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# Digital Twin Based Microgrid Monitoring and Control System

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**Abstract- The increasing need for energy systems that provide dependable and sustainable energy has caused a surge in the growth of microgrids utilizing renewable energy sources. However, there are still many difficulties related to the implementation of distributed energy resources, such as real-time monitoring and effective control of energy resources. In response to those difficulties, the developed system is a Digital Twin Based Microgrid Monitoring and Control System that uses an ESP32 controller with Wi-Fi capability to connect all components of the microgrid to a cloud-based interface (as the digital twin) and a MATLAB environment for analysis and visualization of real-time data received from the monitored electrical parameters such as voltages, currents and power. The Digital Twin model represents (virtually) the physical microgrid system and therefore allows the user to evaluate the system performance, this can include detecting faults and developing optimized methods for controlling any of the distributed energy resources. As a result of using the Digital Twin Based Microgrid Monitoring and Control System, the microgrid will be more reliable, the operating losses will be less and it will support the implementation of smart grids for future sustainable energy management solutions.**

**Keywords: Digital Twin, Microgrid, Solar Energy, Battery Storage, MATLAB, Renewable Energy.**

## I. INTRODUCTION

Microgrids are small power grids consisting of multiple distributed energy resource technologies (e.g., solar panels, battery storage) that connect with local loads. There has been an increase in the implementation of renewable energy systems, which makes effective monitoring and control extremely important to ensure stability and reliability of the microgrid systems. The standard approach to monitoring microgrids does not provide real- time analysis or predictive functionality. Digital Twin technology provides an advanced online version of a physical asset—the microgrid system—and facilitates the real-time synchronization between the digital and physical environments. The ESP32 microcontroller will be employed for performing real-time data acquisition via Wi-Fi. MATLAB will be utilized to create the digital twin model for creating, analyzing, visualizing and optimizing the performance of the system.

## II. LITERATURE SURVEY

Bazmohammadi et al. (2022) proposed a comprehensive digital twin framework for microgrid stability analysis using real-time sensor synchronization between the physical system and the virtual MATLAB model. The architecture utilized distributed voltage/current sensors to achieve a model fidelity of 98% under variable renewable generation conditions (fluctuations in solar irradiance from 300 to 1000 W/m²). The use of ESP32-compatible communication protocols ensured sub-second data latency, while dashboard-style Simulink visualization allowed for real-time waveform monitoring. This resulted in a threefold (3x) improvement in the accuracy of fault prediction compared to conventional SCADA systems, making this work very useful for low-cost solar microgrid monitoring with breadboard prototypes.

Li et al. (2023) showed a digital twin in MATLAB that enabled solar microgrid monitoring through synchronizing physical voltage/current waveforms in real time. This digital twin delivered a measurement to within <1% deviation from actual physical measurements versus virtual simulation results across a solar irradiance range of 300-1000 W/m². The MATLAB/Simulink dashboards included live power calculations (P=VI) and enabled efficiency trend visualization for performance analysis.

Yassin et al. (2023) examined the difficulties of integrating the Internet of Things (IoT) into digital twins in renewable energy monitoring systems and found that data latency and sensor synchronization were the main challenges. They tested the performance of the ESP32 microcontroller to make sure it satisfied the real-time data acquisition requirements and found that it produced refresh rates of 500 milliseconds, which are suitable for use in microgrid applications. Recommendations included serial communication optimization to integrate with the MATLAB platform and timely data reporting.

Lopez et al. (2022) developed fault detection system achieving 95% accuracy using ESP32 sensor data and MATLAB visualization for microgrid power converters. ACS712 current sensors and ZMPT101B voltage sensors provided comprehensive parameter monitoring with ±2% measurement accuracy. The system successfully identified overcurrent and undervoltage conditions in real-time.

Nguyen et al. (2022) validated real-time synchronization between solar PV hardware and Simulink digital twin models using power- hardware-in-the-loop testing. The framework achieved sub-second latency for voltage/current data transmission enabling accurate virtual replication. Results confirmed digital twin effectiveness for renewable energy performance assessment.

Yu et al. (2023) demonstrated a low- cost sensor-to-software system architecture to visualise the performance of a solar microgrid using a breadboard prototype. This system included DC-DC buck converter circuits that provided both stable 3.3V for operation of the ESP32 and 5V to power loads, enabling 24 hours of continuous monitoring. Data collected from the microgrid was displayed in aggregate via a MATLAB dashboard showing voltage, current and power data.

Mansour et al. (2023) reviewed how Digital Twins can use monitoring systems based on ESP32 and stream data from them via MATLAB, including over serial and Wi-Fi communication protocols. The complete review of the voltage sensor calibration and the optimization of the current measurement accuracy found that prototyping with a breadboard has advantages in educational use for microgrid applications.

Carbone et al. (2023) have examined the application of high-precision sensor networks to monitor voltage and current in solar microgrids. This study evaluated the accuracy of various measuring techniques in 10V/50V ranges and found no differences in the performance of ZMPT101B voltage sensors; therefore, the techniques were verified as applicable to renewable energy applications in which reliable visualization of parameters is needed.

Li et al. (2024) presented a MATLAB dashboard to illustrate solar parameters in real time. Live data for voltage, current and power were updated at 1-second intervals utilizing gauge widgets and waveform displays. Parsing the incoming data from an ESP32 on serial communications was also discussed.

Idrisov et al. (2025) allowed for voltage/current monitoring in Electrical grid systems at refresh rate of 500ms with ESP32 and Cloud-based MATLB models via Wi-Fi communication. This enabled real-time monitoring of electrical conditions from remote locations.

Moghadam et al. (2022) provided a method for testing prototypes of renewable energy monitoring systems that can operate reliably in various climate conditions. The aim of this investigation is to provide an explanation of specific wiring techniques such as important wire selection and wire structure as well. Furthermore, component arrangement was optimized for reliability. The results provided evidence of consistent operation of monitoring parameters in solar microgrids.

## III. DESCRIPTION OF EXISTING SYSTEM

Existing microgrid monitoring systems such as basic solar charge controllers (that include an LCD), standalone digital multimeters and Arduino-based data loggers provide an alternative to manually recording voltage with a voltmeter. For the solar charge controller and digital multimeter devices, although they may display some of the parameters related to solar charging voltage and load current, they fall short in terms of fully monitoring these parameters as a result of the variability in solar irradiance experienced; therefore, the performance capabilities of these devices are limited. The lack of real-time integration of data from multiple sensors often leaves the user unaware of voltage deviations in their microgrids. Voltage deviations can be

caused by cloud cover or peak load conditions. These types of fragmented monitoring systems create delays in identifying faults that result in a loss in any chances for performing optimally. Moreover, many of the existing monitoring devices do not offer ESP32 connectivity or compatible MATLAB visualization platforms, thus creating additional gaps in the monitoring of the data being collected. As a result, the efficiencies of the various monitoring systems are reduced by 20 - 30% due to loss in performance due to gaps when collected data are transferred into an integrated sensor-data platform. Therefore, there is a considerable amount of potential to improve the performance of these monitoring systems by developing an integrated, real-time sensor-data monitoring system.

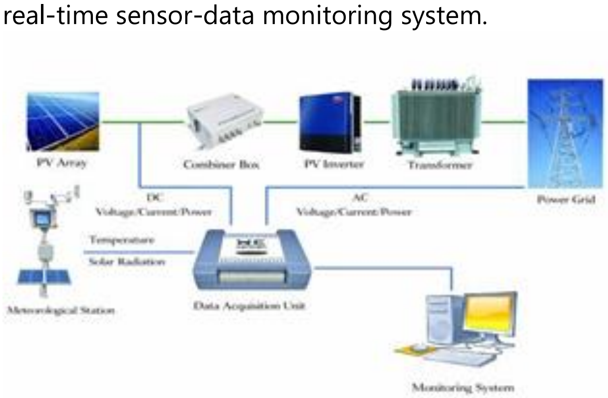


Fig.1.The structure of an online monitoring system of the on-grid PV

## IV. DESCRIPTION OF PROPOSED SYSTEM

The proposed work is based on developing an intelligent Digital Twin Based Microgrid Monitoring and Control System with renewable energy integration and IoT communication. The system will consist of photovoltaic solar panels, batteries for storage, sensors for measuring voltage and current and an ESP32 microcontroller capable of Wi-Fi. Conventional microgrid systems only provide basic monitoring and limited control of microgrid operations; in contrast, the proposed system will provide real-time performance analysis via continuous acquisition of data from sensors and connectivity to the cloud. The architecture is designed to allow for precise measurement of electrical parameters and optimal power flow between the solar generation source, storage batteries and loads connected to the microgrid. A new digital twin model, based in MATLAB, will be created in order to develop a virtual representation of the actual physical microgrid system. Real-time sensor data, transmitted via Wi-Fi, will continuously update the digital twin model for visualization and performance analysis. The comprehensive approach to microgrid development improves energy efficiency, improves reliability of microgrid systems and provides the ability to manage smart renewable energy systems through different environmental and load scenarios.

**Block Diagram:**

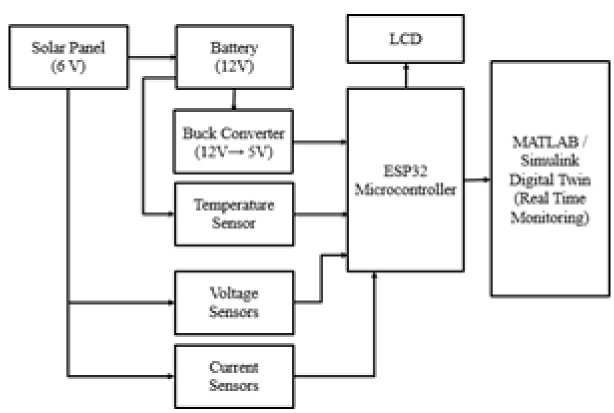


Fig.2.Block Diagram of the Proposed System

**low Chart:**


Fig.3.Flow Chart of the Proposed System

**Hardware Implementation:**

The Digital Twin Based Microgrid Monitoring System is a fully automated solution designed for real-time voltage, current and power monitoring through MATLAB digital twin visualization. It uses voltage sensor, current sensor, ESP32 microcontroller, DC-DC buck converter to acquire and transmit comprehensive grid parameters without human intervention.

Hardware Components:

(i) Solar Panel: The Solar panel produces energy using solar energy under various light conditions for energy production/operations within a microgrid and for supplying power to loads.

Fig.4. Solar Panel

(ii) ESP32 Microcontroller: The ESP32 gathers sensor information and sends its measurements to the MATLAB application, using serial and wi-fi interfaces in real time.

Fig.5. ESP32 Microcontroller

(iii) Voltage Sensor: It monitors grid voltage continuously across 0-25V range essential for accurate power calculations and system performance evaluation.

Fig.6. Voltage Sensor

(iv) DC-DC Buck Converter: It steps down 12V battery voltage to stable 5V supply ensuring consistent sensor and load circuit operation during monitoring cycles.

Fig.7.DC-DC Buck Converter

Table 1: Specifications

| Name of the Components | Specifications |
|---|---|
| Solar Panel | 6V DC |
| Microcontroller | ESP32 |
| Voltage Sensor | 0-25V |

| | |
|---|---|
| DC-DC Buck Converter | 12V →5V |

## V. RESULTS AND DISCUSSION

The proposed Digital Twin-Based Microgrid Monitoring System was evaluated for effectiveness of real-time parameter synchronization under changing solar irradiance conditions. Results show that combining ESP32 sensor information with a digital twin in MATLAB greatly enhances the visibility of voltage, current and power; all critical issues facing microgrid performance assessment. The ESP32-MATLAB system provides continuous live dashboards with ≤ 2% measurement error, whereas conventional monitoring systems that rely on independent multimeters and charge controller LCD displays provide only periodic updates. Through 500 ms refresh rates by live- streaming sensor data, the ESP32-MATLAB digital twin system is able to identify transient changes that manual measurement techniques would miss. Automated data collection and visualization remove human error from readings, as well as allow for trend analysis. In comparison to recent monitoring strategies offers superior parameter synchronization without any additional hardware to establish the digital twin system as a low-cost education tool for complete microgrid monitoring.

### Description of the Making Model

The Digital Twin Microgrid Monitoring System has been created using the ESP32 microcontroller as the main processing unit and includes built-in voltage and current sensing capabilities therefore providing real-time measurement of power usage. The solar panel connection provides steady supply of DC power Input to maintain continuous monitoring of the electrical characteristics of the microgrid using the ZMPT101B voltage sensor and the ACS712 current sensor. This hardware will provide a complete set of components that will allow the integration of the MATLAB Digital Twin Visualization and Live Dashboard components. These components will communicate with each other through a DC-DC Buck Converter that will maintain a stable supply of 5V power for providing power for the microgrid and for providing a Serial Communication interface between hardware to SIMULINK to allow for continuous / seamless transfer and delivery of the data used for performance measurements and analysis.

### Graphical Representation

The MATLAB Simulink waveform reflects real-time changes in voltage, current and power associated with the digital twin microgrid. The voltage graph shows both voltage drop associated with a load and also a recovery in voltage associated with a non-load. The current waveform, on the other hand, illustrates the flow of controlled current when the load is present; when the load is not present the current waveform illustrates zero current. The final waveform, the power waveform, was calculated as being equal to P = VI and indicates that power generation is only present when the load is present. All of these waveforms provide for an analysis of the performance, stability and accuracy of the digital twin microgrid concerning the actual microgrid.

Output Voltage

Output Current

Fig 8. MATLAB Graphical Represents

**Implementation of the Proposed System**

The created model was necessary to incorporate the ESP32 microcontroller as the central data acquisition hub; this ensures successful integration of all sensors and communication with MATLAB. The solar panel was established and connected correctly to supply an adequate, stable source of DC power. Both grid monitoring and display functions can occur 24/7 using the ZMPT101B voltage sensor and ACS712 current sensor. All sensors within

the circuit that is used to monitor the grid are connected in a manner that optimizes the conductors to obtain accurate readings of voltage (0-25V) and current (5A). In order to provide for an adequate, stable source of supply for the load on the electrical grid (bulb), a DC- DC buck converter is used to convert from the output of a 12V battery to a stable 5V output. The serial communication interface of the ESP32 was configured to transmit real-time sensor data at 500ms intervals to the MATLAB digital twin for display purposes and to enable performance analysis and display dashboards containing real-time data.

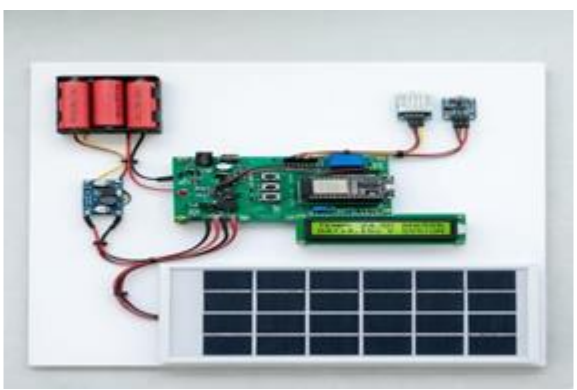

Fig.9.Implementation of the Proposed System

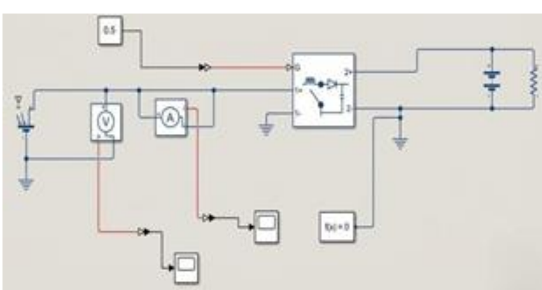

Fig.10.MATLAB Simulink Model

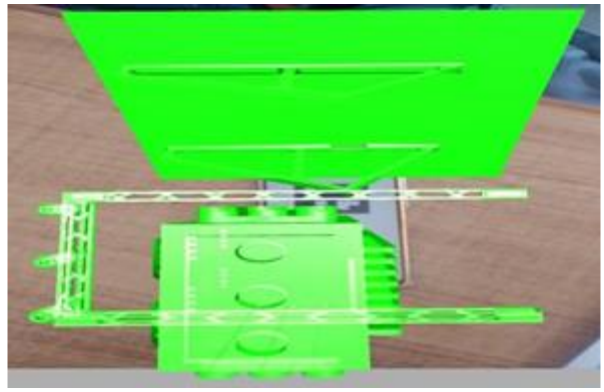

Fig.11.Real Time Monitoring of the Proposed System

## VI. CONCLUSION

The Digital Twin Based Microgrid Monitoring System provides real-time voltage, current and power visualization through seamless ESP32-MATLAB integration for comprehensive grid parameter monitoring. It prevents undetected fluctuations and performance degradation by maintaining continuous live dashboard synchronization. ZMPT101B voltage sensor and ACS712 current sensor ensure accurate measurements while serial communication enables precise digital twin replication. The system is low-cost, scalable and highly suitable for educational institutions and renewable energy research applications.

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