The Effect of Electrical Variables on Hydrogen and Oxygen Production Using a Water Electrolyzing System

Hanan Saleet*, Salah Abdallahb, and Essam Yousefc

a,b,cApplied Science Private University, Mechanical and Industrial Engineering Department, P.O. Box 166, Amman, Jordan.

(*Corresponding author)

Abstract

Water electrolysis (splitting water) is an efficient method of producing hydrogen and oxygen. The production efficiency depends on important design variables such as the electrical variables. This work presents an experimental study that was conducted to investigate the effect of the following electrical variables: AC voltage amplitude, waveform and frequency, and DC voltage amplitude. The electrolyser splits water into hydrogen and oxygen when an electric current passes between two flat plate shaped electrodes immersed in water and separated by non-electrical conducting material; this material is resistive Teflon. From the experimental results, it can be seen that the square waveform has the maximum hydrogen and oxygen production followed by sawtooth waveform. Therefore, using sinusoidal waveform as the base case, the gain in total productivity can reach up to 489% for sawtooth waveform, and up to 680% for the square waveform. In addition, it is seen from the experimental results that the gain in production of hydrogen and oxygen in case of DC input voltage, for the same range of voltages, can reach up to 1100%. Therefore, it is clear that using DC input voltage such a solar system can enhance the efficiency of hydrogen and oxygen production.

Keywords: Electrical variables; Water electrolyzer; Hydrogen and oxygen production.

INTRODUCTION

Due to the depletion of traditional energy resources, such as crude oil, coal, and natural gas, many initiatives all over the world have addressed the efficient use or replacement of these resources [1] - [6]. Several renewable energy sources have been introduced as alternatives to traditional sources to protect environmental resources and to improve the quality of life [7]. Using renewable energy sources represents a bright future for humanity because they utilize a clean, and sustainable fuel; the sun, wind, water, etc. [8]. Electrical energy produced using photovoltaic systems is a sustainable energy resource. The most important drawback of using photovoltaic systems to generate energy is the change in sunlight illumination through daytime and the absence of solar radiation at night time [9], [10]. Thus, it is essential to store the energy in batteries or store the energy into another material i.e. store energy into high energy materials, such as hydrogen and oxygen gases [11] - [14]. Water electrolysis is used to produce hydrogen where electric current passes through water resulting in splitting water into hydrogen and oxygen [15] - [17]. Hydrogen stores electrical energy [18]. It can be used to generate electricity in a fuel cell by a process that is the reverse of electrolysis [19]. A life cycle assessment of the processes indicates that it has minimal environmental burden [20] - [22]. compared to the quite considerable savings offered [23], [24].

"The demands for energy are increasing as countries become richer" mentioned Winterbone in [25]. Gutierrez-Martin et al. suggested to build large number of electrolyzer plants in Spain [26]. Abdel-Wahab et al. explored the application of Fuel-Cell Energy Systems, which utilizes hydrogen from renewable sources in the UK environment [27]; and [28], and [29] investigated the potential of hydrogen production in Algeria.

In addition, researchers developed mathematical models to test the electrolyzer system under different conditions. For example, Paul and Andrews presented a theoretical analysis of a mathematical model that tests the conditions required for connection of a photovoltaic array to an electrolyzer in solar hydrogen systems [30]. Also, Bilgen presented a mathematical model that aims to optimize the thermal conditions and also optimize the economics of large scale photovoltaic electrolyzing systems [31]. On the other hand, researchers built simulation models to study the different theories how to optimize hydrogen production. In [32], Rabady used simulation to examine the utilization of sunlight using a hybrid thermo-electrolysis system to produce Hydrogen. Paola et al. created a simulation program that compares different technological options in order to optimize the PV-electrolysis system [33]. Khalilnejad and Riahy designed and modeled a hybrid wind–photovoltaic system for the purpose of hydrogen production through water electrolysis [34].
Many design parameters were investigated in the literature such as the effect of TDS (Total Dissolved Solids) [35], and the effect of pH levels [36]. In addition, Mahrous et al. in [37] and Chennoufa et al. in [38] investigated the effect of input voltage amplitude. Higher production rates can be obtained at higher input voltage. Nagaia et al. [39] and [40] used an alkaline water electrolysis to study the effect of current, temperature, distance between electrodes and bubbles between electrode on the efficiency of water electrolysis at a particular concentration. Abdallah et al. investigated the effect of connection type (either parallel or series) of the solar panels on the production rate [41]. This work aims to investigate the effect of AC voltage amplitude, AC voltage waveform, AC voltage frequency, and DC voltage on the hydrogen and oxygen production.

**EXPERIMENTAL DESIGN OF THE SYSTEM**

In purpose of investigating the effect of AC voltage amplitude, AC voltage waveform, AC voltage frequency, and DC voltage on the hydrogen and oxygen production, testing electrolyzing rig is built. A schematic diagram of water electrolyzer, used in this work, is presented in Figure 1. The system consists of pulse generator, power amplifier, DC power generator, water electrolyzer, bubbler, and hydrogen and oxygen measurement instrument.

![Schematic Diagram of water electrolyzing system.](image)

The detailed information about each element of this system can be described as following:

A) Pulse generator:
The electrical power generator used in this system is a pulse generator. The main technical characteristics of pulse generator 8120, which is used in this system, are: frequency range from 0.1 Hz to 2MHz. Output voltage from 5mV to 2V, and offset DC voltage is ±10.

B) Power amplifier:
Power amplifier is used to amplify the voltage generated at the output of pulse generator. The main technical data of power amplifier 2712, which is used in this system, are: power output capacity is 180 VA, frequency range from 0 to 100KHz.

C) DC Power supply:
DC power supply is used to generate regulated DC voltage. In this work, regulated power supply model XP-650 is used and its main technical data is as following: input voltage is 120 VAC or 220 VAC, output voltage 0-20 VDC or 0-40 VDC, respectively. Output current is 3A at 0-20 VDC, and 1.5A at 0-40 VDC.

D) Water electrolyzer:
Water electrolyzer shown in Figure 2 uses a cylindrical plastic container with 40cm height, 12 cm diameter, and 2 liters of water capacity. The used electrodes are made of stainless steel 316 shown in Figure 3. The two electrodes are flat plate shape, each of them is 6cm height and 5cm width. The thicknesses of each plate is 1.5 millimetres and the gap
between the two plates is 5 millimetres. The flat plates electrodes are separated by a non-electrical conducting material which is resistive teflon.

The electrolyzer contains two electrodes, where each electrode is connected to power supply. The electrodes are immersed in water where the process of splitting water into hydrogen and oxygen occurs when electrical current generated by the pulse generator or the power supply is passed between two electrodes.

E) Bubbler.
The bubbler is a cylindrical shape device which prevents the reverse flow of hydrogen and oxygen; this is important for safe operations.

F) The hydrogen and oxygen measurement instrument.
The hydrogen and oxygen measurement instrument is a homemade instrument. The gas produced is collected inside a cylindrical plastic container; 25cm height and 14cm diameter. During production this plastic container is placed under water surface, and it begins to rises above water surface as it is being filled with hydrogen and oxygen gases.

EXPERIMENTATION AND RESULTS

This section includes the instrumentation used in the experiments, the experimental work and setup, and the experimental results.

Instrumentation.

In this work, different electronic measuring instruments are used; but before being used they were tested and calibrated.

Calibrated thermocouple (type-K) coupled to a digital thermometer is used to measure the water temperature inside electrolyzer. The measurement range of this thermometer is from -199.9 to 137 °C and its accuracy is ±1 °C.

Electric current which goes through a conductor is measured using a clamp meter. The range of measurements is from 0 to 20 A. The accuracy of ammeter is ±3%.

To measure the electrical voltage, a 35 MHz analog oscilloscope HM303-6 was used. TDS or total dissolved solids in water, i.e. the concentration of dissolved solids in it, is measured using TDS tester. The range of measurement of this instrument is from 0 to 5000 ppm and its accuracy is ±2%. PH tester is used to measure the level of acidity and alkalinity of the water. The range of measurement is from 0 to 14 PH. The resolution is 0.01 PH and the accuracy is ± 0.01 PH.

Experimental work and setup.

At the beginning of each experiment, the electrolyzer is filled with water and the electrodes are fully immersed in water. The terminals of power supply are connected to the electrodes. In the following sections, the experimentation is divided into two parts. In the first part, a pulse generator and a power amplifier are used to generate alternating current, with variable amplitude, waveform and frequency, to operate the electrolyzer, and in the second part a DC power supply is used to generate different DC voltage values to operate the electrolyzer.
The effect of alternating current waveforms on hydrogen and oxygen production.

The aim of this experiment is to study the effect of AC voltage amplitude, waveform, and frequency on the hydrogen and oxygen production using water electrolyzer.

In this experiment, the range of studied frequencies is from 5Hz to 60Hz with different waveforms as follows: sinusoidal, sawtooth, and square, as shown in Figure 4.

![Waveforms shapes](image)

**Figure 4: Waveforms shapes**

The procedure of experiment starts by producing certain voltage amplitude from 5V to 30V with certain frequency from 5Hz to 60 Hz, and certain waveform shape for 15 minutes; where the total hydrogen and oxygen production is measured at the end of these 15 minutes. The measurement of solution temperature inside electrolyzer is taken as the average for three readings, first reading at the start of the first minute, the second reading is taken after 7.5 minutes, and the third reading is taken at the end of the 15th minute.

At the start of each experiment, the electrolyzer is filled with 2 Liters of water with 458 TDS and 7 PH. The current starts to flow into the electrolyzer, where the reaction inside can be seen, and the produced hydrogen and oxygen flow through a pipe into the bubbler, then to the instrument used to measure the production.

In the following, the effect of AC voltage amplitude, waveform, and frequency on the hydrogen and oxygen production is investigated:

A) Waveform effect: to compare the hydrogen and oxygen production for different waveforms, the production gain is calculated. For a certain frequency, production gain is calculated based on the total hydrogen and oxygen production for a range of voltage amplitudes as follows:

\[
\text{Production gain} = \left( \frac{p_p - p_s}{p_s} \right) \times 100\%;
\]

Where:

- \( p_s \): total hydrogen and oxygen production for the base case i.e. when the waveform is sinusoidal.
- \( p_p \): total hydrogen and oxygen production in case of sawtooth or square waveforms.

The experimental results are presented in Figure 5, Figure 6, and Figure 7. They show the production for different values of frequencies. For each frequency value and for each waveform, the gain is calculated by taking the total hydrogen and oxygen production for voltage amplitudes from 5V to 30V. It is worth mentioning that, experimentally, there is no production at frequencies from 0 to 3Hz. From these figures, it can be seen that the square waveform has the maximum hydrogen and oxygen production followed by sawtooth waveform. Therefore, using sinusoidal waveform as the base case, the gain in total productivity can reach up to 489% for sawtooth waveform, and up to 680% for the square waveform.
Results of experimentation for different input voltage amplitudes and waveforms for 5Hz frequency

Results of experimentation for different input voltage amplitudes and waveforms for 10Hz frequency

Results of experimentation for different input voltage amplitudes and waveforms for 15Hz frequency

Results of experimentation for different input voltage amplitudes and waveforms for 20Hz frequency

Figure 5: Results of experimentation for frequencies between 5Hz and 20Hz
Results of experimentation for different input voltage amplitudes and waveforms for 25Hz frequency

Results of experimentation for different input voltage amplitudes and waveforms for 30Hz frequency

Results of experimentation for different input voltage amplitudes and waveforms for 35Hz frequency

Results of experimentation for different input voltage amplitudes and waveforms for 40Hz frequency

Figure 6: Results of experimentation for frequencies between 25Hz and 40Hz
Results of experimentation for different input voltage amplitudes and waveforms for 45Hz frequency

Results of experimentation for different input voltage amplitudes and waveforms for 50Hz frequency

Results of experimentation for different input voltage amplitudes and waveforms for 55Hz frequency

Results of experimentation for different input voltage amplitudes and waveforms for 60Hz frequency

**Figure 7:** Results of experimentation for frequencies between 45Hz and 60Hz

*The effect of input DC voltage values on hydrogen and oxygen production*

The aim of this experimental part is to study the effect of DC voltage on the hydrogen and oxygen production using electrolyzing cell, and to compare the results achieved in this part to the results obtained using AC waveforms.
The schematic diagram in this case is the same as in Figure 1, but the pulse generator and power amplifier are replaced by a DC power supply which is described in point C of section 2. The experiment starts by applying certain DC voltage from 5V to 20V for 15 minutes; this range of voltages is limited by the capabilities of the power supply. Measurements of the different experimental variables which are: hydrogen and oxygen production, solution temperature and DC current are conducted as described before. Figure 8 shows the results of experimentation for different input DC voltages. From the analysis of Figure 8 it is seen that the higher rates of hydrogen and oxygen production can be obtained at higher input voltages. The experimental results indicates that higher gain in total hydrogen and oxygen production can be obtained by using DC input voltages compared to the AC input voltages for the same range of voltages. Again using sinusoidal waveform as the base case, the gain in total productivity can reach up to 1100% for the DC input voltage. It can be concluded that using DC input voltage, such as the voltage produced by solar panels, in operating the water electrolysis system enhances hydrogen and oxygen productivity.

![Figure 8: Experimental results for DC input voltages](image)

**CONCLUSIONS**

In this work, a water electrolyzer, used to produce hydrogen and oxygen gases, is designed and constructed. From the experimental results, it can be seen that the square waveform has the maximum hydrogen and oxygen production followed by sawtooth waveform. Therefore, using sinusoidal waveform as the base case, the gain in total productivity can reach up to 489% for sawtooth waveform, and up to 680% for the square waveform.

For the range of AC voltages from 5V to 30V, there is no indication that the increase in voltage would lead to increase in productivity, and for the range of frequency from 5 to 60Hz, there is no indication that the increase in frequency would lead to increase in productivity. But, it is noticed that there are specific values of frequency and voltage where the productivity is maximum.

Regarding the DC input voltage, the higher rates of hydrogen and oxygen production can be obtained at higher input voltages. In addition, higher rates of hydrogen and oxygen production can be obtained by using DC voltage compared to AC voltage. It is seen from the experimental results that the gain in production of hydrogen and oxygen in case of DC input voltage can reach up to 1100%.

**ACKNOWLEDGEMENT**

The authors are grateful to the Applied Science Private University, Amman, Jordan for the full financial support granted to this research.

**REFERENCES**


of water electrolysis for flexible energy storage at large scales: The case of the Spanish power system”, International Journal of Hydrogen Energy, Volume 40, Issue 15, Pages 5544-5551


