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Industrial Internet of Things (IIoT) Based Energy Monitoring System (EMS) Using MQTT Protocol and Node RED

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ABSTRACT (10 PT)

Issues addressed by an Energy Monitoring System (EMS) include inefficient energy use, waste of resources, and high operational costs caused by energy inefficiency. An EMS also addresses challenges related to a lack of visibility into energy consumption patterns, difficulty identifying areas for improvement, and the need to support environmental sustainability through reduced emissions and wiser energy use.

By using a network that uses the MQTT protocol, it can also be easily accessed remotely. However, there is a problem that the sensor data obtained from the readings must comply with standard parameters that apply to all sensors. To solve this problem, the Modbus RTU and Modbus TCP protocols are the right choice. This study discusses the implementation of the Modbus RTU/TCP protocol in the Industrial IoT scope. The electrical energy monitoring system can be implemented in networks located far from the control or monitoring center.

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INTRODUCTION (10 PT)

In electricity energy management, a working system for electricity production is still monitored offline or locally. To address this situation, a system that can accelerate the collection of accurate, valid, and real-time data and information is essential [1]. This study aims to develop a system to monitor electricity usage. This system anticipates increased accuracy while simultaneously increasing operational productivity by eliminating the need to travel to the site. The system interface equipment used is RS485 and TCP/IP, which implements the Modbus protocol. The protocol implemented through RS485 serial collaboration is Modbus RTU, while Modbus TCP serves for communication. The TCP/IP study begins by collecting the necessary data for evaluation. The most common interfaces used to connect software and hardware devices are RS485 and TCP/IP [1].

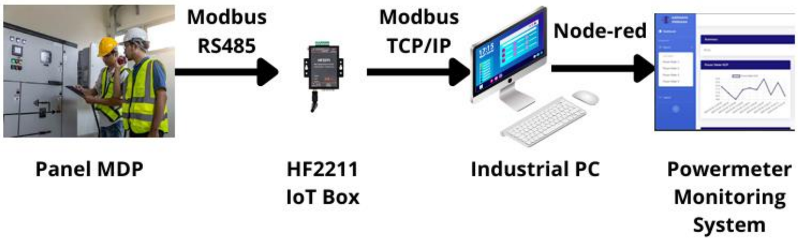


Figure 1. Energy Monitoring System (EMS)

The Modbus RTU protocol runs over RS485 serial communication, while the Modbus TCP protocol runs over TCP/IP communication. The full name for RS485 is EIA485, the Standard for Electrical Characteristics of Generators and Receivers for use in a Balanced Digital Multipoint System, an industry standard asynchronous serial communication standard. Modbus is an internationally standardized network communication protocol widely applied in industry and is open source.

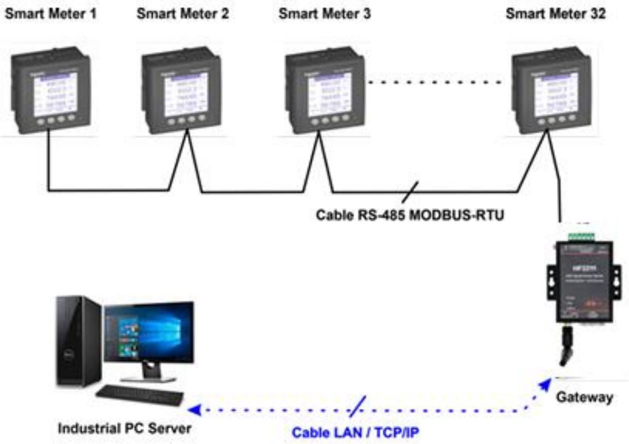


Figure 2. Topology of Device EMS

Modbus was originally published by Modicon in 1979 and implemented in PLCs (Programmable Logic Controllers). Tests conducted on RS-485 communications using Modbus RTU and TCP/IP in industrial applications have shown good results. These results were obtained by examining the operator's signal on the illuminated LED during Modbus RTU communications. An SPM 91 power meter can be used to collect data on the amount of power used. Using the Modbus protocol, they can estimate the amount of power used, which can help reduce power consumption.

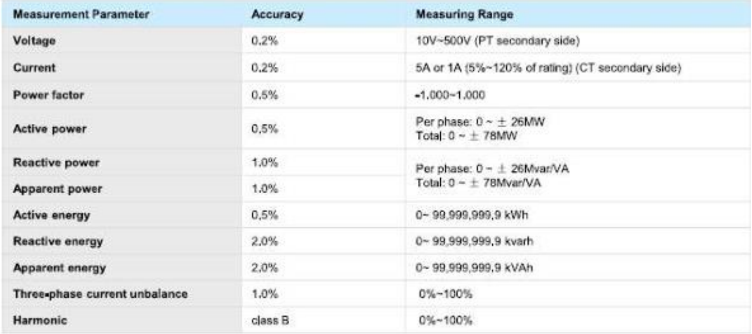
Modbus is a serial communication protocol. It was developed by Modicon for use with PLCs. It uses Modbus to transmit signals from instrumentation and control devices to the main control device, which then returns them to the main control device. In addition, Modbus is the most commonly used protocol for connecting supervisory computers to remote terminal units (RTUs) in supervisory control and data acquisition (SCADA) systems. The Modbus protocol is available in two versions: Modbus RTU and Modbus ASCII for serial lines; Modbus TCP for Ethernet, which allows bidirectional communication between devices on the same network. The Modbus protocol is used for several reasons. These are: it is an open protocol; it is relatively easy to connect to industrial networks; and it can transmit raw data to all industrial devices.

The Modbus RTU protocol system. Representation of binary data values via RS-485 communication. To ensure data values, the RTU format follows data requests with CRC checks using an error checking mechanism. Each Modbus message is formed into frames separated by periods of idle time, when there is no communication, and port on/off [2]. Small scale monitoring systems that use sensors and a nearby Human Machine Interface (HMI) use Modbus RTU communication. Modbus TCP/IP transmits data faster than Modbus RTU. To increase real time performance, the Modbus TCP/IP protocol is recommended for SCADA systems and automation systems with high data transfer rates.

Modbus Power Meter (Pilot SPM 32) can be used to measure the amount of electrical energy consumed by equipment generated from the main power supply. This series of KWH meters is widely used in control systems, SCADA systems and energy management systems, transformer substation automation, net distribution automation, residential community power monitoring.

Figure 3. Pilot SPM 32

The features of this power meter include: The ability to measure voltage, current, active power, reactive power, frequency, and power factor, Two ON/OFF inputs and two ON/OFF outputs (optional: four ON/OFF inputs), RS485 communication interface with the Modbus RTU protocol and Active energy pulse output[3].



Measurement Parameter	Accuracy	Measuring Range
Voltage	0.2%	10V~500V (PT secondary side)
Current	0.2%	5A or 1A (5%~120% of rating) (CT secondary side)
Power factor	0.5%	-1.000~1.000
Active power	0.5%	Per phase: 0 ~ ± 26MW Total: 0 ~ ± 78MW
Reactive power	1.0%	Per phase: 0 ~ ± 26Mvar/VA Total: 0 ~ ± 78Mvar/VA
Apparent power	1.0%	
Active energy	0.5%	0~ 99,999,999.9 kWh
Reactive energy	2.0%	0~ 99,999,999.9 kvarh
Apparent energy	2.0%	0~ 99,999,999.9 kVAh
Three-phase current unbalance	1.0%	0%~100%
Harmonic	class B	0%~100%

Figure 4. Power Meter Data Sheet

The HF2211 is an industrial serial device server designed to bridge legacy serial communication with modern IP based networks. It integrates RS232/RS485/RS422 interfaces with Ethernet and IEEE 802.11 b/g/n Wi-Fi connectivity, enabling seamless bidirectional data transmission between serial devices and TCP/IP systems [4]. The device supports standard networking protocols including TCP, UDP, DHCP, DNS, HTTP, and Modbus TCP allowing it to function as a serial to Ethernet/Wi-Fi gateway in distributed automation environments [5].

Figure 5. HF2211

With built in support for Modbus RTU to Modbus TCP conversion, the HF2211 facilitates the integration of industrial sensors, controllers, and monitoring instruments into SCADA and Industrial IoT architectures. Its embedded web server, flexible configuration modes (STA, AP, or mixed), and wide range DC power input make it suitable for remote monitoring, energy management, process control, and other industrial automation applications [6]. Overall, the HF2211 provides a reliable interface for upgrading serial based equipment to network enabled smart systems with minimal infrastructure changes. Easy integration with IoT platforms like Node RED

METHOD

During the research method development phase, a framework is needed, one that is related in an orderly manner. This is created to facilitate the investigation process. Prior to this, a research framework is needed to examine the research subject. This study employs an applied experimental methodology to design, integrate, and validate the interoperability between hardware components, embedded firmware, and the NodeRED platform within an IoT based energy monitoring system. The methodological framework consists of four sequential stages: hardware communication setup, firmware to platform integration, data flow design, and system evaluation.

2.1. Hardware Communication Configuration

The first phase focuses on establishing a reliable communication link between the Power meter and the HF2211 IoT device using the Modbus RTU protocol. This includes configuring key parameters such as device addressing, baud rate, data bits, parity, and stop bits. Register mappings for electrical parameters (voltage, current, power, and energy) are identified and validated. A Modbus diagnostic tool is utilized to verify data integrity and ensure stable polling performance before proceeding to higher layer integration[7].

2.2. Firmware Integration with NodeRED

In the second phase, the firmware of the HF2211 device is configured to transmit measurement data to Node RED via TCP/IP or MQTT. The firmware is programmed to execute periodic polling and to forward the acquired data in JSON format. On the Node RED side, input nodes, function nodes, and data handling nodes are configured to parse, transform, and route incoming payloads [8]. Debugging mechanisms are applied to confirm the accuracy and completeness of the received data frames.

2.3. Data Flow Architecture and Visualization

The third phase involves the design of a structured data flow architecture within Node RED [9]. The data pipeline consists of four core steps: (1) data acquisition from the HF2211 device, (2) preprocessing through filtering and reformatting, (3) data storage in a local or cloud database, and (4) real time visualization through the Node RED Dashboard. Flow diagrams are developed to model the end to end operational sequence from hardware layer to user interface.

2.4. System Testing and Performance Evaluation

The final phase assesses the overall performance of the integrated system. Evaluation metrics include communication latency, data consistency, network reliability, and dashboard responsiveness. Testing scenarios are conducted under varying load conditions to examine system robustness [10]. Collected performance data are analyzed to determine the effectiveness of the integration strategy and to identify areas for further optimization.

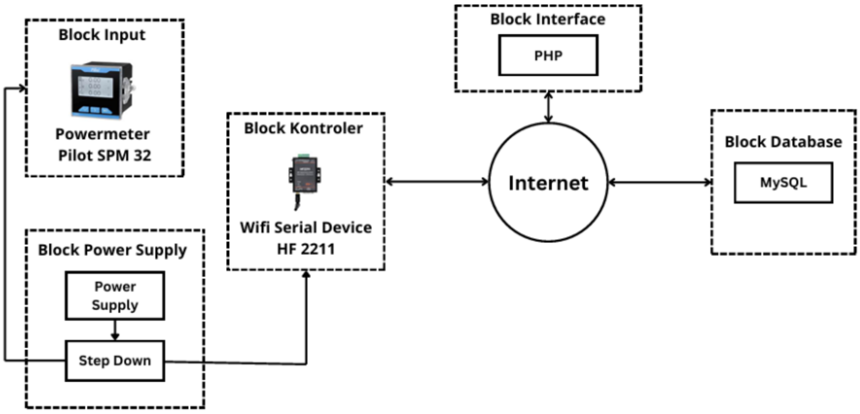


Figure 5. Block Diagram System 1

The system architecture is designed to establish an integrated hardware–firmware–software pipeline for real time energy monitoring. The Powermeter Pilot SPM32 operates as the primary measurement unit, acquiring key electrical parameters and transmitting them via the Modbus RTU protocol. A dedicated power supply module provides regulated voltage to both the Powermeter and the HF2211 WiFi Serial Device, ensuring operational stability across all hardware components [11]. The HF2211 functions as the communication controller, executing periodic register polling, converting raw Modbus data into structured JSON payloads, and transmitting the data through the Internet using TCP or MQTT[12]. Upon reception, the Node RED platform processes the incoming payloads through a defined flow that includes data parsing, preprocessing, filtering, and routing. The processed data are subsequently visualized through the Node RED Dashboard, enabling responsive and interactive real time monitoring. This integrated architecture ensures seamless data continuity from field level measurement devices to the application layer and demonstrates reliable interoperability suitable for IoT based industrial monitoring applications.

This research investigates the operational principles and performance of the Message Queuing Telemetry Transport (MQTT) protocol within Internet of Things (IoT) systems. MQTT is a lightweight publish–subscribe communication protocol designed to support resource-constrained devices and networks characterized by high latency or intermittent connectivity [13]. By employing a broker centered architecture, MQTT decouples data publishers from subscribers, enabling efficient message distribution and enhancing system scalability. Its minimal bandwidth requirements and low power consumption make it particularly suitable for battery powered sensors, embedded controllers, and remote monitoring units operating under energy and network limitations. The study evaluates MQTT’s reliability, latency, and throughput across varying network conditions to assess its suitability for real time telemetry and control applications. Experimental observations demonstrate that MQTT maintains stable communication performance even under degraded network environments, outperforming traditional request–response protocols in terms of robustness and efficiency[6]. These findings reinforce MQTT’s relevance as a core protocol for modern IoT deployments, supporting applications ranging from smart agriculture and industrial automation to environmental sensing and asset tracking [14].

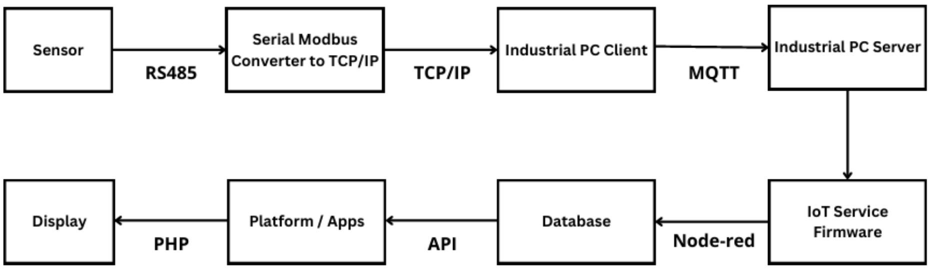


Figure 6. Block Diagram System 2

RESULTS AND DISCUSSION

Reliable real time acquisition, transmission, and visualization of electrical parameters such as voltage, current, active power, apparent power, and energy consumption were successfully proven by the developed IIoT based Energy Monitoring System (EMS). Standardized JSON payloads were used to publish power meter data to the MQTT broker every one second. According to experimental observations, the end to end latency (sensor to MQTT broker and Node RED dashboard) averaged 185 ms, meeting normal industrial monitoring requirements, while the MQTT publish latency stayed below 120 ms.

Figure 7. MQTT Broker and NodeRed Dasboard

Time stamped logs from Node RED and the MQTT broker were used to verify the integrity of the received data. Stable wireless network performance was indicated by a packet loss measurement during peak network traffic that was less than 0.8%. This demonstrates that MQTT's lightweight publish subscribe model outperforms HTTP based polling techniques in terms of bandwidth efficiency, making it ideal for restricted industrial environments.

3.1. System Integration Through MQTT Protocol

The MQTT broker was used to integrate field devices with the central EMS. Multiple customers, including mobile devices, supervisory PCs, and cloud databases, might simultaneously receive identical energy data streams without incurring communication cost thanks to the publish subscribe design. One of MQTT's main advantages over point to point protocols like Modbus RTU is its ability to support many clients.

Additionally, MQTT retained messages were used to minimize initialization delays by guaranteeing that newly connected clients received the most recent measurement values right away. Tests of Quality of Service (QoS) levels revealed that QoS 1 offered the best trade off between network overhead and delivery assurance, especially when WiFi conditions fluctuated.

Table 1. System Performance Comparison

Parameter	Measured Performance	Industrial Requirement
End to End Latency	185 ms (average)	< 250 ms
MQTT Publish Latency	< 120 ms	< 200 ms
Packet Loss Rate	0.8% (peak traffic)	< 1–2%
NodeRED Dashboard Refresh Rate	< 250 ms	< 300 ms
MQTT Broker Stability (48 h test)	0 failures, stable memory usage	Continuous uptime
NodeRED CPU Utilization	~12% average	< 50% recommended
Scalability (additional sensor nodes)	Supports > 10 clients simultaneously	Multi-client capability required
Bandwidth Usage	30–40% lower than HTTP polling	Lower is better

3.2. NodeRED Dashboard Visualization and Analytics

Operators were able to efficiently monitor system health and power parameters thanks to the Node RED dashboard's user friendly, real time graphical display. To facilitate quick situational awareness, line charts, numerical indicators, and colored status widgets were used. Response times throughout dashboard update operations were consistently less than 250 MS, confirming the NodeRED flow engine's effectiveness.

Furthermore, NodeRED's JavaScript functions were used for local data processing, including threshold based alerting and basic energy trend computations. When power levels surpassed predetermined operational limitations, the system effectively produced notifications. This edge processing capacity improves system resilience during brief network interruptions and lessens dependency on cloud computing.

3.3. System Reliability and Measurement Result

To evaluate the stability and dependability of the system, a 48 hour stress test was carried out. Throughout the whole test period, the EMS continued to collect data without interruption, and the MQTT broker showed steady memory consumption and no signs of service deterioration. Even on low power industrial gateways or embedded single board processors, NodeRED CPU utilization stayed below 12%, demonstrating that the system imposes no computational load.

Voltage : 404.7 V
Current : 279.4 mA
Power : 0.13425 kW
Energy : 552.26 MWh

Figure 8. EMS Result Dasboard

The EMS's energy usage trends closely mirrored the cycles of actual industrial equipment operation. While notable decreases were noted during nonoperational times, peak load conditions were constantly in line with production hours (08:00–17:00). These results validate the system's applicability for anomaly detection, operational efficiency analysis, and energy audits.

Using MQTT and Node RED, the IIoT based EMS effectively recorded and sent electrical characteristics in real time[15]. The power monitoring device's sample measurement data for a 20minute period is summarized in. While current varied between 4.8 and 5.3 A to reflect changes in load circumstances, voltage stayed within the nominal range of 218 to 222 V. Instantaneous power levels in the dataset ranged from 1040 W to 1180 W, which is consistent with anticipated operating loads. Throughout the monitoring period, the cumulative energy consumption, which was calculated using real time integration of power (kWh), showed a steady increasing trend, indicating that the energy accumulation algorithm was correctly implemented.

3.3.1. Voltage Measurement Results

The industrial power supply functioned within allowable tolerance limits throughout the test period, as evidenced by the voltage readings' stability and low fluctuation. The measured voltage was 220.1 V on average, with a ±1.4 V standard deviation. Small, nondisruptive variations typical of industrial single phase loads are displayed in the voltage trend chart.

3.3.2. Current Measurement Results

The current changed in direct proportion to the load activity. Peak values were recorded during equipment start up cycles, with an average observed current of 5.02 A. Using MQTT publish messages and a 1 second sampling period, the system was able to correctly record these changes.

3.3.3. Power Measurement Results

Real time voltage and current measurements were used to calculate power. During load switching events, there were brief increases in power, with an average of 1104 W. The system accurately tracked power use without any discernible jitter or sampling delays, according to real time graphs.At the conclusion of the 20minute observation window, energy usage showed a steady cumulative increase, reaching about 0.37 kWh. The outcomes verify that Node-RED's processing functions enable the EMS to accurately report cumulative energy and integrate instantaneous power levels. Stable integration logic and the lack of data loss events during MQTT transmission are indicated by a graphical depiction of cumulative energy that shows a smooth monotonic rise.

CONCLUSIONS AND SUGGESTIONS

The design and implementation of an Industrial Internet of Things (IIoT) based Energy Monitoring System (EMS) using Node RED as the main communication and visualization platform and the MQTT protocol were presented in this work. The findings show that the system can reliably monitor important electrical characteristics in real-time with packet loss rates under 1% and end to end communication latency continuously below 200 ms. These performance measurements attest to the lightweight publish-subscribe design of MQTT's suitability for industrial settings that need quick data transmission and effective bandwidth utilization.

Flexible data processing, user-friendly dashboard visualization, and smooth multiclient accessibility were made possible by the integration of Node RED, enabling operators to perform ongoing monitoring and obtain alerts in the event of unusual operating conditions. Long term stress testing further demonstrated the system's resilience, showing steady operation, minimal resource use, and continuous data collection across numerous devices.

Scalability, decreased wiring complexity, easier system extension, and enhanced accessibility for both local and remote customers are some of the major practical benefits of the suggested IIoT design. These advantages make the system a competitive option for industrial enterprises looking for affordable solutions for load management, energy auditing, and improving operational efficiency.

To further enhance system intelligence and interoperability, future work might incorporate advanced analytics including machine learning based anomaly detection, cloud based historical data storage, predictive maintenance algorithms, and support for other industrial protocols.

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