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IoT application-based remote monitoring and control system for a smart microgrid

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Resumen

En las últimas décadas, la monitorización ha cobrado mayor relevancia en aspectos clave para el correcto funcionamiento de los equipos e instalaciones. En el ámbito industrial, los sistemas de monitorización son esenciales para obtener un flujo constante de información. Sin embargo, estos sistemas suelen implementarse localmente, limitando su acceso desde fuera de la red local donde se encuentran. Actualmente, el auge del Internet de las Cosas Industrial (Industrial Internet of Things, IIoT) ofrece aplicaciones y herramientas para superar estas limitaciones. Este artículo presenta un sistema de monitorización y control remoto basado en aplicaciones de software enmarcadas en el contexto del IoT para una microrred inteligente alimentada con energía renovable e hibridada con hidrógeno verde. La microrred se compone de un conjunto de paneles fotovoltaicos, una carga electrónica programable y un sistema de generación, almacenamiento y consumo de hidrógeno mediante un electrolizador de membrana de intercambio protónico (Proton Exchange Membrane, PEM), tanques de hidruro metálico y una pila de combustible PEM, respectivamente. El funcionamiento del sistema propuesto se basa en la interacción de tres elementos: un controlador lógico programable (Programmable Logic Controller, PLC), que recopila información de un conjunto de sensores instalados en la microrred inteligente; la aplicación móvil Telegram, mediante la cual se implementa la interfaz gráfica de usuario (Graphical User Interface, GUI); y el software Node-RED, un middleware de IoT que facilita el intercambio de datos y la comunicación entre los demás elementos. El manejo del sistema se realiza a través de la GUI y se gestiona mediante un bot de Telegram, a través del cual se visualizan las variables y se controla el equipo. Además, el sistema incluye mensajes de alarma asociados a eventos anómalos que requieren la intervención del operador.

Abstract

In the last decades, monitoring has increased its relevance within the main aspects to maintain a correct operation of the equipment or installation. In the industrial field, monitoring systems are essential to obtain a constant flow of information from the installation. Nevertheless, these systems tend to be deployed locally, limiting their access outside the local network where they are implemented. Nowadays, the rise of the Industrial Internet of Things (IIoT) provides applications and tools dedicated to overcoming these barriers. This paper presents a remote monitoring and control system based on software applications framed in the IoT context for a smart microgrid powered with renewable energy and hybridized with green hydrogen. The microgrid is composed of a set of photovoltaic panels, a programmable electronic load and a hydrogen generation, storage and consumption system by means a Proton Exchange Membrane (PEM) electrolyzer, metal hydride tanks and a PEM fuel cell, respectively. The operation of the proposed system is based on the interaction between three elements: A Programmable Logic Controller (PLC), which collects in-formation from a set of sensors installed in the smart microgrid, the Telegram mobile application, through which the Graphical User Interface (GUI) is implemented, and the Node-RED software, an IoT middleware that facilitates data exchange and communication between the other elements. The handling of the proposed system is approached through the GUI and managed by a Telegram bot, through which the visualization of the variables and the control of the equipment are commanded. Additionally, the system includes alarm messages associated with anomalous events that require the operator's management.

Keywords: Industrial Internet of Things, Remote Monitoring and Control, Smart Microgrid, Node-RED, Telegram.

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1. Introduction

One of the most disruptive current technological advances lies in the Internet of Things (IoT). This term is applied to describe a set of interconnected sensors or devices through the Internet. In recent years, this paradigm has impacted numerous sectors, leading to the development of IoT-based applications and infrastructures, for instance, in the field of medicine (Bhuiyan et al., 2021; Minh Dang et al., 2019; Habibzadeh et al., 2020), telecommunications (Nguyen et al., 2022), and the energy sector (Folgado et al., 2023; Motlagh et al., 2020, Calderón et al., 2024).

In the energy framework, smart grids and microgrids (Dileep, 2020) stand out as installations based on the interaction of power equipment for generation, storage, transportation, and energy management. Currently, these facilities tend to utilize renewable energy sources and integrate IoT-based technologies for equipment management (González et al., 2022; Goudarzi et al., 2022, Calderón et al., 2024). These systems are characterized by a high density of information to be managed, stemming from the diversity of sensors and actuators that gather data and act upon the process. Therefore, the presence of monitoring and control systems is essential in these installations (Motlagh et al., 2020).

In renewable energy-based facilities, such as smart grids and microgrids, the supervisory function is of paramount importance, as previously mentioned. This function is performed through monitoring systems based on a server that collects and stores data acquired from field devices, such as PLCs or remote terminal units (RTUs).

By means of graphical interfaces, commonly referred to as Human-Machine Interface (HMI) or Graphical User Interface (GUI), the operator of the monitored facility is provided with real-time information about the current status of the process (instantaneous values) and with data on the previous evolution over time (historical and trend values). Furthermore, a relevant ability of monitoring systems deals with alarm generation for abnormal operation or deviations with respect to the nominal ranges of the tracked variables. Data transmission between these nodes and the monitoring systems is carried out via industrial networks through communication protocols such as Modbus TCP, PROFINET, etc. It must be noted that a recent trend in monitoring systems is providing online remote access. Thus, the operator is able to observe real-time and historical data in a distant manner, even, allowing for informed decision making, which maximizes the proper management of the process.

Currently, an increasingly popular approach to developing monitoring systems is based precisely on the use of IoT hardware and software. Integrating the IoT environment into energy systems facilitates remote monitoring and efficient energy management (González et al., 2022). Open-source IoT applications offer versatility, applicability, usability, low cost, and broad internet support, among other advantages. To support microgrid applications, IoT technology offers significant opportunities for sensing, communication, processing, and actuation (González et al., 2022).

In this context, Node-RED stands out as an open-source tool for data integration and the development of monitoring interfaces, based visual programming built on Node.js and started in 2013. Its flow-based architecture simplifies the connection between industrial devices and IT systems, allows for the management of lightweight protocols such as MQTT, and enables the creation of customizable dashboards without the need for proprietary software. These features make Node-RED a flexible and cost-effective solution for monitoring applications. It is user-friendly middleware that combines visually intuitive design with drag-and-drop blocks and connections.

On the other hand, Telegram is an instant messaging application created in 2013. It is known for its speed, cloud synchronization, and focus on privacy, allowing users to send messages, photos, videos, and files, as well as make voice and video calls. Among its most notable features are large group chats, broadcast channels, automated bots, and end-to-end encryption for secret chats. Furthermore, Telegram is cross-platform, allowing users to access conversations from multiple devices simultaneously.

The use of Telegram bots in remote monitoring systems has emerged as an efficient and low-cost solution for real-time monitoring and management of distributed infrastructures. These bots, developed using the Telegram API, enable the automatic transmission of alerts, operational data, and control commands through a widely accessible and secure messaging platform. From a technical and scientific perspective, their implementation facilitates integration with IoT devices, monitoring systems, and data acquisition platforms, enabling interoperability between sensors, microcontrollers, and remote servers. Furthermore, the use of HTTPS protocols and token-based authentication mechanisms helps ensure the integrity and confidentiality of the transmitted information. Several studies report that incorporating Telegram bots into industrial and environmental monitoring environments improves responsiveness to critical events, reduces fault detection times, and optimizes predictive maintenance processes, thus making them a relevant tool for automation and smart telemetry applications.

In this paper, the design and implementation of a monitoring and control system for a smart microgrid based on renewable energies hybridized with hydrogen are presented. The described system relies on IoT technologies, employing Node-RED software as the core of the system and the Telegram messaging system as the GUI. Additionally, the components of the smart microgrid and their interaction with the monitoring and control system are described. Finally, the implementation of this system is reported through experimental results.

The structure of the rest of the manuscript is as follows. In Section 2, the components that comprise the smart microgrid are described, along with their operation. The working principles and functions performed by Node-RED and Telegram are also detailed. In Section 3, the results obtained from the implementation of the proposed system are reported. Finally, the main conclusions of the work are presented.

2. Methods and Materials

2.1. Smart microgrid

As mentioned in the previous section, a smart microgrid can be defined as an electrical grid based on the interaction of various small-scale power devices. The term "smart" refers

to microgrids that are self-managed through dedicated elements, such as PLC (Lawrence et al., 2016). These PLCs play a crucial role in the autonomous operation and control of the microgrid.

The smart microgrid employed in this work consists of two systems: a main system based on renewable energies and a secondary system based on hydrogen. In the main system, the primary electrical generation is achieved through a set of 6 photovoltaic (PV) panels arranged in three pairs connected in parallel. The energy generated by this array is stored using a Lithium-Ion (Li-Ion) battery and consumed by a programmable electronic load. This load represents the main energy demand of the microgrid, and its programming allows for adjusting various demand profiles to simulate a multitude of scenarios.

The secondary system, or energy support system, consists of a hydrogen generation subsystem based on a Proton Exchange Membrane (PEM) Electrolyzer (PEMEL). The generated hydrogen is stored in metal hydride bottles and consumed by the secondary electrical generation system by means of a PEM Fuel Cell (PEMFC). Figure 1 illustrates the systems that comprise the smart microgrid and the interaction between its components.

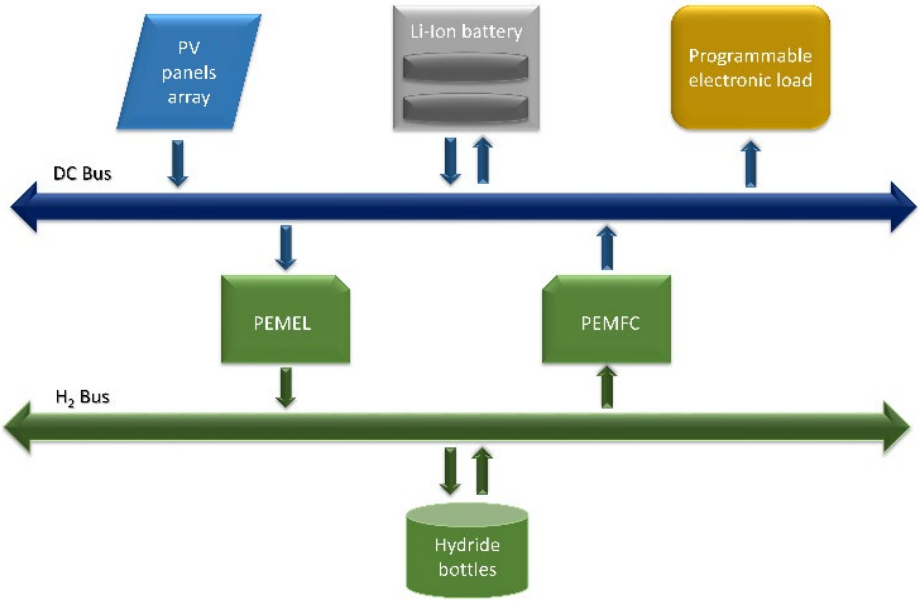


Figure 1: Smart microgrid.

The operation principle of the microgrid can be described through two distinct scenarios: energy surplus and energy deficit. In the first case, the generation from the PV panels exceeds the demand imposed by the electronic load. The surplus energy is then stored in the Li-Ion battery. If this situation persists and the battery is charged beyond a set upper limit, the excess energy is transferred to the support system, where it is used to generate and store hydrogen.

In the situation of energy deficit, the generation from the PV panels fails to meet the demand imposed by the load. As a result, the battery supplies the remaining energy to balance the generation-demand equation. If this situation continues and the battery is discharged below a set lower limit, the secondary electrical generation system comes into operation. Thus, the PEMFC consumes the stored hydrogen to generate the remaining energy required by the load.

2.2. Node-RED

Node-RED is an IoT software dedicated to the interconnection of physical devices, APIs, and online services (Node-RED n.d.). This tool is known for its graphical programming philosophy using blocks or nodes.

Node-RED allows you to establish intuitive connections by graphically linking these nodes using virtual cables. Each node has specific functionality and characteristics and can be oriented towards receiving information (input), sending data (output), or both operations.

This visual programming approach is achieved through a web-based programming environment where all the tools and nodes are available to the user.

For this work, Node-RED has been employed as the central element of the monitoring and control system. In this role, the software performs four main functions:

- Reading data from the equipment that constitutes the smart microgrid through a network of sensors and actuators managed by PLCs.
- Sending the read data to the Telegram GUI for monitoring by the user.
- Reading and managing user instructions/commands from the Telegram GUI.
- Writing/sending control commands to the PLCs of the smart microgrid.

Figure 2 illustrates the operating principle of the monitoring and control system, indicating the main functions performed by Node-RED and the flow of information among them.

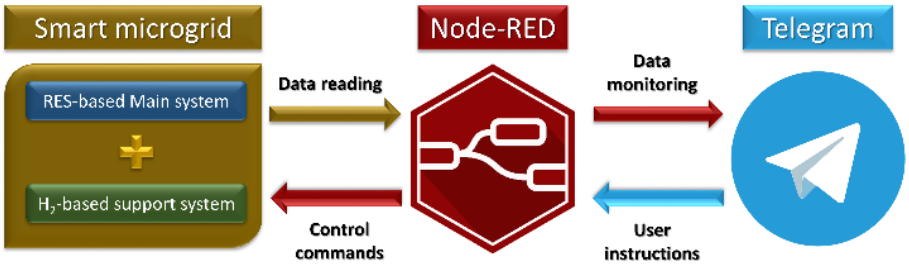


Figure 2: Node-RED main functions and working principle of monitoring and control system.

2.3. *Telegram*

Telegram is a cloud-based messaging application with constant synchronization for electronic devices (Telegram n.d.). This application stands out for its ability to develop and implement bots. Bots are programs integrated within Telegram, enabling specific functions or tasks to be carried out through third-party programs. For this project, the Botfather program from Telegram has been utilized to implement a bot that allows interaction with Node-RED through a Telegram chat. This chat establishes a communication channel between Node-RED and the user while enabling a GUI for monitoring and controlling the smart microgrid.

The operation principle of the GUI is based on navigation through various tabs, which display information to the user through text messages in the chat. When any text is sent in the chat, the main hub tab is displayed, indicating the other specific tabs for each of the systems forming the microgrid. To navigate to a particular tab, the user must enter the corresponding number in the chat. The rest of the tabs in the GUI are as follows:

- System Overview: This tab presents key variables for each sub-system, grouping the information into DC Bus and H2 Bus. It provides an overview of the microgrid's components and their status.
- PV Panels: This tab illustrates information related to the primary electrical generation system, including meteorological data such as wind speed or incident irradiance on the PV panels.
- Battery: Displays data relating to the Li-Ion battery such as input current or state of charge (SoC) as well as the microgrid DC bus voltage.
- PEM Electrolyzer: This tab represents key variables of the hydrogen generation system based on the PEMEL.
- PEM Fuel Cell: Displays data related to the operation of the secondary electrical generation system using the PEMFC.

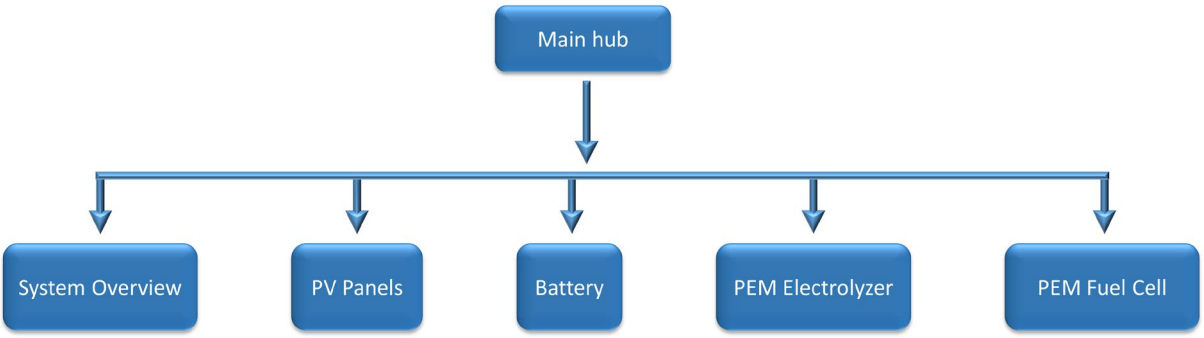


Figure 3: Telegram-based GUI navigation tree.

3. Implementation and Results

To implement the proposed monitoring and control system, the installation has been previously equipped with a set of sensors and actuators. These devices are managed by three PLCs that group the following microgrid systems: primary electrical generation, electrical storage, and consumption; hydrogen generation; secondary electrical generation and hydrogen storage. The PLCs are interconnected through an Ethernet-based network. Simultaneously, Node-RED employs the same protocol to communicate with all three PLCs and acquire data on the operation of the smart microgrid.

Figure 4 depicts the components grouped under each of the PLC, along with the flow of information and the communication protocols employed.

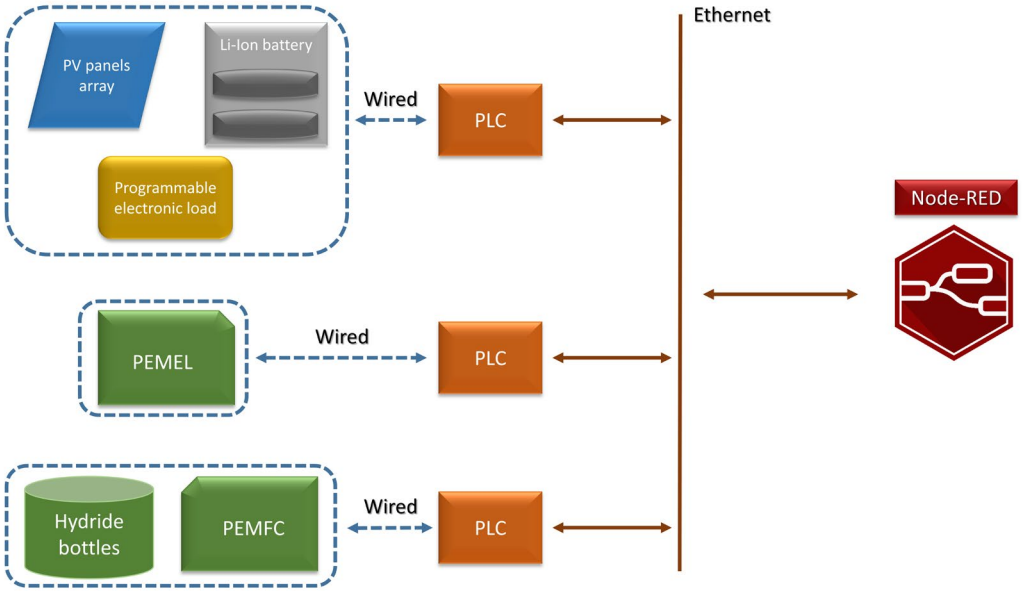


Figure 4: Grouping of smart microgrid components including data acquisition and communications.

Once the data from the smart microgrid has been collected, the user can utilize the Telegram GUI, named "REPLICA_SMG," to monitor and control the installation. Figure 5 displays the initial message of the Telegram chat corresponding to the "Main hub" tab.

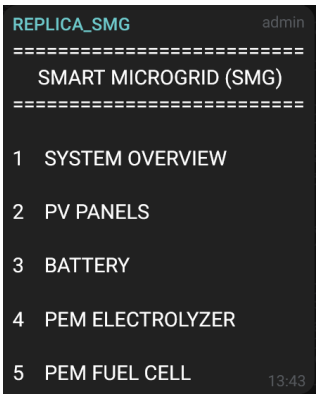


Figure 5: Main hub tab displayed on Telegram chat.

As an operational example, Figure 6 illustrates the "PV Panels" tab, presenting the instantaneous values of the current from the panels before (I_BMPPT) and after (I_AMPPT) the Maximum Power Point Tracker (MPPT), along with the PV panels voltage. Addition-ally, environmental conditions are displayed in correlation with irradiance, wind speed, and ambient temperature. Lastly, the average operating temperature value of each panel is shown.

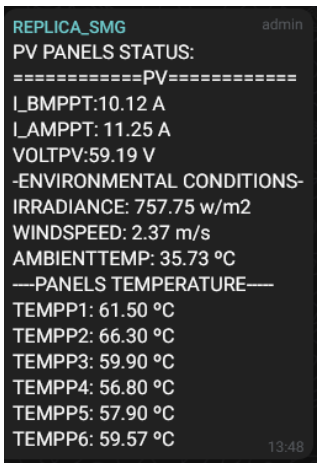


Figure 6: PV Panels tab displayed on Telegram chat.

Finally, the control feature of the proposed system over the smart microgrid is exemplified in Figure 7, where a fragment of the “PEM Electrolyzer” tab is displayed, showing the user the possibility to start or halt the hydrogen generation system by introducing a chat command.

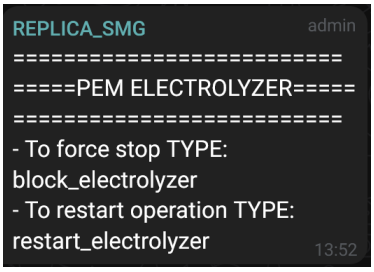


Figure 7. PEM Electrolyzer tab control commands on Telegram chat.

Once experimentally validated the proposed remote monitoring via Node-RED and Telegram, some advantages and disadvantages are commented. To begin with, concerning advantages, it must be remarked three main aspects. The first one is the wide availability of communication protocols supported by the middleware Node-RED, which explains its increasing introduction in industrial and energy-related

facilities. Secondly, both Node-RED and Telegram are free, which reduces the expenditures associated with monitoring systems. The last advantage is related to ubiquitous access provided by the Telegram app. In other words, the user can remotely access to information about the status of the microgrid in every moment from every place and using different devices (smartphones, tablets and computers can execute the Telegram app), facilitating the continuous monitoring of the process. Even, control commands can be sent, avoiding displacements to the physical plant and reducing response time when facing anomalous situations.

Regarding disadvantages of the proposal, two issues are emphasized. Despite the visual-programming features of Node-RED, certain programming expertise is required for low-level configurations. Another limitation is referred to the long-term stability of the developed system, which has not still been tested.

4. Conclusions

This article has presented a monitoring and control system based on IoT applications for a smart microgrid powered by renewable energies hybridized with hydrogen. The proposed system utilizes Node-RED as the core for reading and managing information from the microgrid, as well as handling control commands sent by the user. Additionally, Telegram provides the user with an intuitive GUI dedicated to monitoring the information and serves as a channel for communicating the user's desired actions regarding the microgrid.

As lines of future work, the implementation of alarms associated with key variables of the smart microgrid for display via Telegram is proposed. Furthermore, it has been considered extending the control commands available to the user, as well as the possibility of modifying numerical variables to modify the microgrid process.

Acknowledgements

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