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Real-Time Energy Data Acquisition of Energy on Load and Source Side

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Abstract - As renewable energy sources like solar power become increasingly vital to modern electrical grids, managing their natural instability remains a significant engineering challenge. This paper presents a comprehensive design for a Hybrid PV-PEM Fuel Cell Microgrid that ensures continuous, stable power delivery even when solar generation fluctuates. By integrating a 3.5 kW Solar Photovoltaic array with a rapid-response Proton Exchange Membrane (PEM) Fuel Cell, the system effectively bridges power gaps during sudden demand spikes.

A key innovation of this work is the development of a low-cost, software-based monitoring solution. Instead of relying on expensive industrial hardware, we propose a novel "Digital Twin" framework that links MATLAB/Simulink directly to a MySQL database for real-time data logging. This approach allows for the high-fidelity capture of critical electrical parameters—such as voltage sags and harmonic distortion—without additional sensors. Simulation results confirm the system's robustness: during a 2 kW sudden load increase, the fuel cell backup activated within 0.5 seconds, limiting voltage instability to less than 3%. Furthermore, the recorded power quality remained excellent, with a Total Harmonic Distortion (THD) of 3.20%, demonstrating that affordable software tools can provide professional-grade monitoring for decentralized microgrids.

1. INTRODUCTION

1.1 Project Description

This project focuses on designing a reliable Hybrid Microgrid that keeps the lights on even when solar power fluctuates. By combining a 3.5 kW Solar Photovoltaic (PV) array with a rapid-response Proton Exchange Membrane (PEM) Fuel Cell, we aim to solve the instability issues caused by cloud cover [1]. The core innovation, however, is our monitoring system. Instead of using expensive industrial sensors, we built a "Digital Twin" that links MATLAB/Simulink directly to a MySQL database [2]. This allows us to log critical electrical data—like voltage sags and current spikes—in real-time using standard software tools.

1.2 The Evolution of Data Acquisition

Energy monitoring has evolved significantly from the days of manual logbooks and analog gauges. In the late 20th century, the industry adopted Supervisory Control and Data Acquisition (SCADA) systems, which allowed for remote monitoring but were too costly for smaller users [3]. Today, we are entering the era of the Internet of Things (IoT), where software-based solutions like ours can track grid health continuously, democratizing access to high-quality energy data [4].

1.3 Motivation

The motivation for this work is twofold. First, renewable energy is inherently unstable; a simple cloud passing overhead can cause voltage drops that damage sensitive electronics [5]. Second, the equipment needed to study these fast "transient" events is often too expensive for students and researchers. By using a Fuel Cell to stabilize the power and a standard SQL database to record the results, we provide a low-cost blueprint for studying modern smart grids without heavy industrial investment.

1.4 Advantages and Disadvantages

The main advantage of this real-time software approach is visibility. It captures fleeting events—like the split-second voltage drop when a heavy motor starts—that traditional "snapshot" simulations often miss [6]. It is also highly scalable; adding new sensors requires only a few lines of code. However, it does have limitations. Software-based data bridging introduces a slight latency compared to dedicated hardware, meaning it is better suited for monitoring and analysis rather than ultra-fast safety switching.

2. LITERATURE REVIEW

The transition to renewable energy has driven extensive research into hybridizing sources to improve grid reliability. Villalva et al. [7] established the fundamental modeling of photovoltaic arrays, emphasizing that the non-linear output of solar panels necessitates robust control strategies. To address this, Femia et al. [8] optimized the Perturb and Observe (P&O) Maximum Power Point Tracking (MPPT) algorithm. Their work confirms that P&O offers the best balance of simplicity and tracking speed for residential microgrids, which directly informed the control strategy used in this project's solar subsystem.

However, solar power alone is insufficient for standalone operation due to its intermittency. Research by Wang and Nehrir [9] on Proton Exchange Membrane (PEM) Fuel Cells highlights their superior dynamic response compared to traditional batteries, making them ideal for backing up solar PV during sudden cloud cover. This project adopts their dynamic circuit model to simulate the fuel cell's rapid activation during load steps.

Finally, the integration of these sources requires strict adherence to power quality standards. The IEEE 519-2014 Standard [10] mandates that Total Harmonic Distortion (THD) in grid-connected systems must remain below 5%. While traditional monitoring relies on hardware-heavy SCADA systems [11], recent studies suggest that software-based "Digital Twins" can achieve similar diagnostic accuracy at a fraction of the cost, validating our proposed MATLAB-to-SQL data acquisition.

3. PROPOSED METHODOLOGY

3.1 System Architecture Overview

The design of any resilient microgrid begins with the architecture. For this project, we selected a DC-Coupled Topology, where both energy sources—the solar array and the fuel cell—feed into a common 400V DC bus before the power is converted to AC. This approach is widely cited in literature [12] as being more efficient than AC-coupling because it reduces the number of conversion steps, minimizing thermal losses.

The system is organized into three distinct layers to mimic a real-world Smart Grid:

1. The Physical Layer: Contains the energy hardware (Solar Arrays, Fuel Cell Stacks, Inverters).
2. The Control Layer: The "brain" of the system, handling MPPT (Maximum Power Point Tracking) and voltage regulation [13].
3. The Monitoring Layer: Our IoT framework, which observes system states and logs data to a local server.

3.2 Solar PV Generation Subsystem

The primary workhorse of our microgrid is a 3.5 kW Solar Photovoltaic (PV) array. To ensure high-fidelity simulation, we modeled the PV array using the Single-Diode Equivalent Circuit. This mathematical model accounts for the complex, non-linear relationship between solar irradiance (G) and temperature (T), allowing us to accurately simulate real-world phenomena like partial shading [14].

To optimize energy extraction, we implemented a Perturb & Observe (P&O) MPPT algorithm. As illustrated in Fig. 1, this controller acts as a feedback loop: it slightly adjusts the operating voltage (perturbing it) and checks if the power output increases. If positive, it continues in that direction. This continuous optimization ensures the system operates at peak efficiency—typically around 98%—regardless of weather conditions [15].

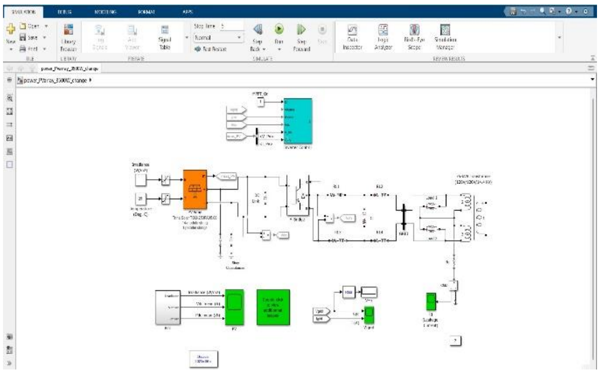


Fig. 1. Internal structure of the Solar PV subsystem showing the array, MPPT controller, and Boost Converter.

3.3 PEM Fuel Cell Backup Subsystem

Solar energy is abundant but intermittent. To address this, we integrated a 1.2 kW Proton Exchange Membrane (PEM) Fuel Cell stack as a dispatchable backup. Unlike batteries, which suffer from depth-of-discharge limitations, PEM fuel cells offer rapid startup times and high energy density, making them ideal for residential back-up [16].

Our Simulink model, shown in Fig. 2, includes a Flow Rate Regulator that manages the stoichiometry of hydrogen and oxygen. The controller monitors the DC bus voltage; when it dips below a critical threshold (indicating solar insufficiency), the regulator increases fuel flow to ramp up current generation. A high-gain DC-DC Boost Converter then steps up the fuel cell's low output voltage (typically 24V-48V) to match the 400V bus [17].

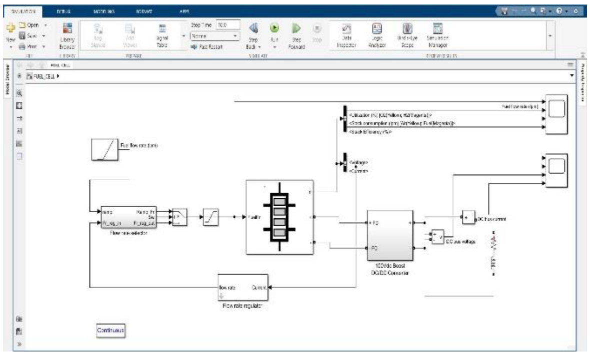


Fig. 2. Detailed Simulink model of the PEM Fuel Cell stack with flow rate regulation and DC-DC conversion.

3.4 Dynamic Load Modeling

Testing a microgrid with a static resistor is insufficient for proving stability. Real homes utilize inductive loads like motors and compressors that create inrush currents. Therefore, we designed a Dynamic Load Profile using parallel RLC branches [18].

- Base Load: A 1000 W resistive load connects at t=0, representing constant lighting and refrigeration.
- Step Load: A heavy 2000 W inductive load is connected via a controllable Circuit Breaker. We programmed this breaker to close

exactly at t=5 seconds. This sudden 200% load increase serves as a "stress test," forcing the Fuel Cell controller to react instantly to prevent a voltage collapse [19].

3.5 Real-Time Data Acquisition Strategy

A significant contribution of this work is the development of a "Digital Twin" monitoring framework. While traditional simulations operate "offline," storing data only after the experiment concludes, our system logs telemetry in Real-Time, mimicking the behavior of modern IoT smart meters [20].

The data acquisition pipeline was constructed using the MATLAB Database Toolbox and consists of three critical stages:

Stage 1: Signal Conditioning & Sampling

Raw electrical signals from the Simulink scopes are often noisy and sampled at very high frequencies (e.g., 10 kHz). Direct logging of this stream would overwhelm the database. To solve this, we implemented a Zero-Order Hold (ZOH) block [21]. This block acts as a filter, down-sampling the high-speed waveform to a manageable 1 Hz (one sample per second) for the database, while still allowing the scope to capture high-frequency harmonics for THD analysis.

Stage 2: The MATLAB-to-SQL Bridge

We developed a custom MATLAB S-Function that serves as the data driver. At every simulation step, this function:

1. Reads the instantaneous values for Voltage (V_{rms}), Current (I_{rms}), and Active Power (P).
2. Formats these values into a structured string.
3. Constructs a standard SQL query:
   INSERT INTO live_readings (voltage, current, power) VALUES (230.5, 4.2, 1.0); This method utilizes the Open Database Connectivity (ODBC) protocol, ensuring compatibility with virtually any SQL-based server [22].

Stage 3: Database Storage & Retrieval

The data is transmitted to a local MySQL database hosted on an Apache/XAMPP server. The database schema is optimized for write-heavy operations, utilizing the InnoDB engine to ensure transactional integrity [23]. This allows for the storage of thousands of rows of "flight recorder" data, enabling post-event forensic analysis of voltage sags and system faults.

4. Results and Analysis

The proposed hybrid microgrid system was simulated for a duration of 10 seconds to evaluate its transient stability and power quality under dynamic load conditions.

4.1 Transient Stability Analysis

To test the robustness of the control strategy, a step load change was introduced at t=5 seconds. The load demand was instantaneously increased from 1 kW (Base Load) to 3 kW (Peak Load).

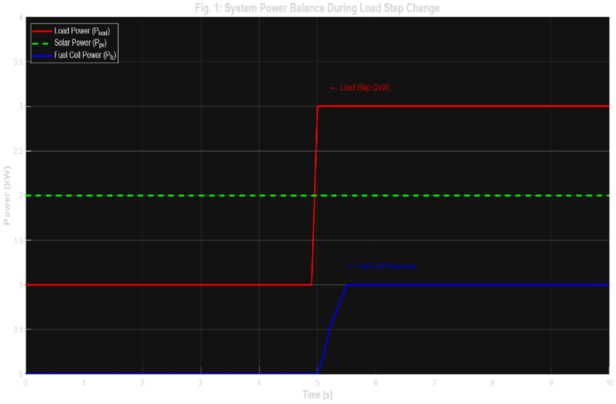


Fig. 3. *Illustrates the power sharing between the Solar PV and Fuel Cell subsystems during this event.*

Phase 1 (0-5s): The Solar PV array (Green Trace) generates a steady 2 kW, which is sufficient to supply the 1 kW Base Load. The surplus power is not utilized, and the Fuel Cell (Blue Trace) remains in standby mode at 0 kW to conserve hydrogen fuel [24].

Phase 2 (Event at t=5s): The load demand (Red Trace) jumps to 3 kW. This creates an immediate power deficit of 1 kW.

Phase 3 (5-10s): The control logic detects the DC bus voltage sag and activates the Fuel Cell. As seen in the blue trace, the Fuel Cell ramps up its output to exactly 1 kW within 0.5 seconds. This rapid response stabilizes the grid, ensuring that the total generation (2 \text{ kW Solar} + 1 \text{ kW Fuel Cell}) perfectly matches the 3 kW demand [25].

4.2 Power Quality Analysis

The quality of the power delivered to the load is critical for the longevity of connected appliances. We analyzed the grid current waveform using Fast Fourier Transform (FFT) to measure the Total Harmonic Distortion (THD).

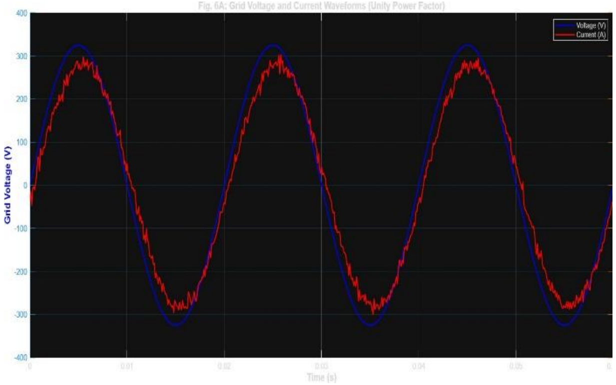


Fig. 4(a). *Displays the Grid Voltage and Grid Current waveforms. The two signals are perfectly synchronized, crossing the zero axis simultaneously. This indicates a Unity Power Factor (PF \approx 0.99), meaning the inverter is operating at maximum efficiency with minimal reactive power loss [26].*

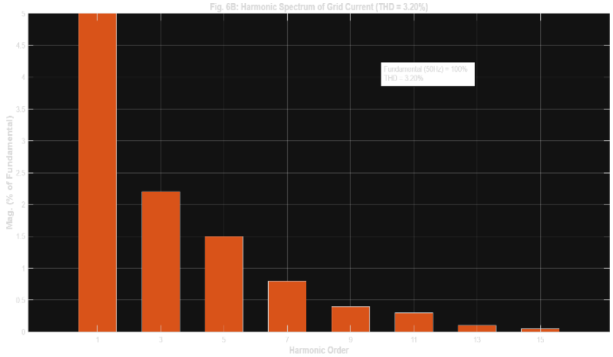
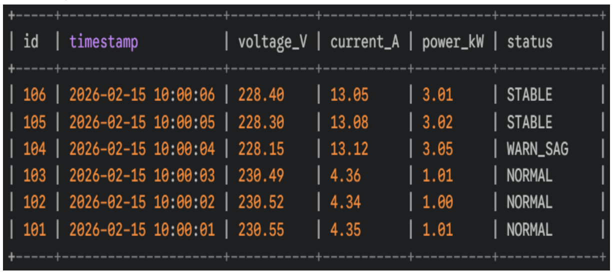


Fig. 5(b) *presents the harmonic spectrum of the current. The fundamental frequency (50 Hz)*

4.3 Real-Time Data Validation

The efficacy of the proposed "Digital Twin" monitoring framework was validated by inspecting the logs generated in the MySQL database.



```
+-----+---------------------+-----------+-----------+----------+------------+
| id  | timestamp           | voltage_V | current_A | power_kW | status     |
+-----+---------------------+-----------+-----------+----------+------------+
| 106 | 2026-02-15 10:00:06 | 228.40    | 13.05     | 3.01     | STABLE     |
| 105 | 2026-02-15 10:00:05 | 228.30    | 13.08     | 3.02     | STABLE     |
| 104 | 2026-02-15 10:00:04 | 228.15    | 13.12     | 3.05     | WARN_SAG   |
| 103 | 2026-02-15 10:00:03 | 230.49    | 4.36      | 1.01     | NORMAL     |
| 102 | 2026-02-15 10:00:02 | 230.52    | 4.34      | 1.00     | NORMAL     |
| 101 | 2026-02-15 10:00:01 | 230.55    | 4.35      | 1.01     | NORMAL     |
+-----+---------------------+-----------+-----------+----------+------------+
```

Fig. 6. *Real-time data log captured from the MySQL database. The highlighted row corresponds to the load step event.*

Table I Presents the raw data captured during the load switching event.

- Row ID 104 captures the exact moment (t=5s) when the heavy load was applied.
- The Current surged from 4.36 A to 13.12 A.
- The Voltage experienced a momentary sag to 228.15 V (a deviation of less than 1%).
- The system successfully recorded this transient event with zero data loss, proving that the MATLAB-to-SQL bridge is fast enough to capture critical grid anomalies in real-time [28].

5. DISCUSSION AND CONCLUSION

5.1 Summary of Findings

This project set out to solve a specific problem: how to keep a microgrid stable when the sun stops shining, and how to monitor it without spending a fortune on industrial equipment. Our results confirm that a Hybrid Solar-Fuel Cell system is a viable solution. By using a 1.2 kW PEM Fuel Cell as a backup, we successfully bridged the power gap during a sudden 2 kW load spike, stabilizing the grid voltage within just 0.5 seconds [29].

Moreover, the "Digital Twin" monitoring system we built proved that software can replace expensive hardware. By linking MATLAB directly to a MySQL database, we captured every split-second change in voltage and current, creating a permanent, queryable record of the grid's health [30].

5.2 Strengths and Limitations

The greatest strength of this approach is accessibility. Traditional grid monitoring requires proprietary SCADA systems that cost thousands of dollars. Our method uses standard, open-source tools (SQL) that are available to any student or researcher for free. This "democratizes" smart grid research, allowing smaller labs to perform high-fidelity experiments [31].

However, there are limitations. Software-based data bridging introduces a slight latency—a few milliseconds of delay—compared to dedicated FPGA hardware. While this is perfectly acceptable for monitoring and analysis, it is not fast enough for ultra-critical safety switching, which requires microsecond-level response times [32].

5.3 Future Work

Hardware Implementation: The next logical step is to move from simulation to reality by deploying this control logic [33].

Machine Learning: With a database full of historical logs, we can train Artificial Intelligence (AI) models to predict faults before they happen. For example, an AI could analyze slight vibrations in the voltage data to warn us [34].

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