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Accidents Review And Control Assessment For Reliable Operation Of PEM Water Electrolyzer Stacks

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Abstract

Proton exchange membrane (PEM) electrolyzers are a promising technology for producing low-carbon hydrogen. However, to maximize their performance, efficiency, lifetime, and safety, it is crucial to have a good understanding of their potential hazards and control strategies. PEM electrolyzers share many similarities with alkaline electrolyzers, another widely used method for green hydrogen production. This report presents accidents reported for both alkaline and PEM electrolyzer plants from 1975 to 2021 to identify potential hazards and important operational variables that should be considered in control design. This work aims to support the future development of control systems to improve stack reliability, and the findings are used to propose a simplified control structure for the regulatory control layer of a PEM electrolyzer stack.

Keywords: hydrogen production, water electrolyzers, hazards, reliability, process control

1. Introduction

To address the issue of climate change, the world is transitioning to a carbon-free energy economy powered by renewable energy sources (RES). Hydrogen is a promising alternative to fossil fuels due to its high energy density and crucial role in chemical processes like steel and fertilizer production (Majumdar et al., 2023). However, the success of this transition depends heavily on the efficiency and sustainability of the hydrogen production process. Currently, most of the world's hydrogen is produced from fossil fuels, leading to around 830 million tons of carbon dioxide emissions annually (Rizwan et al., 2021). Therefore, to achieve the EU's zero-emission target, it is necessary to produce green hydrogen from renewable sources through methods like water electrolysis.

Water electrolysis is the process of breaking down water into hydrogen and oxygen using electricity. Two of the most well-established water electrolyzer technologies currently available are alkaline and PEM electrolyzers. Alkaline electrolyzers have lower investment and maintenance costs and a longer lifespan than PEM electrolyzers (Rizwan et al., 2021). However, PEM electrolyzers are gaining popularity as they are more flexible, compact, efficient, less caustic, and can operate at lower cell voltages, higher current densities, temperatures, and pressures than alkaline electrolyzers (Falcão et al., 2020). Nevertheless, more research is needed regarding how the physical properties of hydrogen, such as diffusivity, solubility, etc., along with the operating conditions of the electrolyzer, affect aspects such as efficiency and longevity in order to scale up the electrolyzer technologies according to (IRENA, 2020).

Reliability is a fundamental attribute that addresses a system's weaknesses and is used to reduce the system’s failure probability, thereby improving overall safety and performance (Zio, 2009). Hence, studying the reliability of electrolyzer technologies has become increasingly important in recent years as more electrolyzer plants are being planned and put into operation. Electrolyzers are found to suffer from rapid degradation, which increases the possibility of hydrogen and oxygen mixing, forming a flammable mixture that may lead to an explosion

(Norazahar et al., 2023). This can directly or indirectly cause damage to human lives, the environment, and properties. Therefore, investigation and identification of associated risk and reliability issues must be addressed to aid in the wider adoption of electrolyzer plants (Groth et al., 2023). To minimize failure events and prevent damage to the electrolyzer stack, studying the causes of such phenomena is essential. Due to a lack of data regarding electrolyzer failures, analyzing past accident scenarios can play a significant role in ensuring reliable and safe operation (Pasman, 2009). This strategy has been widely adopted in the chemical, petrochemical, and nuclear industries (Bowonder and Miyake, 1988; Kosai and Yamasue, 2019; Paltrinieri et al., 2012; Tamascelli et al., 2022). The past accidents offer valuable insight into failure scenarios, their causes, and abnormalities in the operational conditions that might occur prior to the event. At present, there are mainly two public databases dedicated to hydrogen-related accidents. One is the Hydrogen Incidents and Accidents Database (HIAD), which was developed as part of the European Commission-funded Network of Excellence on Hydrogen Safety (HySafe) by the Joint Research Center (JRC) in 2006 (Kirchsteiger et al., 2007) and it has been recently upgraded to HIAD 2.1 in 2023 (European Commission, 2023). Another one, named HydrogenTools (H2TOOLS), was established by the Pacific Northwest National Laboratories and funded by the U.S. Department of Energy (H2Tools, 2023). These databases compile numerous common events, and their main goal is to offer a comprehensive and publicly accessible accident database specifically dedicated to hydrogen-related applications and facilitate risk assessments and lessons learned to prevent similar unexpected events in the future. The knowledge acquired from reviewing the previous occurrences can help adopt appropriate process control structures as it gives an indication of which process variables to monitor and control to provide safe operation and an extended life cycle of the system.

Suitable process control is necessary to achieve efficient operation of a process while adhering to safety regulations and constraints. It is mentioned in ISO 22734 (2019) that an appropriate control system can limit hazardous events from occurring and provide the required safe and reliable electrolyzer performance. Good control of the process is also found to extend the lifetime of the electrolyzer equipment, given the state-of-the-art stack design and materials. The design of control structures for PEM electrolyzer systems face several key challenges due to the complex interdependencies of the system variables. Additionally, good mathematical models are required to accurately describe the system behavior without becoming too computationally expensive to solve (Majumdar et al., 2023). In recent years, various models of PEM electrolyzers have been developed with different levels of complexity, ranging from relatively simple analytical models to more advanced mechanistic models (Falcão et al., 2020). Although there has been a lot of progress in the modeling of PEM electrolyzers, further research is needed to address the control design aspects (Majumdar et al., 2023). One of the most popular control techniques for PEM electrolyzers in the literature is the relatively simple and well-established proportional-integral-derivative (PID) controller. Many studies have used these controllers to control the output current of the direct-current converters. Another common control technique is the model predictive control (MPC) algorithm, which iteratively solves an optimization problem. Given a good model, the MPC can achieve optimal performance without violating operational constraints. However, the use of MPC is often very computationally expensive (Majumdar et al., 2023). (Ogumerem and Pistikopoulos, 2018) used MPC to regulate the stack temperature by adjusting the feedwater flow rate and achieved good target following. To reduce the computational requirements of the system, (Zhao et al., 2022) used a neural network to model the electrolyzer system within the MPC. Thus, the neural network replaced the plant model, and the MPC was found to have a good performance. However, the diverse system architecture and control variables used in the different studies make it difficult to draw direct comparisons between the control structures (Majumdar et al., 2023).

In this work, we identify some of the potential hazards present in alkaline and PEM electrolyzers during operation by analyzing previous accidents reported in hydrogen-related databases. This information is used to identify the conditions that should be monitored and considered when designing control structures for the electrolyzer systems. Finally, a simple control structure of the regulatory control layer of a PEM electrolyzer stack is proposed in adherence to the findings from the accident review. However, methods employed to monitor the identified operating conditions are not discussed in this work.

2. Main electrolyzer technologies

An electrolyzer is an electrochemical energy converter that uses electricity to oxidize water, producing oxygen and hydrogen. The electrolyzer stacks consist of multiple cells divided into a cathode and an anode section by an electrolyte (Falcão et al., 2020).

2.1. Alkaline water electrolyzers

Alkaline electrolysis is a very mature technology and is the standard for large-scale electrolysis. The anode and cathode are usually based on nickel-plated steel and steel, respectively, and the electrolyte is a solution of potassium hydroxide (KOH) or sodium hydroxide (NaOH) in water (Shiva, Kumar and Lim, 2022). This solution is highly caustic, and the alkali concentration is usually around 30 weight % (Rizwan et al., 2021). A membrane is interposed in the gap between the electrodes to avoid mixing the gas products, and it is important to keep the correct pressure balance between the hydrogen and oxygen sides to preserve its integrity. One of the main safety issues is the large amount of the caustic electrolyte solution circulating in the system (Salehmin et al., 2022). A simplified diagram of an alkaline electrolyzer cell is presented in Figure 1b.

2.2. Proton exchange membrane water electrolyzers

PEM electrolyzers are a more recent technology than alkaline and are usually used for small and medium-scale applications. Compared to alkaline electrolyzers, PEM electrolyzers are very compact, more flexible, and can operate at higher pressures. However, PEM electrolyzers are more expensive than alkaline ones due to the expensive and rare catalysts, platinum and iridium, and the use of titanium components (IRENA, 2020). The electrolyte in a PEM electrolyzer is a thin polymeric membrane with an acidic character, usually Nafion or its derivatives. The membrane reduces the crossover of the gases and, thus, the risk of forming flammable mixtures (Majumdar et al., 2023). A simplified diagram of a PEM electrolyzer cell is presented in Figure 1a.

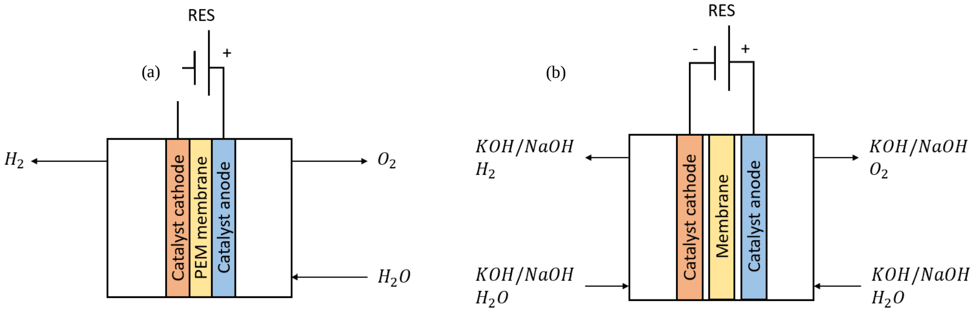

Fig. 1. Simplified diagram of proton exchange membrane (a) (Falcão et al., 2020) and alkaline; (b) (Manabe et al., 2013) water electrolyzer cells powered by renewable energy sources (RES).

3. Methodology

Due to the similarities between the alkaline and PEM electrolyzers, both electrolyzer technologies are considered in the accident review based on the information available in the HIAD 2.1 database. All the accidents related to water electrolysis are presented, while events not directly related to the electrolyzer are excluded. By reviewing the information available in the database, an overview of the accidents is acquired. In addition, relevant literature such as databases like, Sciencedirect (2023) and Web of science (2023) are searched using ‘electrolyzer’, ‘failure’, and ‘accident’ as keywords. Both the database and scientific literature are investigated to review all the accidents related to this field. After analyzing all the events, the reasons that have the potential to lead to the destruction of electrolyzers are considered hazards. Identifying the hazards is crucial for improving the reliability and safety of the electrolyzer since it allows the development of strategies to prevent, mitigate, or manage them. By analyzing the accident description, primary reasons, and lessons learned, three crucial aspects to enhance the performance and safety of electrolyzers are identified:

- hazards present in electrolyzer during water electrolysis;
- lessons learned are analyzed to find which operational conditions are crucial to monitor to prevent failure;
- relationship between the hazards and operational conditions is established, enabling a clear understanding of which hazards impact specific performance conditions.

In the control section of this work, we are considering a generalized PEM water electrolyzer. The control design is based on the first seven steps of the generalized step-by-step design procedure presented by (Skogestad and Postlethwaite, 2005).

1. Study the system and obtain information on the control objectives;
2. Model, and if necessary, simplify the system;
3. Scale the variables in the model;
4. Decide what variables should be controlled (CVs);
5. Selection of measurements and manipulated variables (MVs);
6. Selection of control configuration;
7. Selection of type of controller.

The first three steps in the control design procedure involves creating a model of the PEM stack. It was decided to use the relations presented in the review by (Majumdar et al., 2023) to develop a simplified model, and readers are referred to the original publication for a more detailed description of the process. In this section we give a short summarization of the simplifications and assumptions made in order to complete the model.

To simplify the mass transport submodel it was decided to only consider the gas crossover due to diffusion and pressure difference as the gas crossover based on the electro-osmotic drag usually are neglected in the literature (Majumdar et al. 2023). To find an expression for the pressure, we assume ideal gas and pressure equilibrium between the gas and liquid phase. The pressure is then found from the ideal gas law, where the volume of the gas is found by subtracting the volume of the liquid from the total volume of the cathode/anode section of the cell. The molar outflow of the cell is given by the valve equation. In the thermal submodel it was decided to only consider the heat from generation of the electrolysis process, and we assume constant cell voltage, approximated from the polarization curve, to simplify the electrochemical submodel.

Values of model parameters, such as the membrane thickness, permeability, etc., are gathered from the paper by (Afshari et al., 2021), and the model was implemented in the programming language Julia using ModelingToolkit (Ma et al., 2021).

4. Results and discussion

In this section, the previous accidents involving hydrogen reported for water electrolysis plants is presented. The outcome of this review is further used to identify the potential hazards present in the plants, and the operational conditions associated with the respective hazards are identified. This information is used to propose a control structure for the regulatory layer of a PEM electrolyzer, with focus on addressing the identified hazards.

4.1. Previous accidents in water electrolysis plants

In the HIAD 2.1 database, 713 hydrogen related accidents are reported. Among the accidents, only eight are found to be related to electrolyzers of water electrolysis plants. Apart from the accidents described in HIAD 2.1 database, three more accidents are found during the literature search. A review of the selected accidents is presented below.

An explosion took place at the Laporte Industries Limited factory in Ilford, UK, leading to significant destruction of an alkaline electrolyzer plant and the subsequent death of the plant operator in 1975. Based on the damage caused by the explosion, it was determined that the 1690 L oxygen drum contained approximately 13.5% hydrogen, and the explosion generated a shock wave equivalent to 22 kilograms of TNT. The cell block was dismantled, and heavy sludge deposition in some cells was observed. This led to the corrosion of some electrodes and separators which resulted in the physical breakdown of the cells. Therefore, a mixture of hydrogen and oxygen was formed and ignited.

In 1998, an explosion occurred in the oxygen storage tank of an electrolyzer plant in France. The primary reason behind the accident was assumed to be the entrance of hydrogen in the oxygen gas holder. However, the cause leading to this is unknown. Due to the explosion, the dome of the gas storage was blown 135m away, the collar was blown 33m away, and the concrete elements were blown 80m away. Nobody was injured during the accident.

There was an explosion in a high-pressure hydrogen water electrolysis unit within a university campus in Japan in 2003 (Wada et al., 2007). The water level between the oxygen separation tank and the electrolyzer cell tank decreased, which paved the way for water containing hydrogen to flow into the oxygen separation tank. Therefore, an explosion occurred. However, further details of this accident were not found.

Two years later, in 2005, another accident occurred in the same facility. The electrolysis cell burned down, pipes were damaged, and the peripheral equipment was found all over the facility area. The exposure of the titanium (Ti) electrode to oxygen at high pressure and temperature was considered to be the initiating reason.

Oxygen then flowed into the hydrogen stream, which resulted in an explosion. According to the accident flow progress mentioned in (Wada et al., 2007), a sudden voltage drop in the electrolysis cells and an increase in electric current were detected before the explosion.

An accident occurred while testing a PEM electrolyzer stack in a laboratory at elevated current density (1.8 A/cm2) (Millet et al., 2012). A failure was detected by analyzing the sudden reduction in individual cell voltage and the increased amount of hydrogen in the oxygen production. The power supply was shut down immediately to prevent the destruction of the electrolyzer stack. Perforation of the cell membrane was listed as the primary reason of the failure. There was a white deposit near the hole, which suggested local melting. The authors considered different membrane failure causes to know the reasons behind membrane perforation, but there was no evidence indicating any of these degradation phenomena. In the same laboratory, another test at high current density resulted in severe damage of the electrolyzer. A failure situation indicated by a sudden decrease in current was detected. The power supply was cut off, but combustion could not be avoided. There was a combustion of non-metallic cell components, which resulted in the deposition of carbon all over the titanium (Ti) bipolar plates and the electrolyzer stack was destroyed. Metallic elbow connectors were perforated completely, suggesting the propagation of combustion flame. The primary cause of the accident is determined to be the combustion of a hydrogen-oxygen mixture.

In 2019, a hydrogen buffer tank exploded at a renewable hydrogen production facility in South Korea, also known as the Gangneung accident. It was assumed that the degradation of the electrolyzer membrane caused oxygen to flow into the hydrogen stream. This formed a flammable mixture that caused an explosion. However, the accident is still under investigation, and a final report is yet to come.

There was a leakage of KOH from an alkaline electrolyzer at a renewable hydrogen production plant in Germany in 2021. It was reported that the fire alarm system was triggered due to the smoke. The electrolyzer was shut down and went into safety mode automatically due to the installed safety system. Nobody was injured and there was no environmental damage. According to the investigation results, the formation of deposits in the flow channels of the stack was the primary reason for the accident. This has led to a series of internal events within the stack, triggering the leakage. A summary of the accidents, their causes and consequences, lessons learned is presented in Table 1.

4.2. Hazards in electrolyzers

From the accident's description, it is revealed that the worst possible consequence is an explosion due to the formation of the H_2-O_2 mixture inside the electrolyzer. The primary reasons behind this are mainly, breakdown of the gas separators, membrane and electrodes which are termed as hazards since they can lead to an explosion. Identifying them is crucial for improving the reliability and safety of the electrolyzer since it allows for the development of strategies to prevent, mitigate, or manage them. After reviewing the accidents and their underlying causes, the following hazards are identified:

- damage of cell membrane due to perforation, degradation, etc.;
- physical breakdown of gas separators;
- corrosion of electrode;
- gas crossover;
- sludge formation.

These hazards have an impact over the operational conditions of the electrolyzer. The presence of any of these can be manifested by the hydrogen and oxygen gas composition, cell voltage, cell temperature etc. In the following section the relationship between the hazards and operational conditions of an electrolyzer is described.

4.3. Relationship between the hazards and operating conditions

By reviewing the past accidents, we see that anomalies manifest in the operating variables of the electrolyzer before any hazard occurs. Monitoring the operational conditions, applying alarms, and using a proper control system, can assist in avoiding failure of the electrolyzer. In the majority of accidents, gas compositions exceeded the threshold value before the explosion occurred. The lessons learned from the accidents that occurred in 1975 (HIAD #778), 1998 (HIAD #243), 2012 (Millet et al., 2012), and 2019 (HIAD #970) highlight the need to continuously measure the hydrogen and oxygen purity levels. It is mentioned in the accident report HM Factory Inspectorat (1976) that the most significant test for predicting an accident is the oxygen purity test. Visual and audible alarms should be actuated when oxygen purity falls to 98.8% or hydrogen purity to 99.7%. The plant should be shut down when oxygen purity falls to 98% or hydrogen purity to 99.5%.

Besides, the events in 2012 (Millet et al., 2012) revealed that due to the perforation of the membrane, the cell voltage dropped below the threshold value (1.5 V). The accident in Japan in 2005 (HIAD #1002) also experienced a sudden voltage drop due to the exposure of the Ti electrode to oxygen. The lessons learned from these events indicate that cell voltage should be monitored during operation since an increase in cell voltage can indicate inappropriate water distribution, whereas reduced cell voltage can be related to a cell short circuit and the formation of a hole in the electrolyzer (Azkarate et al., 2020). Reduced electrolyte flow, increase in cell temperature, and electrolyte concentration are also indicators of sludge formation inside the electrolyzer, which can lead to corrosion (HIAD #778, #1037). The accident in 2005 (HIAD #1002) also noted an increase in cell current, which indicated gas crossover inside the electrolyzer. While certain accidents occurred quickly after exhibiting changes in operating variables, others provided warnings by showing abnormalities in performance, as seen in the case of the (HIAD #778). Table 2 shows the connection between the identified hazards and the operating conditions of an electrolyzer.

Failure of the electrolyzer can be prevented by monitoring the operating conditions using proper control structures. To implement an effective control structure, monitoring the beforementioned operating conditions is crucial. The operating conditions of an electrolyzer can be observed by using suitable sensors embedded in the system. This real time data can be given as input to the control structure to ensure reliable and efficient operation of the electrolyzer. Furthermore, it can also be utilized to diagnose failure and predict accidents which is an important research topic.

Table 1. Summary of accidents related to alkaline and PEM water electrolyzer plants.

Source	Year/ Place	Type of electrolyzer	Consequence	Damage & fatalities	Causes	Lessons learned
HIAD #778	1975/ UK	Alkaline	Explosion	Electrolyzer damage. Fatality – 1	Formation of H_2 & O_2 flammable mixture due to the corrosion of electrodes and separators due to sludge formation.	This highlights the importance of continuous monitoring of H_2 and O_2 purity levels. Also, the internal condition of the electrolyzer, such as, sludge formation, cell voltages, cell temperature, electrolyte temperature must be checked regularly.
HIAD #243	1998/ France	Not mentioned	Explosion	O2 tank damage. Fatality – 0	Entrance of H_2 in the O_2 storage tank.	This event indicates the need for monitoring the H_2 composition in the O_2 storage tank.
(Wada et al., 2007)	2003/ Japan	PEM	Explosion	Electrolyzer damage. Fatality – not mentioned	Flowing of H_2 into the O_2 separation tank due to decrease in water level.	This accident highlights the need for increasing the holding water volume in the electrolyzer. Further details are unknown.
HIAD #1002	2005/ Japan	PEM	Explosion	Damage of electrolyzer & pipes attached. Fatality – 0	Water containing H_2 flowed into the O_2 tank due to the burning of Ti electrode.	In the accident flow progress presented in (Wada et al., 2007), sudden voltage drop of electrolyzer cells was seen indicating anomaly in electrolyzer performance. Hence, studying the cell voltage is an important parameter.
(Millet et al., 2012)	2012	PEM	Electrolyzer failure	Damage of electrolyzer. Fatality – 0	Perforation of electrolyzer cell membrane.	This accident reveals that the perforation of cell membrane can be detected by a cell short circuit which drops the cell voltage below the threshold value.
(Millet et al., 2012)	2012	PEM	Fire without explosion	Damage of electrolyzer & metallic elbow connectors. Fatality – 0	Formation of H_2-O_2 mixture.	The test results highlight the need for measuring cell voltage and H_2-O_2 gas composition.
HIAD #970	2019/ South Korea	Alkaline	Explosion	Damage of electrolyzer & H2 storage tank. Fatality – 3 Injury - 6	Formation of H_2-O_2 flammable mixture due to degradation of cell membrane.	This accident also indicates the monitoring of H_2-O_2 gas composition.
HIAD #1037	2021/ Germany	Alkaline	Leakage of KOH	Damage of electrolyzer. Fatality – 0	Deposition of sludge in the flow channel.	This reinforces the regular inspection of internal condition of the electrolyzer, such as, sludge formation, cell voltage, cell temperature, electrolyte temperature etc.

4.4. Control of PEM electrolyzer stacks for reliable operation

To address the hazards identified in Table 2 and the accidents review in Table 1 a simplified control structure is proposed for the regulatory control layer of the PEM electrolyzer stack. The regulatory control layer's primary objective is to stabilize and facilitate the smooth operation of the process, which includes supporting the operators, providing fast local control, tracking setpoints set by higher layers, rejecting disturbances, and avoiding drift. The key questions that we must answer when designing the regulatory control layer are which variables we should control (CVs), which variables we can manipulate (MVs), and how we should pair these CVs and MVs. This is related to steps four to six of the control design procedure presented in the methodology (Skogestad and Postlethwaite, 2005).

The CVs for the PEM electrolyzer are determined from the available measurements. Table 2 lists the key variables that should be monitored, including cell pressure, temperature, current, voltage, and the composition of hydrogen and oxygen. The flow rate of the electrolyte is not considered as it is irrelevant for a PEM electrolyzer.The cell pressure is an important variable to control as it needs to be kept within the pressure limits of the equipment, usually between 1 and 30 bar (IRENA, 2020). The pressure difference between the cathode and anode should also be controlled to prevent damage to the membrane and limit the crossover rate of the gases.The cell temperature is crucial for the efficiency and degradation of the stack. For state-of-the-art PEM, the temperature should be between 50 and 80 degrees Celsius (IRENA, 2020). The temperature is also found to affect the crossover rate, especially for low current densities. The composition of hydrogen and oxygen on the cathode and anode side must be monitored to avoid the formation of flammable hydrogen and oxygen mixtures that can lead to explosions. From the accidents review presented in Table 1 is it apparent that the formation of hydrogen oxygen mixtures is one of the primary reasons for the reported accidents. As such, it is essential to monitor and control the composition. As the cell voltage and current density are closely related through the polarization curve of the stack, controlling the voltage will give secondary control of the current density. However, it was decided to consider the cell current as a manipulated variable instead of a CV, because it is one of the primary inputs for the electrolyzer system. In summary, the anode pressure, pressure difference, cell temperature, hydrogen composition in the cathode, and oxygen composition in the anode are determined to be the five key CVs for the PEM system.

Table 2. Relationship between the hazards and the operating conditions for alkaline and PEM electrolyzers.

Hazards	Operating conditions
Damage of cell membrane	Cell voltage
	H_2 concentration in produced O_2
Physical breakdown of gas separators	H_2 concentration in produced O_2
	O_2 concentration in produced H_2
Corrosion of electrodes	H_2 concentration in produced O_2
	O_2 concentration in produced H_2
Gas crossover	Cell voltage
	Cell current
	Cell pressure
Sludge formation	Cell temperature
	Electrolyte flowrate

The manipulated variables are found from the literature and by studying the system. As the only physical input, the feedwater flow rate is responsible for supplying the reactant and plays a crucial role in phenomena such as bubble formation. The feedwater flow rate is also found to have a significant impact on the pressure on the anode side of the electrolyzer (Majumdar et al., 2023). The temperature of the feedwater is found to greatly affect the cell temperature. The feedwater temperature is not reported to have a direct effect on any of the other system variables (Majumdar et al., 2023). The current density is a crucial and widely studied MV in electrolyzers because it directly affects the rate of hydrogen production. Additionally, the current density has an impact on several other important variables, including the crossover rate, the Faradic efficiency, and voltage degradation (Majumdar et al., 2023). However, rapid changes in the current density are found to damage the electrolyzer components, which may limit its use as a MV. From the layout of the stack, it is apparent that we also can control the flow rate out of the anode and cathode by adjusting the valve openings, resulting in five potential MVs for this system.

The sixth step of the control design procedure is to select an appropriate control structure. As the CVs are important in themself, we should use decentralized control if possible. This includes using multiple single-input-single-output controllers. With this control configuration it is important to choose an appropriate paring of the CVs and the MVs. To decide which of the CVs and MVs should be paired, we find the steady-state relative gain array (RGA) of the PEM stack model with the prebuilt RGA-function from the ControlSystems toolbox (Carlson et al., 2022). We have two main pairing rules for the RGA (Skogestad and Postlethwaite, 2005).

- *Rule 1*: Prefer parings such that the selected pairing along the diagonal gets close to an identity matrix;
- *Rule 2*: Avoid parings at negative steady-state elements.

From the RGA presented in Table 3, it is apparent that the temperature of the feedwater should be used to control the temperature of the stack, the feedwater flow rate should control the pressure on the anode side, the current density should control the pressure difference between the anode and cathode, the anode outflow valve should control the pressure difference between the anode and cathode, the anode outflow valve should control the cathode hydrogen composition, and the cathode outflow valve should control the anode oxygen composition. This configuration corresponds well with the relationships of the variables found in the literature.

Table 3. The relative gain array (RGA) for the PEM electrolyzer model.

	Current density	Feed water flowrate	Valve-opening cathode	Valve-opening anode	Feed water temperature
Cell temperature	0.00	0.00	0.00	0.00	1.00
Pressure anode	-0.02	1.49	0.00	-0.47	0.00
Pressure difference anode and cathode	0.64	-0.04	0.38	0.03	0.00
H2 composition cathode	0.00	-0.45	0.00	1.45	0.00
O2 composition anode	0.38	0.00	0.62	0.00	0.00

The last step we consider in the control design is to select the type of controller to be used for the regulatory layer. Feedback control is recommended to deal with potential signal and model uncertainty as well as instability in the plant (Skogestad and Postlethwaite, 2005). Feedback control is also found to provide better disturbance rejection and to be more robust than feedforward control (Majumdar et al., 2023). Various control algorithms have been studied for PEM systems, but PID controllers are typically used for the regulatory layer due to their robustness and simple design (Khan et al., 2017). PID is appropriate in this case as we have a decentralized control system. Although more advanced control structures, such as MPC, can handle the interdependencies of the system variables better than PID (Majumdar et al., 2023), they are usually placed in a higher layer of the control hierarchy, such as the supervisory control layer (Khan et al., 2017). Therefore, it is recommended to use feedback with PID controllers for the regulatory control layer of the PEM stack. Figure 2 shows the resulting control structure.

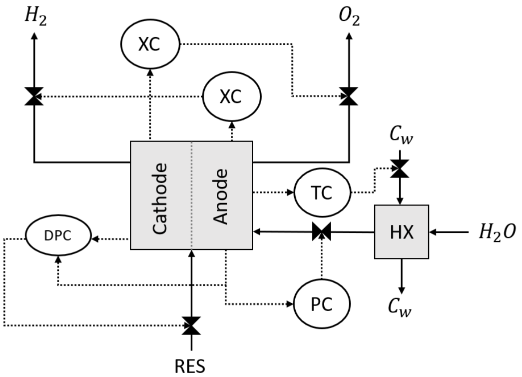

Fig. 2. Simple control structure for the regulatory layer proposed for a PEM electrolyzer stack.
For readability is the stack separated into a cathode and anode section like an electrolyzer cell.
The heat exchanger (HX) is used to adjust the feedwater temperature with the flow of cooling water (C_w).

5. Conclusion

Green hydrogen production through water electrolysis is expected to play a key role in achieving the net zero target by 2050. Therefore, future development in electrolyzer technology is necessary to ensure the safe and reliable operation of electrolyzer plants. As a result, research towards improving the efficiency, and longevity of electrolyzers is widely encouraged. This work studies previous accidents that occurred in water electrolysis plants involving electrolyzers using the HIAD 2.1 database and scientific literature. By reviewing the accidents possible hazards that can lead to severe consequences, such as explosions, are identified. The potential hazards identified for an electrolyzer include damage to cell membranes due to perforation and degradation, breakdown of gas separators, corrosion of electrodes, sludge deposition, and gas crossover. These causes are associated with electrolyzer operating conditions like hydrogen/oxygen composition, cell voltage, cell temperature, etc., by exploring the lessons learned described in the resources. This has facilitated the detection of the hazards by monitoring the listed operating conditions. Any anomaly in the electrolyzer is revealed by the changes in the above-mentioned conditions. Based on the identified hazards a control structure of the regulatory controller of a PEM electrolyzer is suggested and presented in Figure 2. The five key operating variables to control are determined to be the anode pressure, pressure difference between the anode and cathode, cell temperature, hydrogen composition in the cathode, and oxygen composition in the anode. Similarly, the identified manipulated variables are found to be the feedwater temperature, feedwater flow rate, current density, and the valve position for the outflow stream of the anode and cathode. It is recommended to use a decentralized controller as the CVs are important within themselves and the pairings of the MVs and CVs are determined from the RGA of the system.

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