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Safety Considerations for PEM Fuel Cell Power Generation by means of Sensor-Signal Based Algorithms

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Abstract

This paper describes sensor-signal algorithms aimed at ensuring safe and stable operation of a Proton Exchange Membrane Fuel Cell (PEMFC) framed in a renewable-energy powered smart microgrid. The developed algorithms consider operation variables such as working temperature, storage pressure, humidity presence inside the equipment, or voltage and current conditions at the PEMFC output. The purpose of these algorithms lies in maintaining an operation point within the nominal ranges of the PEMFC, avoiding anomalous states to prevent the appearance of long-term degradation mechanisms and materials deterioration and, therefore, of the useful life of the PEMFC. The execution of the algorithms are performed by a Programmable Logic Controller (PLC), which gathers and centralises the information from the sensors of the installation and controls the operating cycle of the fuel cell. The set of sensors and actuators installed are described, together with their relevance in the operation of the PEMFC. Finally, the implemented algorithms for the control of the PEMFC operation are detailed.

Keywords: Hydrogen, Fuel Cell, Proton Exchange Membrane, Automation, Safe Operation.

1. Introduction

The scarcity of fossil fuels and the increase in global energy demand have prompted research and development of technologies to harness new energy sources such as hydrogen. In the energy field, this gas is employed as an energy storage system for its subsequent transformation into electricity from devices known as fuel cells. With regard to their application, fuel cells are characterised by their complex operation and dependence on various operating parameters, resulting in a difficult implementation in a real system.

Hydrogen is an element of considerable potential that exhibits ideal characteristics for its application in various sectors. In the industrial field, its applications are particularly notable within the chemical industry, specifically in petroleum refining processes (Manna et al., 2021), as well as for the production of ammonia (Manna et al., 2021) and urea (Yuksel et al., 2022). In the field of medicine, the significance of this gas is steadily increasing (Du et al., 2020), as it finds utility in cancer treatments (Li, S. et al., 2019) and respiratory diseases (Li, Y. et al., 2020).

In recent decades, the increasing energy demand and the scarcity of fossil fuels have stimulated the development of technologies dedicated to harnessing renewable energy sources (RES), such as solar photovoltaic, wind, and hydropower. Currently, the energy sector has focused on harnessing hydrogen as a key energy carrier and a new energy source (Abdin et al., 2020). The technologies developed around this element enable its utilization in applications such as hydrogen production (Dawood et al., 2020), energy storage (Elberry et al., 2021), and energy transportation (Singh et al., 2020).

In systems such as smart grids and microgrids, hydrogen is integrated as a supportive mechanism to mitigate short and medium-term fluctuations of RES (Folgado et al., 2022; Atlam and Kolhe, 2011). In these support systems, devices called fuel cells are employed. The fuel cell is a hydrogen-based power generation device. Specifically, Proton Exchange Membrane (PEM) fuel cells (PEMFC) are used in RES-based systems due to their ability to respond rapidly to variations in input setpoints caused by RES (Feng et al., 2017).

PEMFC exhibit a complex operation influenced by a range of operational factors and variables such as working temperature and pressure, hydrogen feed flow rate or humidity presence. These parameters exert a significant impact on the device's performance and contribute to the emergence of degradation mechanisms that ultimately curtail its lifespan (Wu et al., 2008; Okonkwo et al., 2021).

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This paper describes sensors signal based algorithms aimed at ensuring a secure and stable operation of a PEMFC framed within a RES-powered smart microgrid. The developed algorithms assess the conditions of the operational variables/factors of the PEMFC to maintain an operating point within the device's nominal ranges, preventing abnormal states and mitigating the occurrence of long-term degradation mechanisms. The operation of the PEMFC and the execution of the algorithms are carried out by a Programmable Logic Controller (PLC), which centralizes the collected information from the installation, enabling prompt and appropriate actions. The set of devices involved in the operation of the PEMFC is described. Finally, the implementation of the described algorithms is illustrated by means of flowcharts.

The structure of the rest of the manuscript is as follows. Section 2 describes the PEMFC and the set of sensors and actuators employed in the power generation system. Furthermore, the control parameters utilized for effective PEMFC management are out-lined. In Section 3, the algorithms applied to ensure safe and stable operation of the PEMFC are detailed. Finally, the main conclusions of the work are reported.

2. **Materials and Methods**

This section provides a detailed description of the hydrogen-based power generation system integrated into the smart microgrid, emphasizing the operational principle of the PEMFC, as well as the network of sensors and actuators employed in the system.

2.1. PEM Fuel cell

The operational principle of the PEMFC is based on an electrochemical redox (reduction-oxidation) process. This process involves two simultaneous chemical reactions: an oxidation reaction at the anode and a reduction reaction at the cathode, expressed by Equation (1) and Equation (2), respectively.

$$H_2 \rightarrow 2H^+ + 2e^- \quad (1)$$

$$\frac{1}{2}O_2 \rightarrow 2H^+ + 2e^- \rightarrow H_2O \quad (2)$$

These sub-reactions converge to yield the overall reaction represented by Equation (3):

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O + Energy \quad (3)$$

As a result of its operation, PEMFC produces both water and energy. This energy encompasses the useful electrical energy delivered by the PEMFC and energy losses in the form of dissipated heat.

Regarding its structure, the PEMFC is composed of a set of cells arranged in series to form a stack. These cells are divided into an anode, a cathode, and a Membrane Electrode Assembly (MEA). Figure 1 illustrates the structure of a PEMFC cell, as well as the sub-reactions occurring within each of its components. Namely, the used PEMFC in this work is the Horizon H-500, composed by 24 cells, with a nominal power of 500 W, an output voltage between 18 and 36 V, an output current up to 30 A, and a hydrogen flow rate at maximum output of 6.5 L/min.

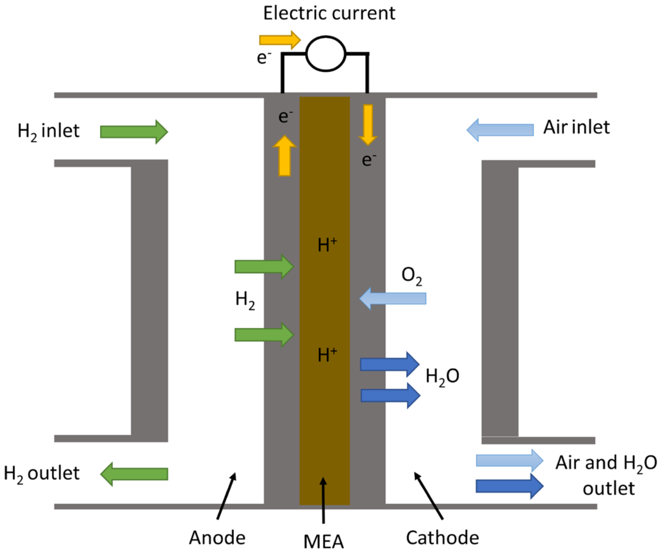

Figure 1: Structure and Operation of a PEMFC cell.

2.2. Sensors and actuators

In order to implement the algorithms and achieve a safe and stable operation of the PEMFC, it is required to gather information related to key variables that affect its operation. To this end, a set of sensors and actuators controlled by a PLC has been deployed. The following parameters have been taken into consideration: working temperature, hydrogen bus pressure, hydrogen availability, humidity presence, voltage level, and output current. Table 1 establishes the relationship between the considered control parameters and the various sensors and actuators employed.

Table 1: Control parameters, sensors and actuators employed in the PEMFC installation.

Control Parameters	**Typology**	**Type**
Working temperature	Sensor	PT-100
	Actuator	DC-fan
H_2 bus pressure	Sensor	Wika A-10
	Actuator	Electrovalve
H_2 availability	Sensor	Mass flow meter
	Actuator	Electrovalve
Water presence/moisture	Actuator	Electrovalve
Output voltage	Sensor	Potentiometric voltage divider
Output current	Sensor	Hall effect sensor

The elements indicated in Table 1 are interconnected in order to control the operation of the PEMFC and generate electricity from high-purity hydrogen. The process carried out in the hydrogen-based power generation system is described below.

First, the hydrogen stored in metal hydride bottles is conducted to the inlet of the PEMFC. During this process, the pressure of the bottles and the hydrogen inlet bus is measured by means of pressure sensors and manually regulated by a pressure regulator. Next, the hydrogen passes through an electrovalve that controls the flow of hydrogen to a mass flow meter and finally to the inlet of the PEMFC. These elements ensure proper conditions of the hydrogen bus at the PEMFC inlet. At the outlet of the PEMFC, an electrovalve controls the purging process to prevent moisture generation. During the operation of the PEMFC, two DC fans maintain an appropriate operating temperature. From an electrical standpoint, the terminals of the PEMFC are connected to a custom-made Printed Circuit Board (PCB) that measures the output voltage and current at those terminals. The voltage is adjusted using a boost-type DC/DC converter, which raises the setpoint to the voltage of the common DC bus of the smart microgrid. Lastly, the voltage and current output of the converter are measured using a PCB identical to the one located at the input of the converter. The diagram in Figure 2 depicts the described power generation system, highlighting the involved components.

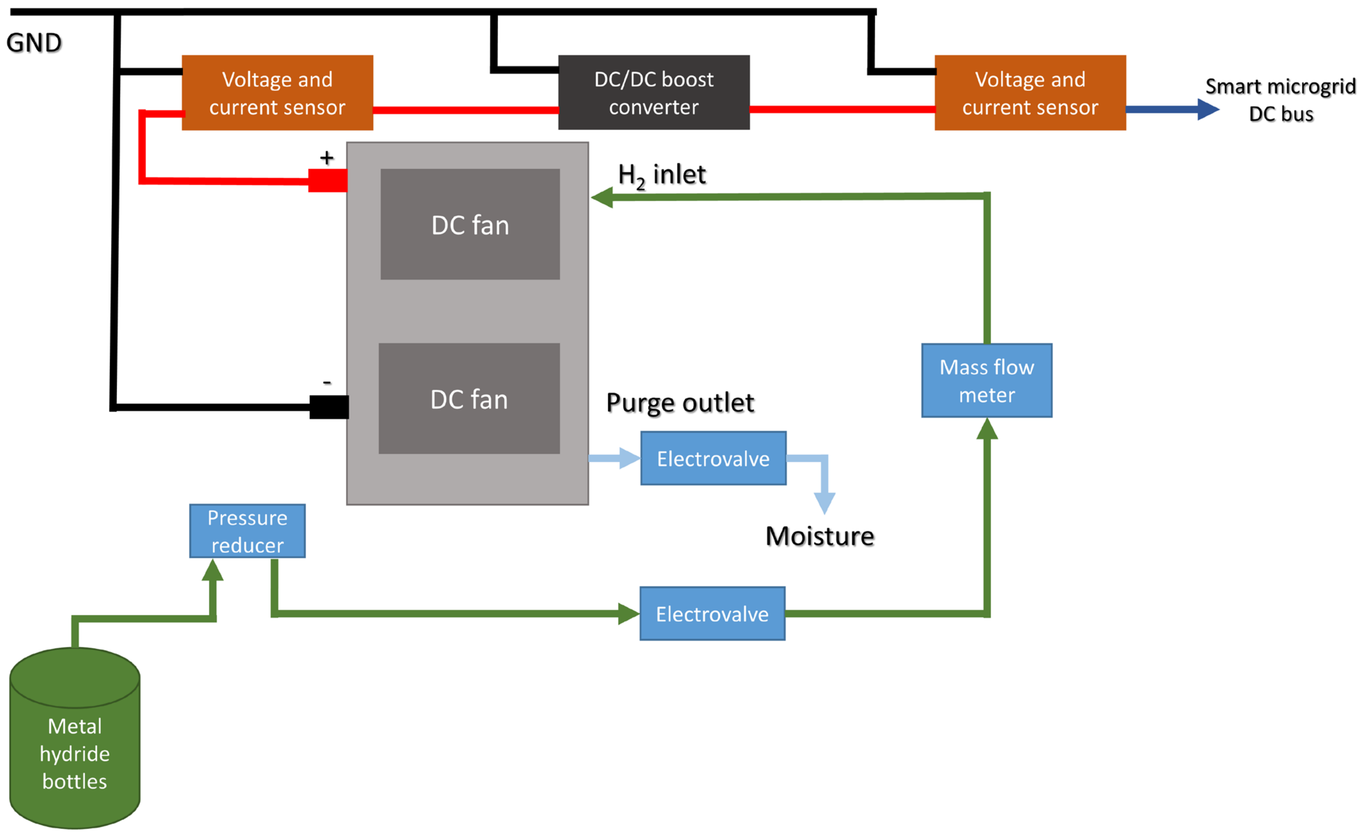

Figure 2: Power generation system based on PEMFC.

2.3. *Control parameters*

The control parameters listed in Table 1 have been carefully selected based on their influence on the operation of the PEMFC and their significance in the occurrence of degradation mechanisms.

The operating temperature of the PEMFC directly affects the device's output voltage, and consequently, the delivered power and efficiency. Furthermore, this factor is linked to the PEMFC's current density limit and the temperature distribution within the membrane, which influences water condensation and the presence of moisture (Askaripour, 2019; Patil et al., 2023).

The hydrogen bus pressure has an impact on the operation of the equipment through which the gas flow circulates. In general terms, excessively high pressure can lead to localized leaks in the involved devices. Moreover, due to hydrogen explosivity, the leaked hydrogen constitutes a serious risk to the safety of people handling the PEMFC. Specifi-cally, operating the PEMFC under high-pressure conditions results in the occurrence of mechanical degradation mechanisms, such as membrane fatigue or stress, which derive in the formation of cracks (Patil et al., 2023).

The available hydrogen flow and relative humidity are critical factors in current density, membrane drying, and electrode flooding (Guvelioglu and Stenger, 2007). The presence of moisture during PEMFC operation is associated with the occurrence of mechanical degradation mechanisms such as membrane fatigue and degradation effects on the MEA (Patil et al., 2023; Zhou et al., 2019). Finally, the control of the output voltage and current of the PEMFC is crucial to ensure a safe inter-connection with other power devices, preventing potential failures due to overvoltages or short circuits.

3. Implementation and Results

In this section, the implementation of the control algorithms for the PEMFC-based power generation system is described. These algorithms are under development at laboratory stage and being implemented to integrate the PEMFC in the microgrid operation.

3.1. Control algorithms

The working temperature of the PEMFC (T_{FC}) is determined based on the mean value of measurements obtained from two PT-100 sensors positioned at the top and bottom of the device. Temperature control is achieved through two variable-speed DC fans, whose rotation speed is contingent upon the supply voltage. During the startup of the PEMFC, if T_{FC} falls within a minimum value (T_{min}) and a median value (T_{med}), the fans are activated and operate at low speed. If the temperature rises above T_{med}, the fans switch to high-speed mode to increase airflow and dissipate heat. If T_{FC} reaches or surpasses a maximum safety temperature (T_{max}), the operation of the PEMFC is halted, while the fans continue running to lower the equipment's temperature.

Regarding the hydrogen bus pressure ($P_{H2\ Bus}$) and the available hydrogen flow rate (v), an evaluation is conducted by means of pressure sensors to determine if $P_{H2\ Bus}$ falls within the minimum (P_{min}) and maximum (P_{max}) operating values. If this condition is met, the PEMFC is activated, and the electrovalve is opened to enable hydrogen flow. During its operation, if P_{max} is reached or exceeded, or if the current flow rate value for the instant t (v_t) varies by ±10% from the previous value (v_{t-1}), the PEMFC is halted, and the electrovalve is closed to block hydrogen passage.

The control of moisture/water presence is managed through the purging process. For this purpose, an electrovalve is employed, which carries out a cyclic opening-closing sequence based on an internal counter within the PLC that is triggered upon reaching a fixed time (t_p).

Finally, information regarding voltage and current is acquired both before and after DC/DC boost converter. The interconnection between the PEMFC and the smart microgrid DC bus is safeguarded through automatic overcurrent and overvoltage protection mechanisms, ensuring reliable operation. Figure 3 illustrates the control algorithms using flowcharts and displays the equipment used in the power generation system.

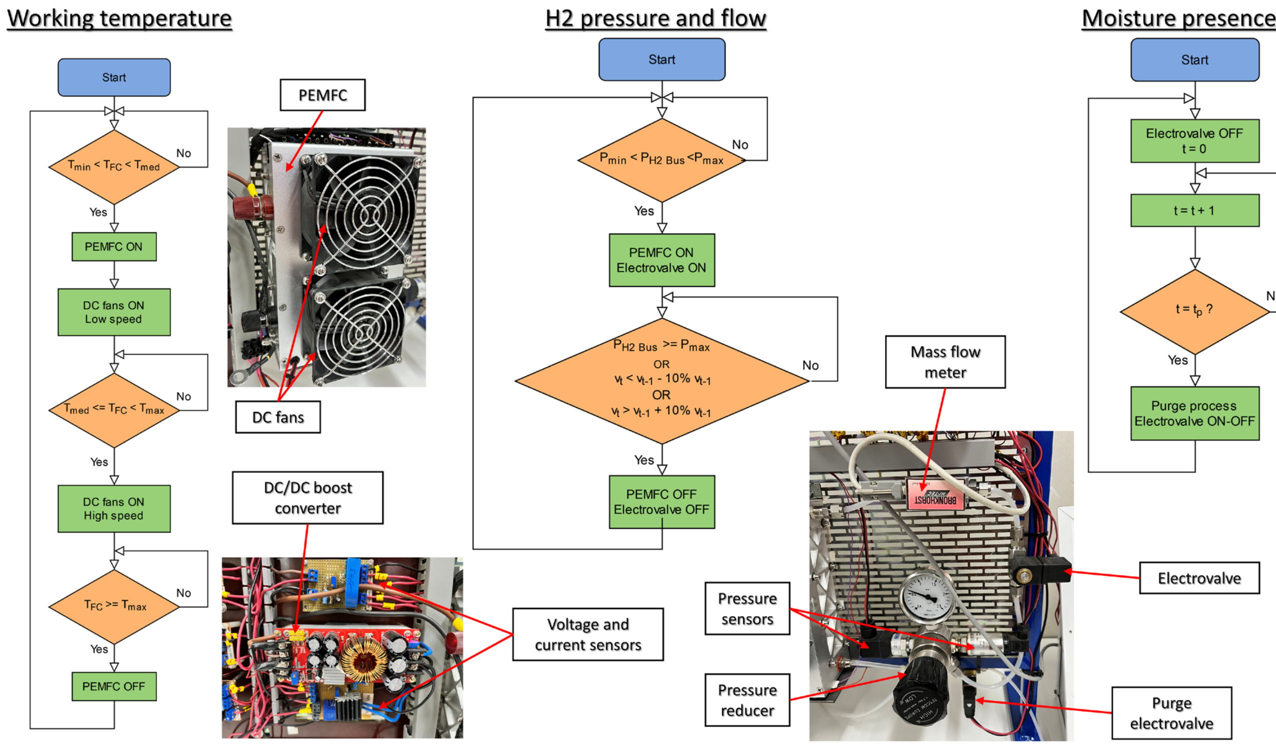

Figure 3: Flowcharts of control algorithms.

4. Conclusions

This paper has presented a power generation system based on PEMFC and managed by means of sensor-signal based algorithms. The PEMFC has been described as the central device, along with its operating principle and structure. The key parameters/factors affecting the performance of the PEMFC and the set of sensors and actuators employed for measurement and control have been detailed. The selection of these parameters has been justified based on their impact on the operation of the PEMFC and their relevance to degradation mechanisms. Finally, the various algorithms implemented in the system have been described. Future research directions include studying the long-term operation of the PEMFC under the control of the described algorithms.

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