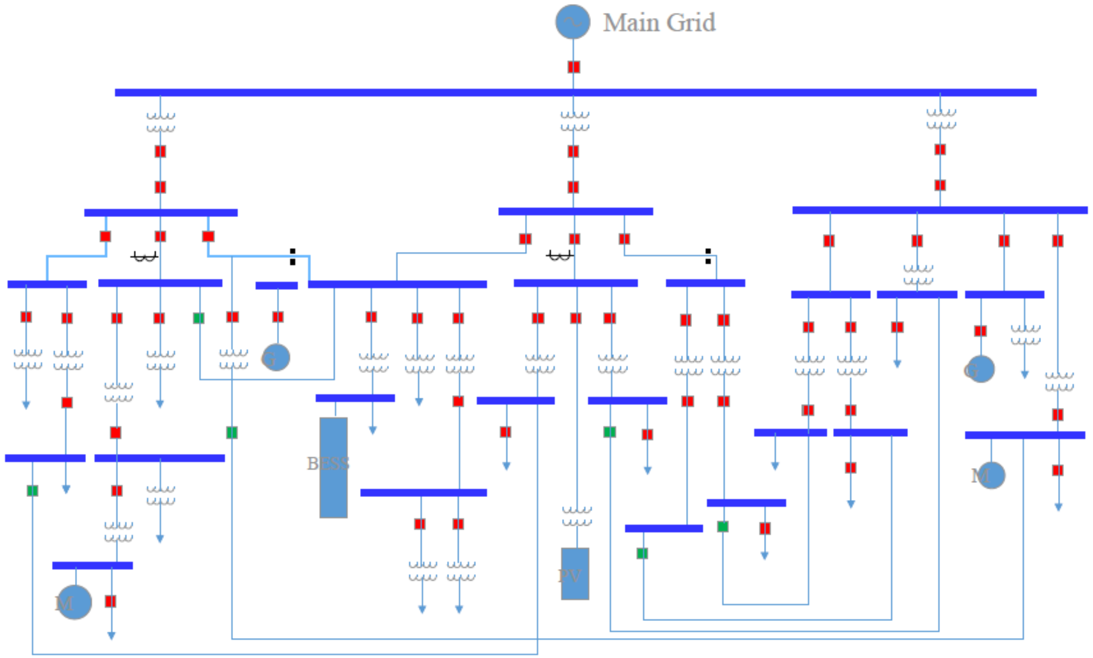
IoT TWP – Architecture and Test System



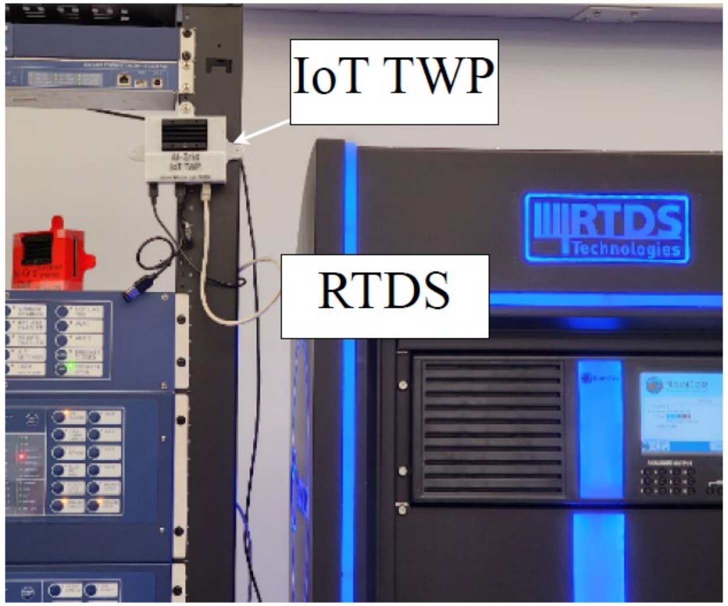
Implemented Traveling Wave Protection (TWP) in an IoT-based device, built on Nvidia Jetson Nano, integrated into the Banshee Microgrid System. The device supports remote monitoring via SSH (Putty), with the latest version featuring a built-in screen for enhanced user experience.



HIL– Architecture and Test System



Microgrid Systems in RTDS Environment



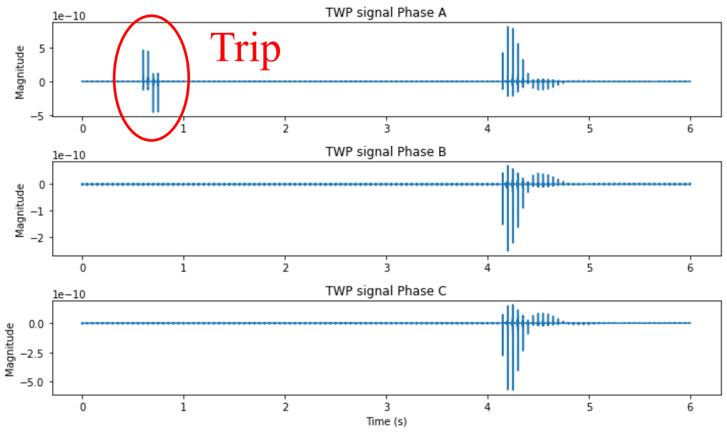
Physical HIL Testbed

The Banshee Microgrid System combines 50kW solar panels and 50kW wind turbines with an optional 30kW diesel generator for backup. A 100kWh lithium-ion battery bank stores excess energy. This system efficiently manages and distributes power between renewable sources and loads, ensuring reliable energy supply in remote or off-grid locations.

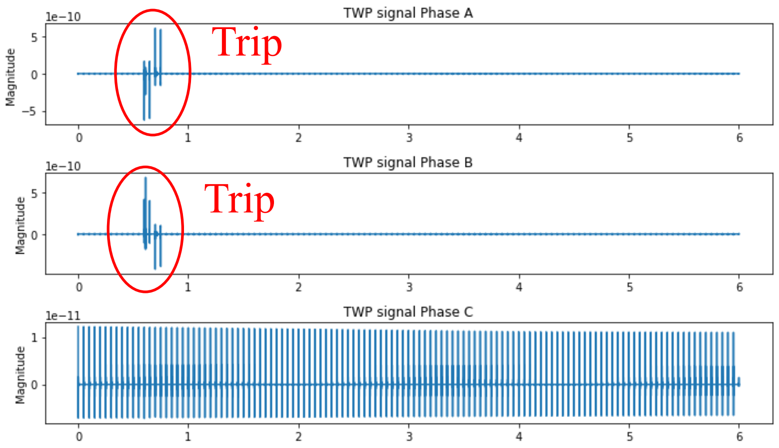
The Microgrid is integrated with RTDS NovaCor for real-time HIL simulation. It is interconnected with an IoT prototype through the UDP and GTNET interface of RTDS.

Trip Performance –Extracted Fault Signals' Features

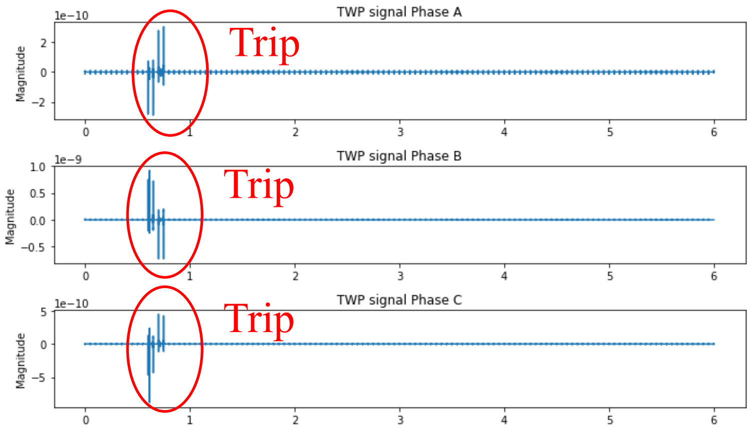
Three-phase operation is provided in comparison with presentation where the operation was based mostly on B phase.



1-Phase fault

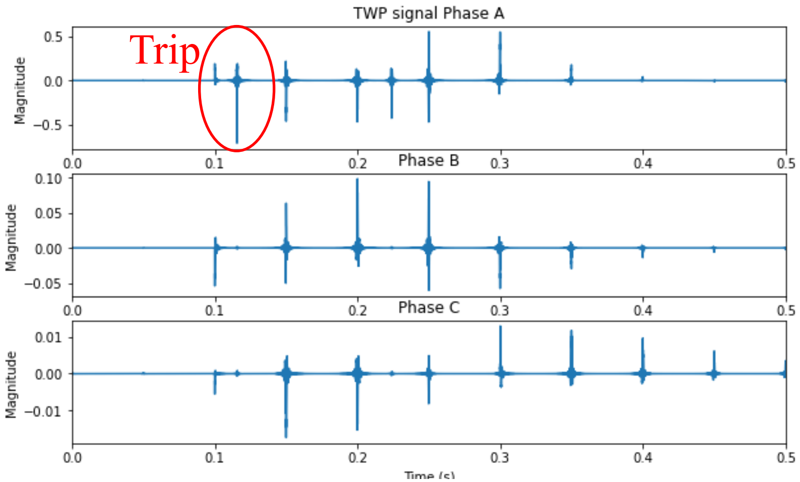


2-Phase fault

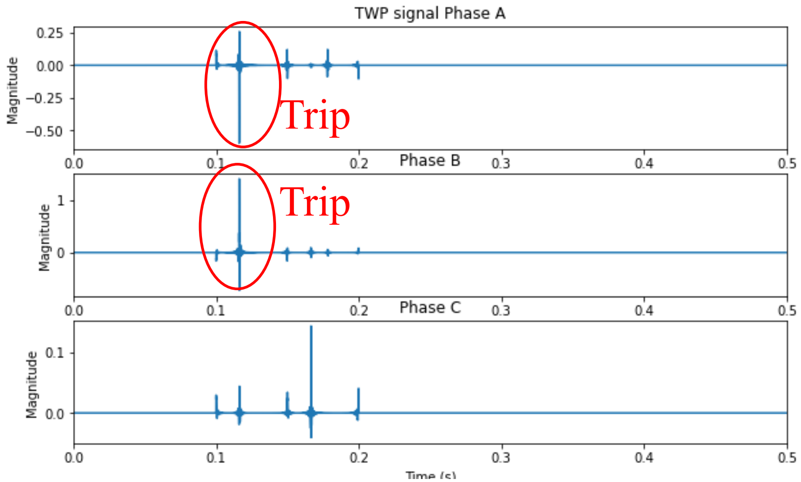


3-Phase fault

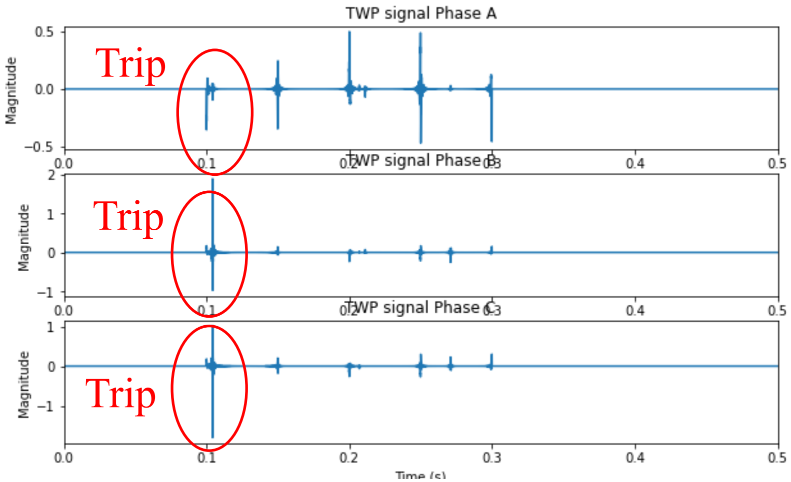
Function estimation for the operation is provided for complex Banshee microgrid



1-Phase fault



2-Phase fault



3-Phase fault

Python comes equipped with an automatic scaling capability for plotting. It is crucial to carefully monitor variations in the magnitude for external and internal faults

MHO Characteristics

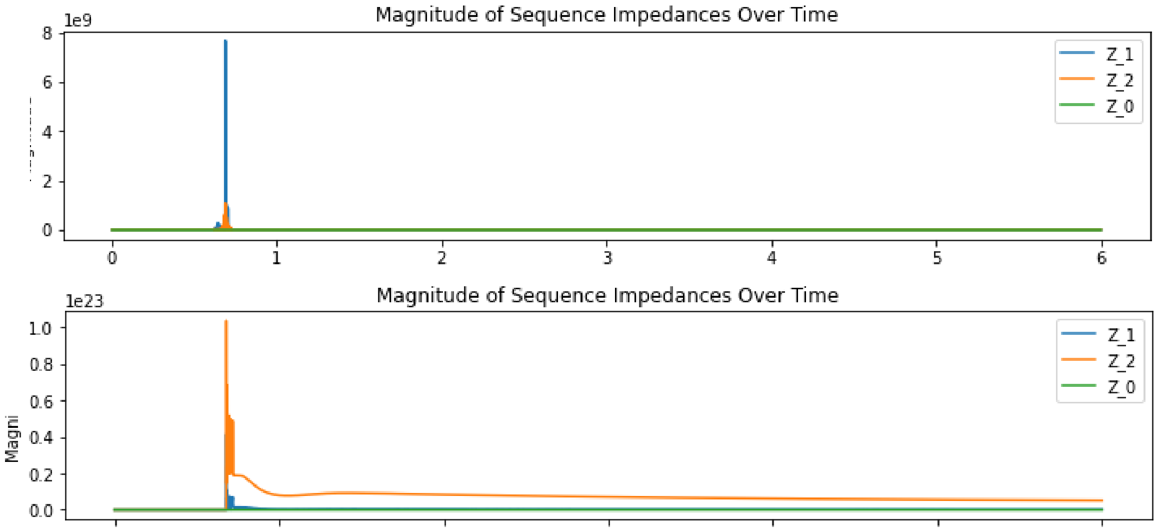
The relationship between composite wave impedance and conductance for forward and reverse faults is established to identify the fault direction and improve sensitivity.

The function developed for remote conditions monitoring.

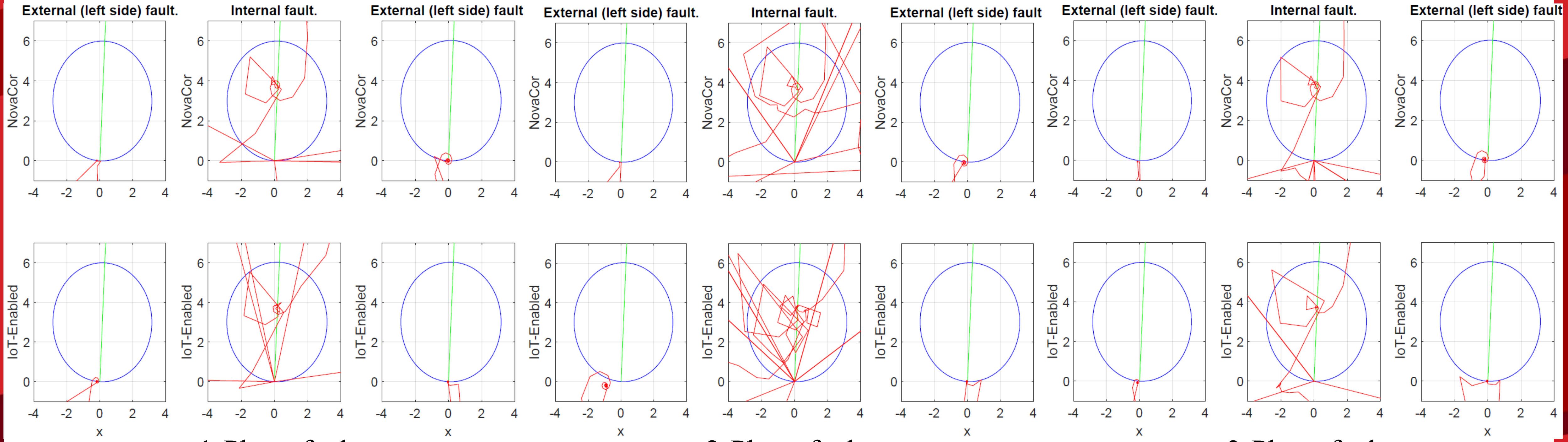
The sequence impedance function is developed for a sensitivity purposes.

```
Fault in phase A detected at time 0.600400s, direction: Forward

Fault in phase B detected at time 0.600050s, direction: Forward
Signal values:
pack1: 1
pack2: 0.05105447769165039
Signal sent to the server successfully!
```



Plots for magnitude of sequences Impedances over time for different cases



1-Phase fault 2-Phase fault 3-Phase fault

Conclusion

• The method combines wave impedance methods and Discrete Hilbert Transform for fast, accurate fault detection in microgrids.
• Hardware-in-the-loop testing confirmed performance under both normal and fault conditions, including islanding and grid-connected modes.
• Demonstrated high fault detection accuracy, even with challenging low fault currents and single-phase faults.
• Effectively reduces false positives, especially during re-synchronization with the main power grid.

- **IoT TWP can compete with traditional protection** in speed and fault handling.
- **Cost-effective and power-efficient** compared to commercial solutions.
- **High accuracy** in fault detection with strong directional sensitivity.
- **Resilient** to false positives during re-synchronization and islanding.
- **Scalable** for **microgrids and distribution systems** with renewable integration.

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Table 1: IoT TWP trip times (*Back 2* signal) for Microgrid Systems based on Nvidia Jetson Nano 2GB capabilities

System Scale	Fault Type	Time (s)
Small Microgrid	Three-phase (ABC) fault	0.0540
	Two-phase (AB) fault	0.0558
	One-phase (A) fault	0.0570
Banshee Microgrid	Three-phase (ABC) fault	0.058
	Two-phase (AB) fault	0.0581
	One-phase (A) fault	0.0589

Table 2: Comparison of Protection Schemes for Microgrids

Metric	IoT TWP	Overcurrent*	Distance*	TWP
Trip Time (s) (3-Phase)	0.054	0.1+	0.08+	0.004
Fault Detection Accuracy	Very High	Medium	High	Very High
Directional Sensitivity	High	Low	High	Very High
Low Fault Current Handling	High	Poor	Fair	Not Applicable
False Tripping Resilience	High	Low	Medium	High
Cost-Effectiveness	Very High	High	Low	Moderate
Estimated Price	$150	$3,000+	$9,000+	$18,000+
Power Consumption (W)	15	150+	150+	100
Applicability in Microgrids	Applicable	Applicable	Moderate	Not Applicable

* Tests performed on mainstream standard commercial products.

Thanks for your attention!