

Design and Implementation of a Real-Time Hybrid Solar–PEM Fuel Cell DC Microgrid with Intelligent Energy Management using ESP32 and Node-Red

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Abstract-- Renewable-energy systems are increasingly required to provide dependable electrical power while reducing dependence on conventional energy sources. This paper presents the design and implementation of a real-time hybrid direct-current microgrid that combines a 12 V, 100 W photovoltaic (PV) panel, a proton exchange membrane (PEM) fuel cell, a rechargeable battery, power electronic converters, an ESP32 controller and a Node-RED based monitoring platform. The proposed system uses solar energy as the primary source and coordinates the battery and fuel cell according to generation availability and load demand. A maximum power point tracking (MPPT) stage and DC-DC power-conditioning circuits are used to regulate energy transfer to a common DC bus. The ESP32 measures source voltage, source current, battery condition, DC-bus voltage, load power and temperature, and executes an energy-management strategy without directly carrying the high current of the storage or fuel-cell paths. Control signals are instead applied to MOSFET-based converters. The measured variables are transmitted over Wi-Fi using MQTT to Node-RED, where a graphical dashboard presents real-time operating conditions, power flow, operating mode and alarms. The proposed architecture demonstrates how renewable generation, electrochemical energy storage, fuel-cell backup, embedded control and IoT monitoring can be integrated into a compact DC microgrid. The approach also incorporates battery protection concepts such as state-of-charge monitoring, thermal supervision and controlled charging and discharging.

Keywords-- DC microgrid, solar PV, PEM fuel cell, battery energy storage, ESP32, MQTT, Node-RED, energy management, MPPT.

I. INTRODUCTION

Electric power systems are moving toward distributed renewable generation in order to improve energy utilization, reduce dependence on fossil-fuel based generation and support cleaner electrical infrastructure. Solar photovoltaic systems are particularly suitable for small-scale applications because they can generate electricity directly from sunlight.

However, solar output is variable and depends on irradiance, temperature and operating conditions. A renewable source therefore benefits from an energy-storage or auxiliary-generation path that can compensate for short-term and prolonged variations in generation.

The proposed project addresses this requirement through a hybrid DC microgrid in which solar PV, a rechargeable battery and a PEM fuel cell are connected through suitable power electronic interfaces. The common DC bus provides a controlled electrical point for the load, while the individual converters regulate the transfer of power between each source and the bus. The battery is used for energy buffering: it can absorb surplus solar power and provide power during temporary solar deficits. The PEM fuel cell is treated as a supplementary source that can support the bus when the battery reaches a defined lower operating limit or cannot satisfy the required load power.

An intelligent controller is necessary because the sources cannot simply be connected together without considering voltage levels, current limits, charging conditions and source availability. In the proposed system, the ESP32 performs measurement, decision-making and communication functions. It evaluates source and load conditions and selects an operating mode. The controller does not switch the high-power path directly; instead, PWM or control commands are supplied to appropriate MOSFET-based converter stages.

Real-time visibility is provided through Node-RED. The ESP32 publishes measured data through MQTT over Wi-Fi, and Node-RED displays the information on a dashboard. This creates a practical link between electrical power management and IoT-based supervision. The overall concept is therefore suitable for demonstrating renewable energy integration, battery management, fuel-cell support, power electronics and embedded systems within a single laboratory-scale DC microgrid.

II. SYSTEM ARCHITECTURE

The proposed architecture is organized around a regulated common DC bus. The solar PV source is connected through an MPPT-enabled DC-DC converter. The rechargeable battery is connected through a bidirectional or suitably controlled battery converter so that

it can either absorb excess energy or deliver energy to the bus. The PEM fuel cell is connected through a dedicated DC-DC converter because its output voltage and current characteristics must be matched to the DC-bus requirement. The load is supplied from the common bus, while the ESP32 supervises measurements and control signals.

12 V, 100 W SOLAR PV	→	MPPT CONVERTER	+	DC-DC	→	COMMON DC BUS
RECHARGEABLE BATTERY	↔	BATTERY DC-DC STAGE			→	DC LOAD
PEM FUEL CELL	→	FUEL-CELL DC-DC STAGE			→	COMMON DC BUS
VOLTAGE / CURRENT / TEMPERATURE SENSORS	→	ESP32 CONTROLLER			→	PWM SIGNALS / ENABLE
ESP32 WI-FI	→	MQTT			→	NODE-RED DASHBOARD

Fig. 1. Functional architecture of the proposed hybrid DC microgrid

The architecture separates low-power measurement and control from the high-current energy path. This is important for safe operation because the ESP32 is used as a supervisory controller rather than as a direct power switch. Converter stages provide electrical isolation where required by the chosen hardware and regulate the current or voltage delivered to the DC bus.

III. MAJOR HARDWARE COMPONENTS

3.1 Solar PV Source

A 12 V, 100 W solar panel is selected as the primary renewable source. Its output varies with solar irradiance and temperature. The MPPT stage is intended to operate the panel near an appropriate operating point so that available solar power can be transferred efficiently to the DC bus or battery.

3.2 PEM Fuel Cell

The PEM fuel cell acts as a supplementary electrical source. Its DC output is passed through a dedicated converter so that the voltage can be regulated to the common bus. The fuel-cell path is activated according to the energy-management conditions rather than being used continuously.

3.3 Rechargeable Battery

The battery provides short-term energy storage and stabilizes the DC microgrid during changes in solar generation or load demand. Controlled charging and discharging are essential. Battery voltage, current and temperature are monitored, while a defined lower and upper state-of-charge region is used by the controller to avoid undesirable operating conditions.

3.4 Power Electronic Converters

The converters form the power interface between the sources, storage unit and common DC bus. MOSFET-based switching stages are controlled by PWM signals generated by the controller or by dedicated converter control hardware. The converter ratings must be selected according to the expected voltage, current and power levels.

3.5 ESP32 Controller

The ESP32 provides analog/digital measurement, control logic, Wi-Fi communication and PWM generation. It receives sensor information, calculates the available and required power and selects the operating mode. Protection thresholds can be implemented in software so that abnormal conditions cause the corresponding source or converter to be disabled.

3.6 Node-RED and MQTT

MQTT provides lightweight message communication between the ESP32 and the monitoring computer or server. Node-RED receives the data and converts them into dashboard elements such as gauges, trend graphs, numerical values, operating-state indicators and alarm messages.

IV. MEASUREMENT AND SENSING STRATEGY

Real-time energy management depends on reliable measurement. The proposed system monitors the voltage and current of the solar source, battery and PEM fuel cell, together with the DC-bus voltage, load demand and temperature.

Electrical power for a monitored path can be estimated from $P = V \times I$. Comparing total available source power with load power enables the controller to identify whether the system has a power surplus or deficit.

Table 1. Proposed monitored variables and their control significance

Measured variable	Purpose	Energy-management use
Solar voltage and current	Estimate PV operating power	Determine available renewable input and charging opportunity
Battery voltage and current	Estimate storage condition and power	Select charge, discharge or standby mode
Battery temperature	Observe thermal condition	Protect against operation outside the selected temperature range
Fuel-cell voltage and current	Estimate auxiliary source power	Confirm fuel-cell contribution when activated
DC-bus voltage	Verify bus regulation	Detect undervoltage/overvoltage conditions
Load current/power	Determine demand	Compare demand with total available generation

V. INTELLIGENT ENERGY MANAGEMENT STRATEGY

The energy-management system prioritizes renewable energy while maintaining the battery and DC bus within their selected operating limits.

Table 2: Simplified operating modes of the proposed controller

Mode	Main condition	Power path	Controller action
Solar + Load	PV power $\geq$ load power	PV $\rightarrow$ Bus $\rightarrow$ Load	Prioritize solar supply
Solar + Charge	PV power $>$ load and battery not full	PV $\rightarrow$ Bus + Battery	Charge battery with controlled current
Battery Support	PV power $<$ load and battery available	PV + Battery $\rightarrow$ Bus $\rightarrow$ Load	Discharge within limits
Fuel Cell Support	Battery below lower limit / insufficient	PV + Fuel Cell $\rightarrow$ Bus $\rightarrow$ Load	Enable fuel-cell converter
Protection	Abnormal V/I/T condition	Affected path reduced/off	Disable or limit affected source; raise alarm

VI. ESP32 CONTROL AND MQTT COMMUNICATION

The ESP32 is programmed as a supervisory controller. At each control cycle, it reads the sensor values, filters or validates the measurements as required, calculates the corresponding power values and evaluates operating thresholds.

The controller repeatedly acquires sensor values, estimates source and load power, checks protection conditions and selects the appropriate operating state. The basic operating sequence is designed around the following rules.

- *Solar-priority operation:* When sufficient solar power is available, the PV source supplies the DC load through the MPPT and power-conditioning stage.
- *Battery charging:* When PV generation exceeds the instantaneous load requirement and the battery is below its selected upper limit, the surplus power is directed to the battery.
- *Battery support:* When PV generation is insufficient, the battery supplies the difference between available solar power and load demand, provided its voltage, temperature and state-of-charge conditions remain acceptable.
- *PEM fuel-cell support:* If solar generation is insufficient and the battery reaches its minimum permitted operating condition or cannot supply the required deficit, the fuel-cell converter is enabled to provide supplementary power.
- *Protection mode:* If an abnormal voltage, current or temperature is detected, the affected converter is disabled or its power command is reduced, and an alarm condition is transmitted to the monitoring dashboard.

The resulting state determines the enable commands and PWM references supplied to the converter stages. To prevent rapid switching between operating states, practical implementations can introduce hysteresis or a short decision delay around threshold values.

For monitoring, the ESP32 connects to a Wi-Fi network and publishes structured measurements using MQTT topics. Typical messages may contain solar voltage, solar current, solar power, battery voltage, battery current, battery state, fuel-cell voltage, fuel-cell current, DC-bus voltage, load power, temperature, operating mode and alarm status. Node-RED subscribes to the relevant topics and updates the dashboard. This arrangement separates the real-time control function from the visualization layer and makes the system easier to expand.

VII. NODE-RED REAL-TIME MONITORING

The Node-RED dashboard provides a human-readable representation of the electrical condition of the microgrid. Numerical gauges can show source voltages and currents, while trend graphs can display solar power, battery power, fuel-cell power and load consumption over time. A mode indicator can show whether the system is operating in solar, charging, battery-support, fuel-cell-support or protection mode. Alarm widgets can be used to indicate overvoltage, overcurrent, excessive temperature or other selected limits.

The monitoring system also supports analysis of energy-management behavior. For example, a change in solar irradiance can be observed as a reduction in PV power, followed by battery support and, if necessary, fuel-cell activation. Similarly, when the load is reduced or solar generation increases, the dashboard can show the transition toward battery charging. These observations provide a useful demonstration of the closed-loop relationship between measurement, decision-making, power conversion and visualization.

VIII. BATTERY RELIABILITY AND PROTECTION CONSIDERATIONS

Battery reliability is an important part of any hybrid electrical system because repeated charging and discharging, temperature variation and electrical overstress can reduce useful performance. The reference study on EV battery reliability identifies failure mechanisms, testing approaches and lifetime prediction as important areas of battery reliability, and it discusses monitoring of voltage, current and temperature as significant battery parameters. It also describes the relevance of state of charge (SOC), state of health (SOH), thermal protection, cell balancing and tolerance control. □filecite□turn0file0□L170-L191□

For the proposed microgrid, the practical implementation can therefore include battery voltage, current and temperature monitoring as basic protection inputs. SOC can be used by the energy-management logic to define when charging should stop or when battery support should be reduced.

Where a multi-cell battery pack is used, an appropriate battery-management system should provide cell-level protection and balancing rather than relying only on the ESP32 supervisory controller.

The reference paper also describes thermal protection, SOC/SOH monitoring and cell equalization as battery improvement considerations. In particular, it explains that temperature, battery condition and balancing influence reliable operation. These concepts are directly relevant to the proposed hybrid microgrid because the battery is used as an active energy buffer between intermittent solar generation and the load. □filecite□turn0file0□L199-L227□

IX. TESTING AND VALIDATION PLAN

The prototype should be validated in stages so that the behavior of each energy path can be confirmed before full hybrid operation. The testing procedure should begin with sensor calibration and converter verification, followed by individual source tests and finally integrated energy-management tests.

Sensor validation: Compare ESP32 voltage, current and temperature readings with calibrated meters and confirm acceptable measurement error.

PV and MPPT test: Operate the solar source under different available-power conditions and verify stable converter operation and useful power transfer.

Battery charge test: Confirm controlled charging when solar power exceeds load demand and verify the selected upper voltage/SOC limit.

Battery discharge test: Apply a controlled load deficit and confirm that the battery supports the DC bus within its permitted operating range.

Fuel-cell support test: Reduce solar availability or battery capability and verify that the fuel-cell converter starts and contributes to the DC bus.

Transition test: Change load demand or solar input and observe whether the controller transfers between modes without unacceptable bus disturbances.

Protection test: Introduce controlled threshold conditions and verify converter shutdown/reduction and alarm reporting.

IoT monitoring test: Verify MQTT transmission, Node-RED reception, dashboard updating and logging of operating variables.

Note: The manuscript currently reports the proposed operating behavior. Quantitative experimental values should be inserted from the completed prototype measurements before final journal submission.

X. RESULTS AND DISCUSSION

The following results are estimated/simulated values prepared from the proposed 12 V, 100 W PV–battery–PEM fuel-cell architecture and the operating sequence described in this manuscript. They are included to demonstrate the expected journal presentation format. They must not be reported as measured prototype results; the final submission should replace them with experimental data obtained from the implemented system.

10.1 Estimated power-sharing response

The estimated power-sharing profile indicates the intended operating principle of the hybrid microgrid. When PV generation is higher than the load requirement, the PV source is prioritized and the surplus can be directed toward battery charging. As solar availability decreases, battery support is expected to increase. The proposed controller can subsequently enable the PEM fuel-cell converter when the battery reaches its selected lower operating condition or cannot meet the load deficit. This sequence is consistent with the energy-management rules described in Section 5.

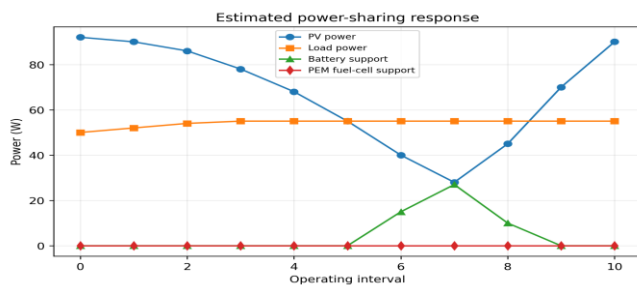


Fig. 2. Estimated power-sharing response of PV, battery, PEM fuel cell and load. Values are simulated/estimated and are not experimental measurements.

In the estimated profile, PV power varies from approximately 28 W to 92 W while the representative load remains close to 50–55 W. The battery contribution is introduced during the lower-PV intervals, illustrating its role as an energy buffer. The graph therefore demonstrates the expected qualitative response of the supervisory energy-management algorithm rather than establishing measured performance.

10.2 Estimated DC-bus voltage regulation

Maintaining the DC-bus voltage within a narrow range is an important requirement because the PV, battery and fuel-cell interfaces operate at different electrical conditions. The estimated profile below assumes a nominal 24 V DC bus and small deviations during changes in source availability. The final experimental paper should report the actual maximum deviation, settling time and steady-state ripple obtained from oscilloscope or data-logger measurements.

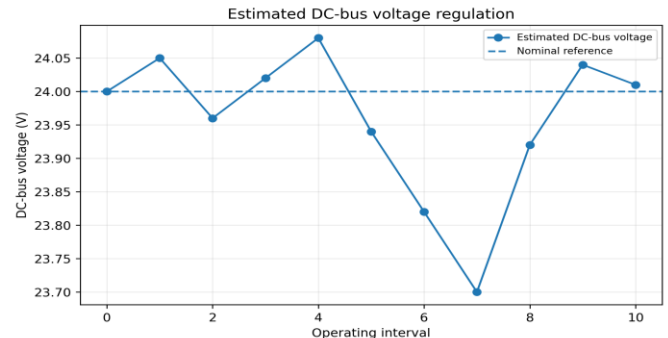


Fig. 3. Estimated DC-bus voltage regulation around a nominal 24 V reference. Values are simulated/estimated and are not experimental measurements.

The estimated bus voltage remains approximately within 23.70–24.08 V, corresponding to a maximum deviation of about 1.25% from the nominal 24 V value. This figure is only an illustrative engineering estimate; the reported deviation must be recalculated from actual measurements before publication.

10.3 Estimated battery SOC behaviour

Battery SOC is an important supervisory variable because the proposed controller uses an upper and lower operating region to determine charging, discharging and fuel-cell support. The estimated SOC profile shows an increase during periods of adequate PV generation and a decrease during periods in which the battery supplies part of the load demand.

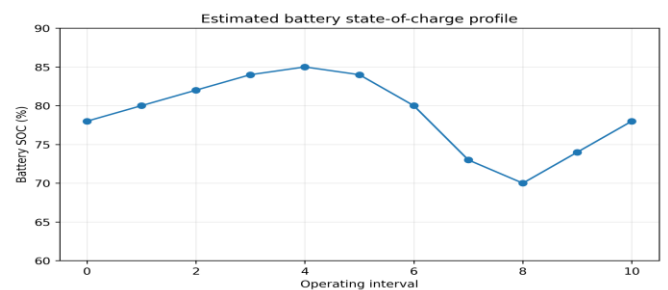


Fig. 4. Estimated battery state-of-charge profile during representative operating intervals. Values are simulated/estimated and are not experimental measurements.

The estimated SOC changes between approximately 70% and 85% during the representative cycle. This range illustrates controlled energy buffering without assuming a complete battery charge or deep discharge. For journal publication, the SOC estimation method must be stated explicitly, together with the battery rating, initial SOC, current measurement method and test duration.

10.4 Estimated converter efficiency

Converter efficiency is another important performance indicator for a hybrid DC microgrid because losses in the PV, battery and fuel-cell interfaces directly affect the useful energy delivered to the load. An illustrative efficiency profile is shown below. The final manuscript should calculate efficiency from simultaneous input and output power measurements using $\eta = P_{out}/P_{in} \times 100$.

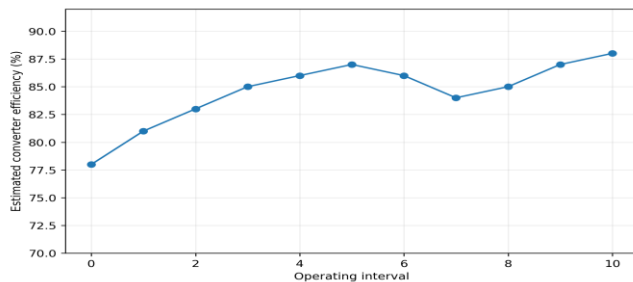


Fig. 5. Estimated converter efficiency over representative operating intervals. Values are simulated/estimated and are not experimental measurements.

10.5 Estimated performance summary

Parameter	Estimated value	Final journal measurement required
PV power range	28–92 W	PV voltage/current under different irradiance levels
Representative load	50–55 W	Actual load power and load profile
DC-bus voltage	23.70–24.08 V	Measured bus voltage and ripple
Battery SOC range	70–85 %	Measured/estimated SOC with stated algorithm
Converter efficiency	78–88 %	Measured input/output power
PV rating	100 W	Actual panel datasheet and operating measurements

10.6 Discussion and publication requirements

The estimated results support the feasibility of the proposed operating concept, but they do not by themselves validate the implemented prototype. For journal submission, the experimental section should report the hardware ratings, measurement instruments, sampling interval, test duration, irradiance conditions, battery chemistry/capacity, PEM fuel-cell rating, converter ratings and controller thresholds. The measured results should then be compared with the estimated trends shown above. In addition, quantitative comparison with recent hybrid DC microgrid or renewable energy-management studies would help establish the research contribution.

Accordingly, the manuscript can be developed into a journal paper after replacing the estimated figures with measured prototype data and adding quantitative validation.

The estimated efficiency varies from approximately 78% to 88%, suggesting that the converter stages should be evaluated over a range of operating points rather than at a single nominal load. These values are illustrative only and should be replaced with measured efficiencies for the actual converter hardware.

The ESP32–MQTT–Node-RED monitoring architecture and the coordinated PV/battery/fuel-cell energy-management strategy provide the basis for the implementation contribution described in the manuscript.

XI. ADVANTAGES AND PRACTICAL LIMITATIONS

The hybrid configuration provides multiple energy paths and can reduce dependence on a single intermittent source. Solar energy can be prioritized, the battery can buffer short-term variations, and the PEM fuel cell can act as an additional source when required. The ESP32 and Node-RED combination also provides a low-cost platform for measurement, control and visualization.

However, the prototype has practical limitations. The actual performance depends on the ratings and characteristics of the selected PV panel, battery, fuel cell and converters.

Fuel-cell activation and response depend on the specific PEM fuel-cell system. Accurate SOC estimation may require a more advanced battery-management method than simple voltage thresholds, especially under dynamic load conditions. Converter efficiency, sensor accuracy, communication latency and protection design also influence overall system behavior.

XII. FUTURE SCOPE

- Implementation of a more advanced MPPT algorithm and comparison of tracking performance under changing irradiance.
- Integration of a dedicated battery-management system with cell-level voltage and temperature monitoring.
- Improved SOC and SOH estimation using coulomb counting, model-based estimation or data-driven methods.
- Adaptive energy-management logic that considers predicted solar generation and load demand.
- Addition of data logging and historical analytics in Node-RED for efficiency and battery-life evaluation.
- Expansion to bidirectional DC loads or vehicle-to-home/vehicle-to-grid style research at an appropriate power level.
- Development of a larger-scale prototype after validating the laboratory-scale architecture and protection strategy.

XIII. CONCLUSION

The proposed real-time hybrid solar-PEM fuel-cell DC microgrid integrates renewable generation, electrochemical storage, auxiliary fuel-cell generation, power electronics, embedded control and IoT monitoring in one coordinated system. A 12 V, 100 W solar panel is used as the primary renewable source, while the battery provides energy buffering and the PEM fuel cell provides supplementary support. The ESP32 supervises measurements and operating decisions, whereas the converter stages perform the high-current switching and regulation.

MQTT and Node-RED provide a practical real-time monitoring interface for observing source power, battery condition, DC-bus voltage, load demand, temperature and operating mode.

The design also reflects the importance of battery reliability. The reference study emphasizes failure recognition, battery testing, lifetime prediction and monitoring, while identifying thermal protection, SOC/SOH monitoring and cell balancing as relevant improvement measures. The proposed microgrid applies these principles at the supervisory level through controlled charging/discharging, measurement and protection. Overall, the project provides a practical platform for demonstrating intelligent renewable-energy management and can serve as a foundation for future work involving advanced battery estimation, predictive energy management and larger DC power systems.

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