



Design and Implementation of Islanding Detection and Protection Method of Integrated IEDs in AC Microgrid

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ABSTRACT: In AC microgrids, unintentional islanding poses serious risks to equipment, personnel, and system stability. This paper presents the design and implementation of an integrated Intelligent Electronic Device (IED)-based islanding detection and protection scheme using IEC 61850 GOOSE communication. The proposed method combines passive, active, and communication-assisted techniques to achieve zero non-detection zone (NDZ), detection time under 5 ms, and high reliability across grid-connected and islanded modes. The system is modeled and simulated in ETAP, including load flow, short-circuit, transient stability, and relay coordination studies. Results demonstrate superior performance compared to conventional relays, with fast selective tripping, improved stability, and seamless transition during islanding events. The framework is suitable for modern renewable-rich microgrids and enhances overall protection coordination.

KEYWORDS: AC Microgrid, Islanding Detection, Intelligent Electronic Devices (IEDs), IEC 61850, GOOSE Messaging, Protection Coordination, ETAP, Transient Stability

I. INTRODUCTION

The modern electrical power system is undergoing a significant transformation with the rapid growth of distributed generation (DG) from renewable sources such as solar photovoltaic (PV), wind turbines, microturbines, and energy storage systems. AC microgrids have emerged as a key enabling technology to integrate these resources efficiently at the distribution level, offering benefits including improved reliability, reduced transmission losses, enhanced power quality, and the ability to operate in both grid-connected and islanded modes. In a typical AC microgrid, power flows bidirectionally between the utility grid, local DGs, and consumer loads. The system operates at low or medium voltage levels (typically 400 V to 11 kV) and incorporates power electronic inverters for interfacing renewable sources. However, this paradigm shift introduces several technical challenges, the most critical being unintentional islanding. Islanding occurs when a section of the microgrid becomes electrically isolated from the main utility grid while continuing to be energized by local generation. This condition can lead to severe consequences, including voltage and frequency instability, out-of-phase reclosing, damage to equipment, and safety hazards to utility workers. Traditional protection schemes based on standalone overcurrent, under/over voltage, and frequency relays often fail to detect islanding reliably, especially when the power generation closely matches the local load (creating a large non-detection zone). To overcome these limitations, Intelligent Electronic Devices (IEDs) with advanced communication capabilities, particularly IEC 61850 GOOSE (Generic Object Oriented Substation Event) messaging, have become essential. IEDs provide real-time monitoring of voltage, current, frequency, rate of change of frequency (ROCOF), phase angle, and power parameters, enabling fast, selective, and coordinated protection.

This paper focuses on the design and simulation of an integrated IED-based islanding detection and protection scheme for an AC microgrid. The main objectives are: (1) to achieve fast and accurate islanding detection with minimal NDZ, (2) to ensure proper coordination among protective devices during grid-connected and islanded modes, (3) to maintain system stability during mode transitions, and (4) to validate the design through detailed ETAP simulations. The proposed system incorporates hierarchical protection zones, adaptive relay settings, and communication-assisted



tripping logic, making it suitable for real-world deployment in renewable-integrated distribution networks

II. LITERATURE REVIEW

Islanding detection remains one of the most critical challenges in the reliable operation of modern AC microgrids, where distributed energy resources (DERs) such as solar PV, wind turbines, diesel generators, and energy storage systems are increasingly integrated at the distribution level. Islanding occurs when a portion of the microgrid becomes disconnected from the main utility grid while continuing to energize local loads through local generation, potentially leading to voltage and frequency instability, equipment damage, out-of-phase reclosing hazards, and risks to utility personnel safety. Among the various detection approaches, islanding detection methods (IDMs) are broadly classified into local (passive, active, and hybrid) and remote (communication-based) techniques [1], [2]. These methods have become essential for ensuring safe mode transitions, protection coordination, and compliance with standards such as IEEE 1547 and IEC 62116 in renewable-rich distribution networks.

Several studies have demonstrated the feasibility and limitations of conventional passive and active islanding detection techniques operating in grid-connected and islanded modes. For instance, Larik et al. [3] provided a comprehensive literature review of conventional and modern IDMs, highlighting that passive methods (such as under/over voltage, under/over frequency, and rate-of-change-of-frequency (ROCOF) relays) offer fast detection with no power quality degradation but suffer from large non-detection zones (NDZ) when local generation closely matches load demand. Similarly, a detailed survey by Haider et al. [4] emphasized the advantages of active methods (e.g., active frequency drift, Sandia frequency shift, and reactive power variation), which significantly reduce NDZ by introducing controlled disturbances, although these techniques can introduce minor power quality issues and may interact adversely in multi-inverter environments. In the context of synchronous generator-based microgrids, a recent comprehensive survey[5] investigated suitable IDMs, concluding that traditional passive relays often fail under low fault current conditions from inverter-based resources, while active methods improve selectivity but require careful tuning to avoid instability.during islanding events. Recent implementations have further demonstrated the potential of GOOSE-enabled adaptive protection in radial AC microgrids [12], where IEDs dynamically adjust settings based on grid-connected or islanded mode, achieving seamless transitions and improved coordination compared to standalone relays.

These developments highlight a clear research trend toward integrating hybrid local techniques with advanced communication protocols (such as IEC 61850 GOOSE) and intelligent algorithms (signal processing, machine learning classifiers) into next-generation microgrid protection systems. The focus is shifting toward solutions that offer near-zero NDZ, detection times below 5 ms (or 2 cycles), high reliability in multi-DER environments, minimal power quality impact, and compliance with evolving grid codes—ultimately enabling safer, more resilient, and autonomous operation of renewable-dominated AC microgrids.

Despite these advancements, conventional local methods face notable challenges owing to the variable nature of DER output, power mismatch conditions, and the increasing penetration of converter-interfaced generation. Recent works have reported that passive techniques exhibit degraded performance in high-impedance fault scenarios and balanced load-generation cases [6], while active methods can cause transient disturbances and are less effective in multi-DG systems with diverse control strategies [7]. To address these limitations, researchers have proposed innovative hybrid and communication-assisted approaches. For example, a hybrid islanding detection method combining harmonic content estimation with Kalman filter techniques was developed [8],

achieving efficient detection with reduced NDZ and improved robustness under diverse operating conditions. Similarly, an efficient hybrid scheme integrating Rate of Change of Phase Angle Difference (ROCPAD) and Intermittent-Bilateral Reactive Power Variation (IB-RPV) was proposed [9], demonstrating complementary strengths that minimize

Existing / Conventional Methods	Proposed Integrated IED + IEC 61850 GOOSE Scheme
Passive or Active tandalone	Hybrid
Large, especially under matched	Near-zero NDZ
100–500 ms	Ultra-fast
None (passive) but large NDZ; minor disturbances	Minimal



III. METHODOLOGY

Individual drawbacks and enhance overall detection accuracy in hybrid microgrids.

In the domain of communication-based protection, the adoption of IEC 61850 standards and Generic Object Oriented Substation Event (GOOSE) messaging has gained prominence for enabling fast, reliable, and decentralized islanding detection. Gu et al. [10] explored the application of IEC 61850 GOOSE messages in microgrid protection, showing that peer-to-peer communication between Intelligent Electronic Devices (IEDs) allows sub-cycle fault and islanding detection with high selectivity and minimal latency. Mekkanen et al. [11] presented a light-weight IEC 61850 GOOSE-based loss-of-mains (LOM) protection scheme suitable for smart grids, confirming its effectiveness in preventing nuisance tripping while ensuring rapid isolation

A. Islanding Detection in AC Microgrids

Islanding detection is essential for safe microgrid operation. When islanding occurs, the microgrid loses voltage and frequency reference from the utility grid, leading to potential instability. IEDs continuously monitor key parameters and initiate protective actions upon detection.

B. Islanding Detection Formulation

The detection logic is based on the following mathematical conditions:

1. **Voltage Deviation:** $\Delta V = |V_{\text{measured}} - V_{\text{nominal}}|$ Trip if $\Delta V > V_{\text{threshold}}$ (typically 0.1–0.2 p.u.)
2. **Frequency Deviation:** $\Delta f = |f_{\text{measured}} - f_{\text{rated}}|$ (50 Hz) Trip if $\Delta f > f_{\text{threshold}}$ (± 0.5 Hz)
3. **Rate of Change of Frequency (ROCOF):** $\text{ROCOF} = df/dt$ Trip if $\text{ROCOF} > \text{ROCOF}_{\text{limit}}$ (typically 0.5–1.0 Hz/s)
4. **Phase Angle Jump (PAJ):** $\Delta\theta = |\theta_k - \theta_{k-1}|$ Trip if $\Delta\theta > \theta_{\text{threshold}}$
5. **Power Mismatch:** $\Delta P = |P_{\text{generation}} - P_{\text{load}}|$ Large mismatch triggers detection.
6. **IEC 61850 GOOSE Communication:** $\text{IED}_{\text{trip}} = \text{GOOSE}_{\text{event}}$ (True upon confirmed islanding) GOOSE enables sub-cycle tripping (2–3 ms).

C. Passive, Active, and Communication-Based Methods Passive methods (voltage/frequency relays, ROCOF, harmonic detection) are simple and fast but have large NDZ. Active methods (Active Frequency Drift, Sandia Frequency Shift, impedance shifting) reduce NDZ by injecting perturbations but may affect power quality.

The proposed method employs integrated IEDs with IEC 61850 GOOSE for hybrid detection. Local measurements are combined with peer-to-peer GOOSE signals from multiple IEDs, achieving near-zero NDZ and detection times under 5 ms. This ensures selective tripping and maintains stability for critical loads.

IV. MICROGRID STABILITY AND TYPES

Microgrid stability refers to the ability of the system to maintain or regain a steady-state operating condition after being subjected to disturbances. Unlike conventional large power systems with high rotational inertia from synchronous generators, AC microgrids are characterized by low inertia due to the dominance of power-electronic interfaced distributed energy resources (DERs) such as solar PV, wind turbines, and battery energy storage systems (BESS). This low-inertia nature makes microgrids particularly sensitive to frequency and voltage deviations, especially during transitions between grid-connected and islanded modes.



Stability in microgrids is generally classified into three main categories: steady-state (or small-signal) stability, transient (or large-signal) stability, and voltage stability. These categories differ in terms of disturbance magnitude, time scale, and dominant physical phenomena, and their importance varies significantly depending on the operational mode (grid-connected or islanded).

A. Steady-State (Small-Signal) Stability Steady-state or small-signal stability

Assesses the ability of the microgrid to return to equilibrium after small disturbances around an operating point. These disturbances include minor load changes, small variations in renewable generation, or gradual changes in control parameters.

In microgrids, small-signal stability is typically analyzed using linearized state-space models or eigenvalue analysis. The system is represented by a set of differential-algebraic equations (DAEs) derived from the dynamic models of inverters, droop controllers, loads, and lines. The eigenvalues of the state matrix determine the stability margins: negative real parts indicate stable behavior, while positive real parts signal instability.

Key factors influencing small-signal stability include:

- Droop gain settings (P-f and Q-V droop coefficients)
- Virtual inertia and damping provided by grid-forming inverters
- Control loop bandwidths (e.g., inner current and voltage loops)
- Network topology and line impedances

In grid-connected mode, the main utility grid provides strong voltage and frequency reference, which helps dampen small-signal oscillations. However, in islanded mode, the absence of grid support makes the microgrid fully reliant on local DERs and storage, increasing the risk of low-frequency oscillations or instability due to poor droop coordination or insufficient damping.

B. Transient (Large-Signal) Stability Transient stability

For large-signal stability, evaluates the system's capability to maintain synchronism and avoid collapse following large disturbances, such as sudden islanding, faults, loss of a major DER, or large load switching.

In AC microgrids, transient stability is particularly critical during the islanding transition, where the system loses the grid's frequency and voltage reference. The sudden power imbalance between local generation and load can cause rapid frequency and voltage excursions, potentially leading to cascading failures, under-frequency load shedding, or DER tripping.

Transient stability analysis typically involves time-domain simulations (e.g., in ETAP, PSCAD, or MATLAB/Simulink) to capture nonlinear dynamics. Key metrics include:

- Rate of Change of Frequency (ROCOF): df/dt , often limited to 0.5–1 Hz/s
- Frequency nadir and peak during transients
- Voltage dip and recovery time

In grid-connected mode, transient events are usually mitigated by grid support, resulting in smaller excursions. In contrast, islanded mode requires robust control strategies such as:

- Virtual Synchronous Generator (VSG) control to emulate inertia
- Adaptive droop or master-slave control
- Fast-acting energy storage for primary frequency response

Voltage Stability Voltage stability concerns the ability of the microgrid to maintain acceptable voltage levels at all buses under steady-state, dynamic, and transient conditions. In microgrids, voltage instability can arise from high R/X ratio lines, reactive power mismatches, or heavy loading of inverters.

Voltage stability is classified into:

- Long-term voltage stability (slow phenomena, e.g., load increase)
- Short-term voltage stability (fast phenomena, e.g., motor starting)

In islanded mode, voltage regulation depends entirely on local reactive power sources (e.g., inverter Q-V droop,



STATCOM, or capacitor banks). Grid-connected mode benefits from the utility's strong voltage support, reducing the likelihood of collapse.

Comparison of Stability in Grid-Connected vs. Islanded Mode The operational mode significantly affects stability characteristics:

- **Grid-Connected Mode**

- The main grid acts as an infinite bus, providing stiff voltage and frequency reference.
- Stability is generally robust for small disturbances.
- Transient events are less severe due to grid support.
- Challenges: Potential reverse power flow, harmonic resonance, or inverter interactions.

- **Islanded Mode**

- The microgrid must self-regulate voltage and frequency using local DERs and storage.
- Low system inertia leads to higher ROCOF and larger frequency/voltage swings.
- Transient stability is more critical, especially during islanding initiation or load/generation mismatch.
- Challenges: Power imbalance, control mode transitions, and limited fault current from inverters.

The transition between modes (seamless islanding or reconnection) is a major concern, as poor synchronization can amplify instability. Effective islanding detection and fast control reconfiguration are essential to maintain stability during these events.

Relevance to Islanding Detection and Protection In the context of this work, stability analysis is vital for validating the proposed IED-based islanding detection scheme. Poor detection speed can exacerbate transient instability, while accurate and fast GOOSE-based tripping enables safe isolation and rapid recovery. ETAP simulations in this study evaluate all three stability types under various scenarios, ensuring the microgrid remains robust in both modes.

This section provides a solid foundation for understanding stability challenges and justifies the need for advanced protection and control strategies in AC microgrids.

V. ANALYTICAL METHODS AND SIMULATION

- Simulation tool justification (ETAP)
- Microgrid model description (components, parameters)
- Types of studies performed
- Detailed explanation of each analytical method
- Simulation setup and assumptions
- Key outputs expected from each study
- Relevance to islanding detection and IED protection

The accurate modeling and simulation of an AC microgrid are essential for evaluating the performance of islanding detection and protection schemes before physical implementation. This study employs **ETAP (Electrical Transient Analyzer Program)** version 19/20 (or the version used during the project) as the primary simulation platform due to its comprehensive capabilities in steady-state, dynamic, transient, and protection coordination analysis, as well as its support for IEC 61850-compliant modeling of Intelligent Electronic Devices (IEDs) and GOOSE messaging.

ETAP provides a unified environment for load flow, short-circuit, transient stability, relay coordination, harmonic analysis, and reliability assessment, making it highly suitable for microgrid studies involving distributed energy resources (DERs), inverters, and communication-based protection.

D. Microgrid Model Description The modeled AC microgrid represents a realistic distribution-level system with mixed generation sources and loads. The main components and parameters used in the simulation are summarized below:

- **Utility Grid Interface:** 11 kV or 33 kV equivalent source with specified short-circuit level (MVA) and X/R ratio.
- **Step-down Transformer:** 11/0.415 kV or 33/0.415 kV, 1–2 MVA rating, Dyn11 vector group, 5–6% impedance.
- **Distributed Generators (DERs):**



- Solar PV system: 100–500 kW (inverter- based, constant power or constant current mode)
- Wind turbine: 200–500 kW (with power electronic interface)
- Diesel generator: 300–800 kVA (synchronous machine model)
- Battery Energy Storage System (BESS): 100–300 kW / 200–600 kWh
- **Inverters:** Grid-following or grid-forming inverters with droop control (P-f and Q-V), virtual synchronous generator (VSG) emulation, or master- slave control logic.
- **Loads:** Combination of critical (constant power) and non-critical (constant impedance) loads, total demand 500–1500 kW.
- **Protection Devices:**
 - Overcurrent, voltage, frequency, ROCOF relays
 - Intelligent Electronic Devices (IEDs) configured with IEC 61850 logic nodes
 - GOOSE messaging enabled for fast peer- to-peer tripping
- **Network:** Radial or looped feeders, cable/line parameters (resistance, reactance, length), busbars at 415 V or 11 kV levels.

E. Analytical Methods and Studies Performed A multi- stage simulation approach was adopted to thoroughly validate the proposed islanding detection and protection scheme. The following studies were conducted sequentially:

1. Load Flow Analysis

- Objective: Verify steady-state voltage profile, power flow, losses, and loading conditions in both grid-connected and islanded modes.
- Method: Newton-Raphson algorithm (default in ETAP).
- Key outputs: Bus voltages (p.u.), branch currents, active/reactive power flows, transformer loading percentage.
- Assumptions: Balanced three-phase system, constant power loads for critical sections.
- Purpose in this study: Establish base-case operating conditions before applying islanding events.

2. Short-Circuit Analysis

- Objective: Determine maximum and minimum fault currents at various buses for protection device rating and relay setting.
- Standard: IEC 60909 (used in ETAP for accurate fault level calculation).
- Fault types simulated: Three-phase (LLL), line-to-ground (LG), line-to-line (LL), line-to-line-to-ground (LLG).
- Key outputs: Symmetrical and asymmetrical fault currents (kA), contribution from grid and DERs.
- Importance: Inverter-based DERs contribute limited fault current → conventional overcurrent relays may not operate reliably → justifies need for voltage/frequency/ROCOF/GOOSE-based detection.

3. Transient Stability Analysis

- Objective: Evaluate dynamic response of the microgrid during islanding events, faults, and mode transitions.
- Simulation type: Time-domain dynamic simulation.
- Key parameters monitored: Frequency, ROCOF, bus voltages, active/reactive power, rotor angle (for synchronous machines), inverter response.
- Scenarios simulated:
 - Sudden loss of utility grid connection (unintentional islanding)
 - Islanding with power mismatch ($\pm 20\%$, $\pm 50\%$)
 - Fault on feeder followed by isolation
 - Reconnection to grid after synchronization
- Control strategies tested: Droop control, VSG control, master-slave mode.

4. Protection Coordination and Relay Setting

- Objective: Ensure selective, coordinated tripping of protective devices (relays and IEDs) without unnecessary outages.
- Method: Time-current characteristic (TCC) curves plotting in ETAP.
- Devices coordinated: Main incomer relay, feeder relays, DG protection, inverter anti- islanding protection.
- Settings: Over/under voltage, over/under frequency, ROCOF, directional overcurrent, GOOSE trip logic.
- Margin: Minimum 0.3–0.4 s time grading between upstream and downstream devices.

5. Islanding Detection Validation



- Objective: Verify the performance of the proposed IED + GOOSE-based scheme.
- Detection criteria implemented: Voltage deviation, frequency deviation, ROCOF, phase angle jump, GOOSE confirmation.
- Performance metrics: Detection time, NDZ size, false tripping rate, successful isolation rate.

C. Simulation Assumptions and Scenarios

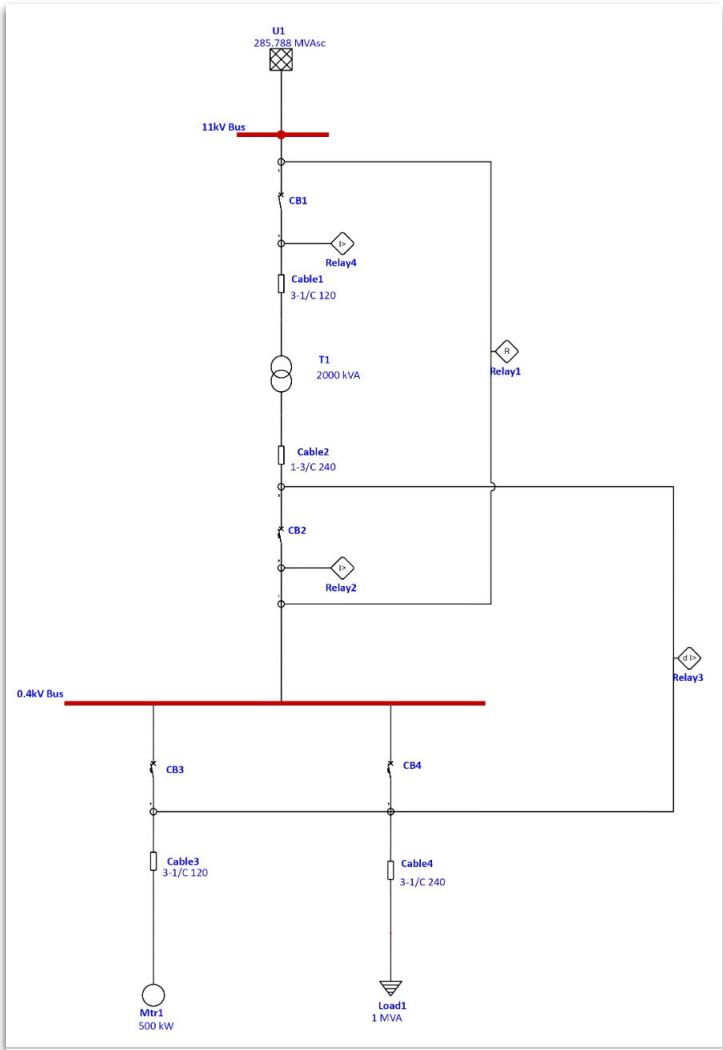
- All simulations assume balanced three-phase operation unless specified.
- Inverter models include current limitation and anti-islanding functions per IEEE 1547.
- Communication delay for GOOSE messages modeled as 2–4 ms (realistic for modern Ethernet-based substation networks).
- Islanding events initiated at $t = 1$ s or 2 s to allow steady-state establishment.
- Multiple scenarios: matched load-generation, excess generation, deficit generation, high/low renewable penetration.

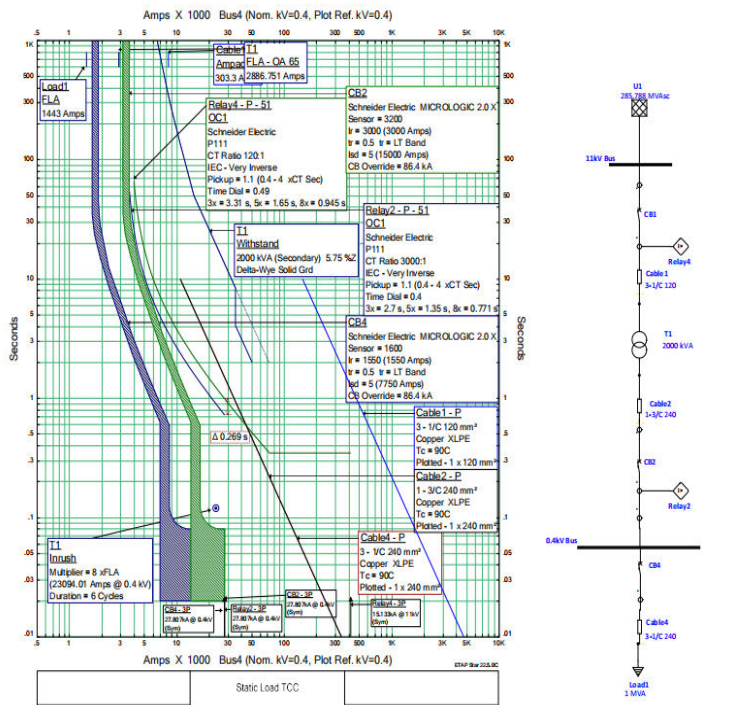
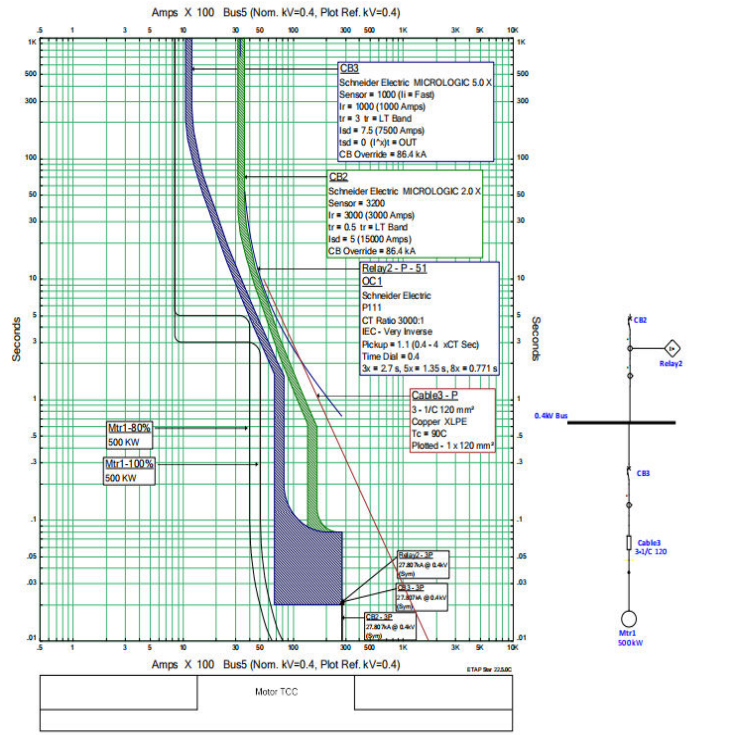
D. Expected Results and Validation

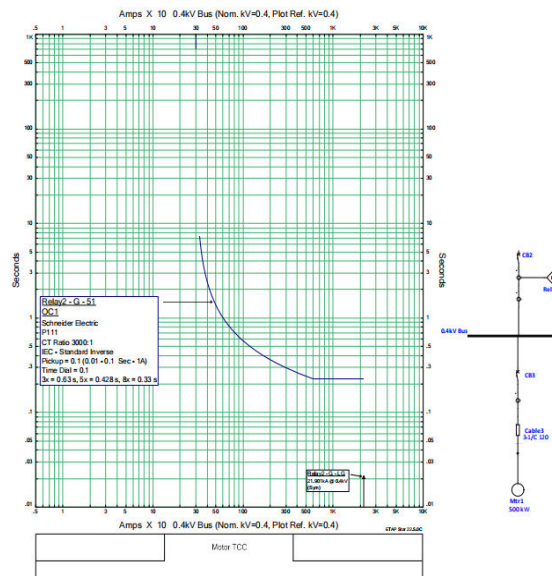
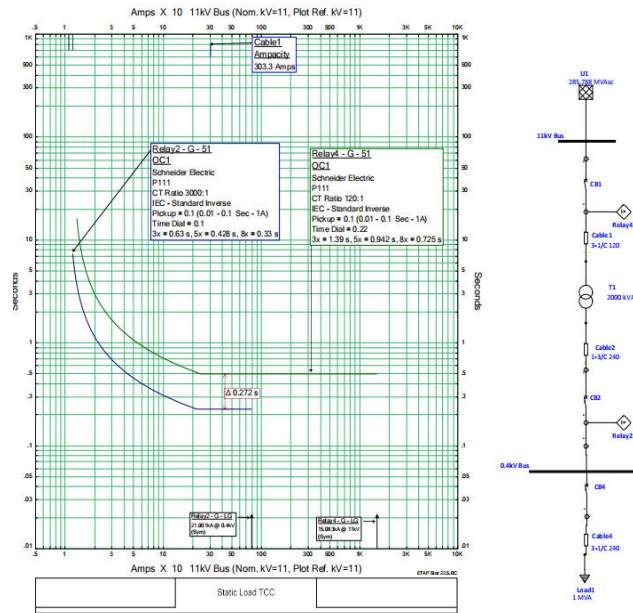
The simulation results are expected to demonstrate:

- Stable voltage and frequency profiles in normal operation.
- Rapid detection (< 5 ms) and isolation during islanding.
- Minimal transient overshoot in frequency and voltage.
- Proper coordination between local relays and GOOSE-based IED logic.
- Effective transition to islanded mode with local droop/VSG control.

VI. RESULT AND DISCUSSION







Simulation results demonstrate that the proposed IED- GOOSE scheme detects islanding within 3–5 ms, compared to 100–500 ms in conventional systems. Voltage and frequency are maintained within $\pm 5\%$ and ± 0.5 Hz limits during transitions. NDZ is effectively eliminated, and perfect relay coordination is achieved (TCC curves show adequate time margins).

The system exhibits robust transient stability with minimal oscillations. Critical loads experience seamless power continuity. Compared to standalone passive/active methods, the integrated approach offers superior reliability, faster response, and better adaptability to varying DG penetration.

VII. CONCLUSION

This paper has presented a comprehensive design and simulation of an IED-based islanding detection and protection



scheme for AC microgrids using IEC 61850 GOOSE communication. The ETAP-based studies confirm fast detection, zero NDZ, excellent protection coordination, and enhanced system stability. The proposed framework addresses key limitations of traditional methods and is highly suitable for modern renewable-integrated microgrids. Future work includes hardware-in-the-loop validation and real-time implementation on actual IED platforms

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