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REVERSE POWER FLOW DETECTION AND ANTI-ISLANDING FOR GRID-TIED SOLAR: DESIGN AND DEVELOPMENT OF A LABORATORY TEST KIT

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Abstract

The increasing penetration of grid-connected solar photovoltaic (PV) systems creates operational challenges for distribution networks, including bidirectional power flow and unintentional islanding. Reverse power flow occurs when local PV generation exceeds the load demand and surplus power is exported towards the utility grid. Islanding occurs when the utility supply is interrupted but a distributed generator continues to energize a local electrical section. This paper presents the design and development plan of a low-cost laboratory test kit for demonstrating reverse power flow monitoring and anti-islanding protection in a grid-tied solar setup. The proposed kit uses an ESP32 microcontroller, voltage and current sensing, an LCD, LED/buzzer indications, and a relay/contactor-based trip interface. The system is intended to monitor electrical parameters at the point of common coupling (PCC), identify operating states, and disconnect the inverter when a grid-loss/islanding condition is confirmed. Three laboratory conditions—normal operation, reverse power flow, and grid failure/islanding—are defined for evaluation. The paper describes the proposed hardware architecture, control sequence, testing procedure, and parameters to be recorded. Quantitative performance results will be added after the physical test kit is assembled, calibrated, and experimentally validated.

***Index Terms*—**Anti-islanding, ESP32, grid-connected photovoltaic system, laboratory test kit, point of common coupling, reverse power flow, solar PV protection.

I. INTRODUCTION

Solar photovoltaic generation is increasingly being connected to low-voltage distribution networks. A grid-tied PV installation may supply local loads and, when generation exceeds consumption, export surplus energy to the utility network. This bidirectional exchange makes monitoring the direction and magnitude of power flow at the point of common coupling (PCC) important for understanding system operation and protection.

Reverse power flow is not necessarily an abnormal or unsafe condition; it can be an expected operating state in installations that permit energy export. In contrast, unintentional islanding is a safety concern. It occurs when the utility source is disconnected while the PV inverter continues to energize a local section. Such a condition can create hazards for utility personnel and may cause voltage and frequency conditions outside acceptable limits. Grid-interconnection requirements, including IEEE Std 1547-2018, specify requirements for distributed energy resources under abnormal grid conditions [3].

The proposed work converts the conceptual model described in the project synopsis into a physical laboratory test kit. The kit is intended for controlled demonstration and measurement of the sensing-to-decision-to-trip sequence. It is not presented as a certified protection relay or as equipment approved for direct connection to a public utility network.

II. RELATED WORK

Existing islanding-detection approaches are commonly grouped into passive, active, remote, and hybrid methods. Passive methods observe local electrical quantities such as voltage, frequency, phase, and harmonic behaviour. Active methods introduce a controlled disturbance and observe the system response, while remote methods use communication between the utility and distributed generator. Reviews by Ahmad et al. [1] and Khan et al. [2] discuss the advantages, limitations, detection speed, and non-detection zones (NDZ) associated with these approaches.

The literature also examines reverse power flow and its impact on distribution protection as PV penetration increases [5]–[7]. ESP32-based monitoring has been explored for solar applications, including real-time acquisition of PV parameters [8]. These studies motivate a compact educational hardware platform that combines electrical sensing, operating-state indication, and a protective trip output.

A key design consideration is that reverse power flow alone must not be treated as proof of islanding. The proposed test kit therefore treats power-flow direction as one monitored parameter and uses grid-presence and supporting voltage/frequency checks in the islanding decision. The final decision logic and thresholds must be calibrated and validated for the chosen laboratory arrangement.

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III. PROBLEM DEFINITION AND OBJECTIVES

Low-cost educational demonstrations often show solar generation and load operation without providing an integrated means to observe power-flow direction and demonstrate automatic disconnection following loss of the grid source. A laboratory platform is therefore required to make the operating states visible, record electrical measurements, and demonstrate a controlled trip action.

The objectives of the proposed laboratory test kit are:

1. To measure voltage and current at the selected PCC and estimate the direction and magnitude of power flow.
2. To distinguish normal operation, reverse power export, and grid-failure/islanding test conditions.
3. To implement the monitoring and decision logic using an ESP32 microcontroller.
4. To display measured parameters and system status on a 16×2 LCD and provide LED/buzzer alerts.
5. To operate a relay/contactor interface to disconnect the inverter output during a confirmed islanding test.
6. To evaluate the response through repeatable laboratory tests and record detection and trip performance.

IV. PROPOSED SYSTEM ARCHITECTURE

The laboratory test kit consists of a solar PV source, charge controller, battery, DC–AC inverter, PCC sensing stage, ESP32 control unit, display and alert unit, relay/contactor interface, and a controllable load. The PV panel provides DC energy. The charge controller regulates battery charging, and the battery supplies the inverter. The inverter produces AC output for the laboratory arrangement. Voltage and current sensors acquire electrical measurements at the selected PCC and provide conditioned signals to the ESP32.

The ESP32 processes the sampled measurements, determines the operating state according to the programmed decision logic, updates the LCD, and controls the visual and audible indicators. When the grid-loss/islanding criteria are satisfied, the controller issues a trip command to the relay/contactor driver. The switching device then isolates the inverter from the test supply/load arrangement as defined by the laboratory wiring design.

V. HARDWARE COMPONENTS

Sr. No.	Component	Purpose
1	Solar PV panel	Provides DC solar energy for the demonstration.
2	Charge controller and 12 V battery	Regulates charging and stores energy for the inverter.
3	12 V DC–230 V AC inverter	Converts stored DC energy into AC for the test setup.
4	Voltage and current sensors	Measure electrical quantities at the PCC.
5	ESP32 development board	Processes sensor data and executes monitoring/trip logic.
6	16×2 LCD	Displays measured values and operating status.
7	LEDs and buzzer	Provide visual and audible status indications.
8	Relay/contactor with driver and protection	Performs controlled isolation following a trip command.
9	Load bank / resistive loads	Provides controllable local demand for test conditions.
10	Wires, connectors, MCB and enclosure	Provide interconnection and basic laboratory protection.

VI. MEASUREMENT AND CONTROL METHOD

The voltage and current sensing circuits must be selected for the actual voltage, current, isolation, and input range of the laboratory setup. Sensor outputs are conditioned to remain within the ESP32 analogue-input limits. Calibration is required before collecting data. The measurement algorithm should sample voltage and current synchronously or with a known sampling relationship to reduce calculation error.

For a single-phase AC system, the real power can be estimated from the sampled waveforms using the average instantaneous product:

$$P = (1/N) \Sigma [v(k) \times i(k)]$$

where v(k) and i(k) are the sampled voltage and current values and N is the number of samples in the calculation window. A consistent sign convention must be established during wiring and calibration. For example, positive power may be defined as power flowing from the grid towards the local load, while negative power represents export from the PV/inverter side towards the grid. The chosen convention must be documented on the kit.

The controller classifies the measured condition using power direction together with grid availability and supporting voltage/frequency checks. Reverse export is indicated as an operating state, not automatically tripped. A trip is commanded only when the configured grid-loss/islanding criteria are met. The final thresholds, time delays, and trip response must be determined from the applicable standard, component ratings, and supervised laboratory validation; they are not assumed in this design paper.

VII. OPERATING SEQUENCE

A. Normal operation: The grid source is healthy and the local load is supplied under the normal test arrangement. The LCD indicates normal status, and the corresponding indicator is activated.

B. Reverse power flow: The PV/inverter generation is adjusted so that it exceeds the local load demand. The measured power direction indicates export towards the grid side. The kit displays the reverse-flow state and records the measured values. This state is not treated as an islanding trip by itself.

C. Grid failure/islanding test: The grid source is intentionally interrupted using the laboratory-approved isolation arrangement while the inverter and local load are configured for the test. The controller checks the configured grid-loss and supporting electrical conditions. If the

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islanding criteria are met, the ESP32 activates the fault indication and commands the relay/contactor to isolate the inverter.

VIII. EXPERIMENTAL TEST PLAN

After assembly, the test kit will be checked for wiring continuity, sensor polarity, isolation, protective-device ratings, and correct relay operation. Sensors will be calibrated against suitable reference instruments. Each operating condition will then be repeated under controlled load settings. The following table defines the observations to be recorded.

Test	Condition	Expected indication/action	Measurements to record
1	Grid healthy; normal PV/load balance	Normal status; no trip	V, I, real power, grid status
2	PV generation greater than local load	Reverse-flow indication; no trip solely due to export	V, I, signed power, load setting
3	Grid source interrupted under supervised test	Islanding/fault indication and inverter isolation command	Grid-loss time, detection time, trip time, V and I before/after trip

The experimental results section should be completed only after actual measurements are available. At minimum, the final paper should report the number of trials, measured detection time, trip time, sensor measurement error, successful trip count, and any missed or false detections. Numerical values must be obtained from the assembled kit and must not be estimated or invented.

IX. EXPECTED OUTCOMES AND DISCUSSION

The expected outcome is a compact laboratory test kit that demonstrates the complete measurement, classification, indication, and trip-control sequence for the selected grid-tied solar test arrangement. The kit is expected to make the difference between permissible reverse power export and an islanding condition understandable through measured parameters and visible status indications. It will also provide a platform for studying sensor calibration, microcontroller-based protection logic, and relay/contactor response.

The actual effectiveness of the proposed logic can only be assessed after testing. In particular, the non-detection zone, detection time, false-trip behaviour, and reliability depend on the inverter, load characteristics, sensing accuracy, decision thresholds, and test configuration. These quantities will be reported in a revised results section after experimental validation.

X. SAFETY CONSIDERATIONS

The prototype is intended for supervised laboratory use. Mains-voltage circuits must be enclosed, fused or protected by correctly rated protective devices, and assembled only by competent personnel under faculty supervision. Appropriate galvanic isolation and sensor ratings must be verified before energizing the circuit. The grid-failure test must use an approved isolation method; the prototype must never be connected to a live utility network without formal engineering review, certified protection, and authorization. The relay/contactor and inverter disconnection path must be fail-safe for the intended laboratory arrangement.

XI. CONCLUSION

This paper presents the proposed design of an ESP32-based laboratory test kit for reverse power flow monitoring and anti-islanding demonstration in a grid-tied solar PV system. The system combines PCC voltage and current sensing, power-direction estimation, operating-state indication, and a relay/contactor trip interface. Three test conditions are defined: normal operation, reverse power flow, and grid failure/islanding. An important feature of the proposed approach is that reverse power export is identified as a valid operating state and is not, by itself, considered proof of islanding. The next stage is physical assembly, calibration, and controlled laboratory testing. Detection-time and reliability claims will be made only after recording and analysing the experimental results.

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