Implementation Of Fuzzy Logic Control System For Oxyhydrogen Generators

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An HHO generator produces a mixture of hydrogen and oxygen gas through the electrolysis process, requiring reliable monitoring and control to ensure safe and efficient operation. This study presents the development of an IoT-based monitoring and control system for an HHO generator using a fuzzy logic approach. The system employs voltage, current, and temperature sensors integrated with an ESP32 microcontroller to acquire real-time operating data. Sensor calibration was conducted by comparing sensor outputs with standard measuring instruments, and the results showed low error values with high accuracy, indicating reliable sensor performance. The measured data are transmitted and visualized in real time through the Blynk IoT platform. A fuzzy logic controller was implemented to automatically control the generator operation based on voltage, current, and temperature conditions. Experimental results demonstrate that the proposed system operates stably, provides accurate monitoring with a reading accuracy of over 98%, and effectively enhances operational safety. The developed system is suitable for small-scale experimental and research applications of HHO generators.

Keywords: HHO Generator, Fuzzy Logic, IoT, Parameter Control, Electrolysis.

I. INTRODUCTION

The global energy demand continues to increase as industrial activity and transportation systems expand. At the same time, dependence on fossil fuels raises serious environmental concerns, including greenhouse gas emissions and air pollution. As a result, renewable and environmentally friendly energy technologies have become an important focus of research[1].

Hydrogen-based energy systems have attracted significant attention due to their high energy density and clean combustion characteristics. One practical approach to hydrogen utilization is the Hydrogen–Hydrogen–Oxygen (HHO) generator, which produces a mixture of hydrogen and oxygen gases through water electrolysis. HHO generators have been widely applied in automotive workshops and small-scale industrial systems as supplementary fuel devices to improve combustion efficiency[2].

Despite their potential, conventional HHO generators generally rely on manual or fixed control mechanisms. This causes unstable operating conditions, particularly in voltage, current, and temperature parameters during electrolysis. The nonlinear nature of the electrochemical process often leads to current surges, voltage drops, and excessive heat generation. These conditions reduce system efficiency, shorten electrode lifespan, and increase safety risks such as overheating and gas instability[3].

Adaptive control methods are required to address these challenges. Fuzzy logic control offers advantages in handling nonlinear and uncertain systems without requiring precise mathematical models. When combined with Internet of Things (IoT) technology, fuzzy logic enables real-time monitoring and remote supervision of system parameters. Therefore, this study proposes an IoT-based fuzzy logic control system to improve the stability, safety, and monitoring capability of HHO generator operation[4].

II. LITERATURE REVIEW

A. HHO Generator

An HHO generator is an electrolysis device designed to produce a mixture of hydrogen and oxygen (HHO) gas from water. This process is very important in the development of clean energy technology, because HHO gas can be used as an alternative fuel in internal combustion engines and as an environmentally friendly energy source. The use of HHO generators is not limited to the automotive sector, but has also been applied in industry, power plants, and heating systems. The design of an HHO generator generally consists of electrodes (anodes and cathodes) immersed in an electrolyte solution, usually KOH or NaOH solution. The electric current that is passed causes water molecules to split into hydrogen and oxygen gases

that can be collected and used as needed. The efficiency of this generator is highly dependent on the quality of the electrode material, the concentration of the electrolyte, and the electrical parameters used[5].

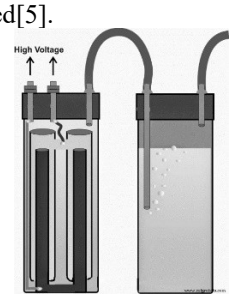

FIGURE 1
HHO Generator

HHO generator technology continues to evolve with innovations in electrode materials and electrolysis methods. Recent research shows that the use of transition metal-based catalysts such as nickel and cobalt can increase efficiency and reduce energy consumption in the electrolysis process. In addition, the development of IoT-based systems enables real-time monitoring and control of operational parameters, improving system safety and efficiency.

B. HHO Gas/Brown Gas

HHO gas, also known as brown gas or oxyhydrogen, is a mixture of hydrogen (H_2) and oxygen (O_2) gases in a 2:1 volumetric ratio produced through the electrolysis of water using direct current (DC) electricity. This process breaks down water molecules (H_2O) into their constituent elements through the chemical reaction $2H_2O \rightarrow 2H_2 + O_2$, in which electrical energy overcomes the O-H covalent bond with a theoretical minimum voltage of 1.23V, although in practice it requires 2-3V per cell due to overpotential. HHO gas is highly reactive due to the presence of oxygen, which facilitates the complete combustion of hydrogen, producing a clean flame without carbon dioxide residue.

Electrolysis for HHO production can be carried out in acidic or alkaline conditions, with electrolytes such as potassium hydroxide (KOH) or sodium hydroxide (NaOH) increasing the conductivity of the solution and the efficiency of the process. The reaction occurs at two electrodes: reduction at the cathode produces hydrogen (HER: $2H_2O + 2e^- \rightarrow H_2 + 2OH^-$), while oxidation at the anode produces oxygen (OER: $4OH^- \rightarrow O_2 + 2H_2O + 4e^-$). Transition metal-based catalysts such as nickel and iron are often used to reduce kinetic barriers and increase gas production rates, replacing expensive platinum catalysts. Process efficiency is influenced by electrolyte concentration, operating temperature, electrolysis cell design (dry cell vs. wet cell), and control of electrical parameters to prevent energy waste.

C. Electrolysis of Water

Water electrolysis is a chemical process that breaks down water molecules (H_2O) into hydrogen gas (H_2) and oxygen (O_2) with the help of an electric current. This process is key to the production of environmentally friendly and sustainable green hydrogen. Water electrolysis can be carried out in acidic or alkaline conditions, with the selection of the appropriate electrolyte to improve conductivity and efficiency.

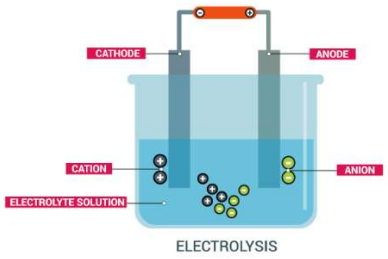

FIGURE 2
Electrolysis

The water electrolysis reaction consists of two half-cell reactions: reduction at the cathode (hydrogen evolution reaction/HER) and oxidation at the anode (oxygen evolution reaction/OER). The HER reaction produces hydrogen gas, while the OER produces oxygen gas. To accelerate these reactions, catalysts are used to reduce overpotential and increase the rate of gas production. Recent research shows that transition metal-based catalysts, such as nickel, cobalt, and iron, have great potential to replace precious metal-based catalysts due to their lower cost and abundant availability. The efficiency of the water electrolysis process is influenced by various factors, including electrolyte concentration, temperature, pressure, and electrolysis cell design. Recent innovations in water electrolysis technology, such as the use of membranes and magnetic field-based systems, have successfully increased efficiency and reduced energy consumption. In addition, the development of renewable energy-based water electrolysis systems is also a major focus of current clean energy research.

D. Electrical Parameters

The main electrical parameters in HHO generator operation are voltage and current. Voltage determines the amount of energy required to start the electrolysis process, while current determines the rate of HHO gas production. The greater the current, the more gas is produced, but system efficiency and safety must be considered. Monitoring electrical parameters is very important to maintain the performance and reliability of the generator. Too low a voltage will not be able to start the electrolysis process, while too high a voltage can cause damage

to the electrodes and inefficient energy consumption. High current can increase the rate of gas production, but it can also cause overheating and corrosion of the electrodes.

Electrical parameters can be optimized by adjusting the electrolyte concentration, temperature, and electrolysis cell design. Research shows that the use of dynamic voltage and current control techniques can increase efficiency and reduce energy consumption in the water electrolysis process. In addition, real-time monitoring of electrical parameters also enables early detection of system malfunctions or damage, thereby improving operational reliability and safety.

E. Internet of Things (IoT)

Internet of Things (IoT) refers to a technological paradigm that enables physical devices to be connected via the internet, allowing automatic and real-time data collection, communication, and control. In HHO generator applications, IoT technology is utilized to monitor key operating parameters such as voltage, current, and temperature during the electrolysis process using various sensors integrated with microcontrollers and communication modules. The implementation of an IoT-based monitoring system enables continuous observation of the HHO generator operating conditions and provides remote access to system data, thereby reducing the need for manual monitoring while improving measurement accuracy and operational efficiency. Real-time data transmission supports faster decision-making, particularly in maintaining safe operating limits and preventing system overheating or electrical overload. Several studies indicate that IoT-based monitoring systems can enhance system reliability, operational safety, and performance consistency, making IoT an essential component in the development of intelligent and modern HHO generator systems.

F. Microcontroller

A microcontroller is a compact computing system that integrates a processor, memory, and input-output peripherals on a single chip, enabling control and data processing tasks in embedded systems. In IoT-based HHO generator applications, the microcontroller functions as the main control unit responsible for processing sensor data, executing control algorithms, and managing communication between sensors, actuators, and IoT platforms. The microcontroller enables real-time monitoring of critical HHO generator parameters such as voltage, current, and temperature, as well as the implementation of control strategies, including fuzzy logic-based decision making. In addition, microcontrollers support wireless data transmission through integrated or external communication modules, allowing remote monitoring and control of the HHO generator. Low power consumption, flexibility, and ease of programming make microcontrollers suitable for continuous operation in HHO generator systems, particularly when combined with renewable energy sources.

G. Sensor

Sensors are devices used to detect and measure physical parameters, then convert them into electrical signals that can be processed by a microcontroller or control system. In HHO generator systems, sensors play a crucial role in monitoring operating parameters such as voltage, current, and temperature during the electrolysis process. These parameters are essential indicators of system performance, efficiency, and operational safety. The use of sensors enables real-time data acquisition, allowing continuous monitoring of the HHO generator and early detection of abnormal operating conditions. When integrated into an IoT-based system, sensor data can be transmitted wirelessly for remote monitoring and analysis. The reliability and accuracy of sensors significantly affect overall system performance, as precise measurements are required to support effective control strategies, protect system components, and ensure stable and safe HHO gas production.

H. Fuzzy Logic

In fuzzy logic, truth values are not limited to two states (true or false) but can have continuous degrees of truth between 0 and 1, reflecting uncertainty in data or information. Fuzzy logic is rooted in the theory of fuzzy sets developed by Zadeh. This theory allows for the representation of imprecise or unclear data through membership functions, which define how much an element belongs to a fuzzy set[6]. For example, in the context of temperature control, a temperature can be considered “warm” with a certain degree of membership, rather than simply ‘warm’ or “not warm.” In fuzzy logic, truth values are not limited to 0 (false) or 1 (true) but can take on continuous values between the two. Some of the basic formulas and concepts used in fuzzy logic are Membership Functions, Fuzzification, Fuzzy Rules, Fuzzy Operations, and Defuzzification. This process includes Fuzzification, Interference Engine, and Defuzzification. Fuzzification is the process of converting crisp inputs (definite values) into fuzzy values. Each input is grouped into a membership function that represents various levels of membership in a particular fuzzy set. The Interference Engine is the stage where fuzzy rules are applied to produce fuzzy outputs. This process involves evaluating rules in the form of if-then, where fuzzy values from inputs are used to determine output values, and Defuzzification, which is converting outputs back into crisp values that can be used for control. A commonly used

defuzzification method is the centroid method, where outputs are determined based on the center of mass of the output membership function.

III. METHOD

In this study, an IoT-based hydroponic monitoring system was created. The divisions in this design are system block diagram, hardware design, and software design.

A. System Design

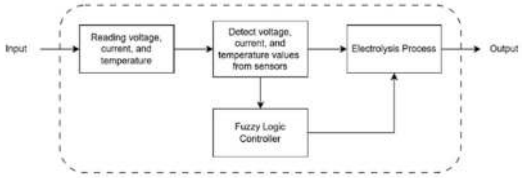

FIGURE 3
Solution Concept Design

Based on the design concept of the proposed system, the HHO generator operates by utilizing several key input parameters obtained from electrical and thermal conditions during the electrolysis process. Voltage, current, and temperature sensors are employed to continuously measure the operating state of the HHO generator in real time. The acquired sensor data are processed by an ESP32 microcontroller, which serves as the main control and data-processing unit. These parameters are then evaluated using a fuzzy logic control algorithm to determine appropriate control actions for maintaining safe and stable electrolysis conditions. Subsequently, the processed monitoring data and control outputs are transmitted to an IoT platform through a wireless network connection for data storage and analysis. The information is displayed on a monitoring dashboard, enabling users to observe voltage, current, temperature, and system status in real time, thereby improving operational safety and system supervision.

B. Functions and Features

The functions and features contained in this final project are as follows:

1. The system reads voltage, current, and temperature values from the HHO generator using dedicated sensors installed on the electrolysis system.
2. Sensor data is detected and collected by the microcontroller, representing the real-time operating conditions of the HHO generator.
3. The collected voltage, current, and temperature data are processed and used as input variables for the fuzzy logic controller.
4. The fuzzy logic controller evaluates the input parameters based on predefined fuzzy rules to determine the appropriate control decision.
5. The control output is applied to the electrolysis process, ensuring stable, safe, and optimal operation of the HHO generator under varying conditions.

C. Block Diagram

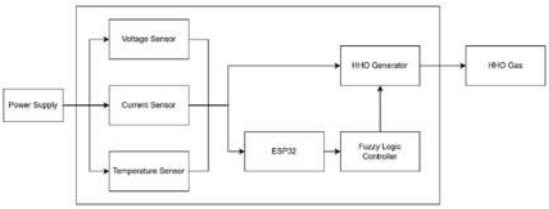

FIGURE 4
Block Diagram

Based on the block diagram, the proposed system operates by supplying electrical power from a DC power source to the HHO generator and the control system. Voltage, current, and temperature sensors are installed to continuously monitor the electrical and thermal conditions of the HHO generator during the electrolysis process. The voltage sensor measures the input voltage, the current sensor monitors the current flowing through the generator, and the temperature sensor detects heat generated during operation. All sensor data are collected and processed by an ESP32 microcontroller, which serves as the main processing and communication unit. The processed data are then evaluated using a fuzzy logic control algorithm to determine appropriate control actions for maintaining safe and stable operating conditions. Furthermore, the monitoring data and control status are transmitted to an IoT platform via a wireless network connection, allowing users to observe voltage, current, temperature, and system status in real time through a monitoring application.

IV. RESULT AND ANALYSIS

This section presents the experimental results obtained from the implementation and testing of the IoT-based fuzzy logic control system for the HHO generator. The discussion focuses on sensor calibration accuracy, system monitoring performance, fuzzy logic control behavior, and overall system reliability.

A. Sensor Calibration Result and Discussion

Sensor calibration was conducted to evaluate the accuracy and reliability of the voltage, current, and temperature sensors used in the IoT-based HHO generator monitoring system. The calibration process was carried out by comparing sensor readings with reference instruments, including a digital multimeter for voltage and current

measurements and a digital thermometer for temperature measurements. The calibration results show that all sensors exhibit relatively small error values with high accuracy, indicating good agreement between sensor outputs and reference measurements across the operating range of the system.

The current sensor demonstrated high accuracy in measuring current fluctuations during the electrolysis process, while the voltage sensor provided stable and consistent readings of the supplied voltage. Similarly, the temperature sensor was able to detect temperature variations caused by prolonged electrolysis with acceptable deviation from the reference value. Overall, the calibration results confirm that the voltage, current, and temperature sensors are suitable for reliable data acquisition and can support real-time monitoring, IoT-based visualization, and fuzzy logic control in the HHO generator system.

B. System Integration Testing

System integration testing verified that all hardware and software components—including sensors, ESP32 microcontroller, relay module, fuzzy logic algorithm, and IoT platform—worked together as a unified system. Sensor readings were first validated via the Serial Monitor before being transmitted to the Blynk dashboard. The results confirmed that sensor data acquisition, fuzzy logic processing, and relay actuation were successfully integrated without delays or system errors.

C. Real-Time IoT Monitoring

Real-time monitoring tests demonstrated the system's ability to transmit and display voltage, current, and temperature data accurately on the Blynk dashboard. The displayed values matched those shown on the Serial Monitor in both magnitude and response time. Additionally, the generator operating status was visualized using an LED indicator, providing clear and intuitive feedback regarding system conditions. This confirms the reliability of the IoT-based monitoring system.

D. Fuzzy Logic Control System Testing

The fuzzy logic control system was tested to assess its ability to make automatic decisions based on voltage, current, and temperature inputs. Under normal operating conditions, the fuzzy controller activated the HHO generator through the relay module. When abnormal conditions were detected, such as excessive current or temperature, the system automatically shut down the generator to protect system components. These results demonstrate that the fuzzy logic controller operates adaptively and effectively in real time.

E. System Performance Discussion

Overall system testing results indicate that the developed IoT and fuzzy logic-based HHO generator monitoring system performs reliably and meets the design objectives. Data consistency between local and remote monitoring platforms confirms stable data acquisition and transmission. The automatic control response enhances system safety, efficiency, and operational flexibility, making the system suitable for practical implementation.

F. HHO Generator Performance Analysis

Based on direct measurements, the HHO generator operates at 11–12 V and 6–7 A, resulting in a power consumption range of 66–84 W with an average of approximately 75 W. Using Faraday's law of electrolysis, the theoretical HHO gas production rate was calculated to be 62.9–73.2 ml/min. The generated gas pressure was estimated to be slightly above atmospheric pressure, within the range of 106–122 kPa. These results indicate that the HHO generator performance is directly influenced by operating current and is suitable for small-scale experimental and research applications

V. CONLCUSION

This study successfully developed an IoT-based HHO generator monitoring and control system using fuzzy logic. Calibration results show that the voltage, current, and temperature sensors provide accurate and reliable measurements, with low error values and high accuracy. System integration testing confirmed that all hardware and software components operate cohesively, enabling stable data acquisition, processing, and real-time visualization through the Blynk platform.

The fuzzy logic control system demonstrated effective decision-making by automatically activating or deactivating the HHO generator based on operating conditions, thereby enhancing system safety and reliability. Performance analysis indicates that the HHO generator operates at a power range of 66–84 W and produces HHO gas at a rate of 62.9–73.2 ml/min, making the system suitable for small-scale experimental and research applications.

Future research may focus on incorporating additional sensors, such as gas pressure and flow rate sensors, to improve performance analysis and system safety. Further optimization of the fuzzy logic rules or the application of alternative control strategies could also be explored to enhance system efficiency. Moreover, long-term operational testing and cloud-based data storage integration are

recommended to support advanced data analysis and real-world implementation.

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