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Design of an integrated power system using a proton exchange membrane fuel cell

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ABSTRACT

Integrated power systems could be a solution to provide energy to remote communities based on the use of renewable energies (such as wind or sun). This work proposed the design of one of those systems including alkaline water electrolysers, storage tanks and a proton exchange membrane fuel cell for generating of 53 kW (working at 60% of its maximum power). Electrode sizes and the quantity of unit cells proposed in this work were the same as those suggested in the research work by Yang et al., where a phosphoric acid fuel cell was built and studied. The results obtained in that research allowed comparing energy efficiency by scaling a laboratory prototype. The dimensions of the alkaline water electrolysers are the result of satisfying the necessity of fuel and oxidant. The energy consumption results from extrapolating laboratory devices. The integrated power system has a storage tank capacity of 16 h.

1. Introduction

Advances in the development of fuel cell and electrolyser technologies have allowed to define hydrogen position as a chemical energy storage medium. To confirm this fact a considerable number of production plants have been installed in different countries to investigate technical and commercial feasibility of the use of hydrogen as an energy carrier [1–8]. The majority of those plants are operated by universities and national energy agencies. With the purpose of offering a solution to the energy power supply to communities in remote areas, a lot of integrated renewable power systems were designed, built and studied [6–8]. Integrated power systems are based on the use of a primary renewable energy source such as wind and solar power through wind turbines or photovoltaic panels, respectively. As if it known, during the day the consumption of energy varies so in the periods when there is excess of primary energy, this could be stored in the form of hydrogen to be saved and later used when primary energy becomes insufficient. The most important equipment in those types of systems are: electrolysers, storage tanks and fuel cells. The electrolyser transforms excess of electric energy into chemical energy in the form of hydrogen. The fuel

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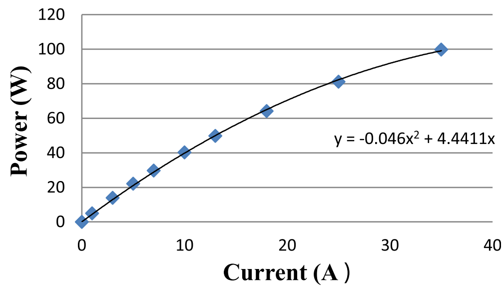

Fig. 1 – Graphic representation of power as a function of current for a laboratory PEM fuel cell with an active area of 100 cm^2.

cell transforms chemical into electrical energy through a combustion reaction. [9]

The majority of the integrated power systems proposed, were based on commercially available equipment such as alkaline water electrolysers, proton exchange membrane (PEM), alkaline and phosphoric acid fuel cells and storage tanks.

In this work an integrated power system is proposed, scaling laboratory equipment capable of generating 53 kW, at 60 percent of PEM fuel cell maximum power. We assume the size of the electrodes and the number of unit cells to supply the necessity for fuel and oxidant flow. The main objective is to evaluate and compare these laboratory prototypes with commercial equipment or known prototypes and establish the design of the integrated power system.

2. Material and methods

2.1. *Laboratory PEM fuel cell*

A laboratory PEM fuel cell was tested in order to compare its energy efficiency with that proposed by Yang et al. [10], after scaling. This laboratory prototype has an active area of 100 cm^2 and it consists of a stack of six unit cells. One typical unit cell is comprised by a membrane electrode assembly, two bipolar plates and two seals. This stack has a membrane electrode assembly that consists of Nafion® 117 membrane, two dispersed catalyst layers that have a metal loading of 0.5 mg Pt/cm^2 as catalyst for both electrodes and two gas diffusion layers of carbon paper. The material for the bipolar plates is titanium with a protective coating layer of gold. Silicone is the material used for the seals. Fig. 1 shows power as a function of the current for this prototype at an operating room temperature. Hydrogen and oxygen obtained by alkaline water electrolysis are used as fuel and oxidant respectively.

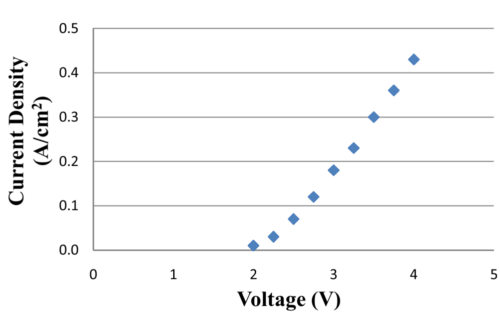

Fig. 2 – Graphic representation of the current density as a function of voltage for the water alkaline electrolyser.

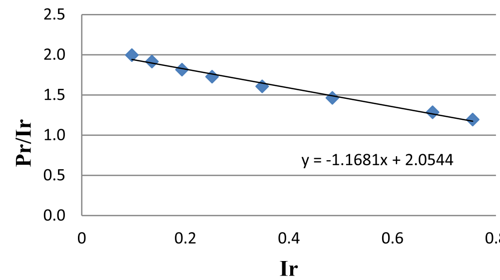

Fig. 3 – Graphic representation of the division between relative power and relative current density as a function of relative current density.

2.2. *Laboratory alkaline water electrolyser*

The relevant components of an alkaline water electrolyser are the electrodes, the separator and the electrolytic solution. The laboratory prototype uses stainless steel 316L as electrode material, a Zirfon® membrane as separator and a high concentration solution of KOH (35% w/w) as electrolyte. To analyse the functioning of the electrolyser, it was connected to a power source Agilent N5743A System DC Power Supply (12.5 V/60 A, 750 W) once the device had been assembled. Current measurements were made at a certain potential between 0.0 and 4.0 V. The operational conditions are room temperature and atmospheric pressure. The monitor parameters are current and voltage. Fig. 2 shows the current density as a function of the voltage for the alkaline water electrolyser.

3. Results and discussion

3.1. *Laboratory PEM fuel cell*

To compare the energy efficiency between the phosphoric acid fuel cell by Yang et al. [10] and the laboratory PEM fuel

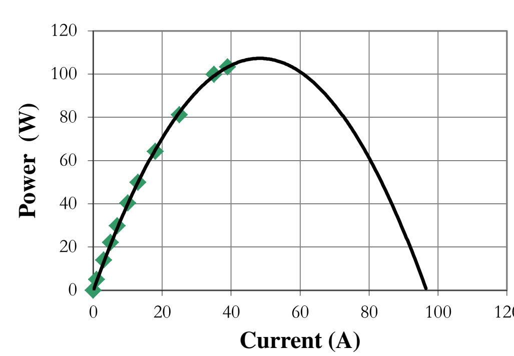

Fig. 4 – Behaviour representation of laboratory PEM fuel cell.

Table 1 – Voltage, current density and power values for the scale PEM fuel cell, working at 60% of its maximum power.

Voltage (V)	66
Current density (A)	800
Power (kW)	53

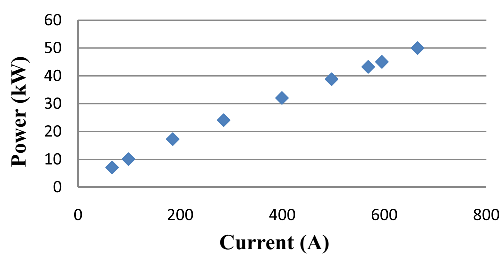

Fig. 5 – Graphic representation of power as a function of current for the phosphoric acid fuel cell.

cell, the last one was scaled. The active area (4225 cm^2) and the number of unit cells (109) were equalised. For that purpose the power that can be delivered by the laboratory prototype at 60% of its maximum power was calculated once this structural characteristic was achieved. The equation used was as follows,

$$P_r/I_r = 2 - I_r \quad (1)$$

where, P_r is the relative power and I_r is the relative current density [11]. The relative power is defined as the division between power (P) and maximum power (P^*). The relative current density is defined as the division between current density (I) and maximum current density (I^*). The equations are expressed as follows:

$$\text{Relative power,}\ P_r = P/P^* \quad (2)$$

$$\text{Relative current density,}\ I_r = I/I^* \quad (3)$$

Thus, power (P) is a quadratic function of the current density (I). Fig. 3 shows the graphic representation of the division between relative power and relative current density as a function of relative current density.

In order to determine the energy produced at 60% of PEM fuel cell maximum power, relative power value has been calculated as 0.6, by applying the equations above.

To estimate the value of relative current density the constants from the linear equation in Fig. 3 were considered. Solving the final equation the value of I_r is obtained. Values for I^* and P^* are determined from Fig. 4 and then all parameters can be calculated.

Table 1 presents values of voltage, current density and power of PEM fuel cell with an active area of 4225 cm^2 and 109 unit cells.

Fig. 5 is the graphic representation of power as a function of current density for the phosphoric acid fuel cell. From that Figure it is clear that the power obtained is lower (around 43%).

3.2. *Laboratory alkaline water electrolyser*

Mass balance calculations allow to determine hydrogen mass flow for the PEM fuel cell feed (46 m^3/h). Equalizing the electrodes size with those used for PEM fuel cell and considering a 85% efficiency for the alkaline water electrolyser, 66 unit

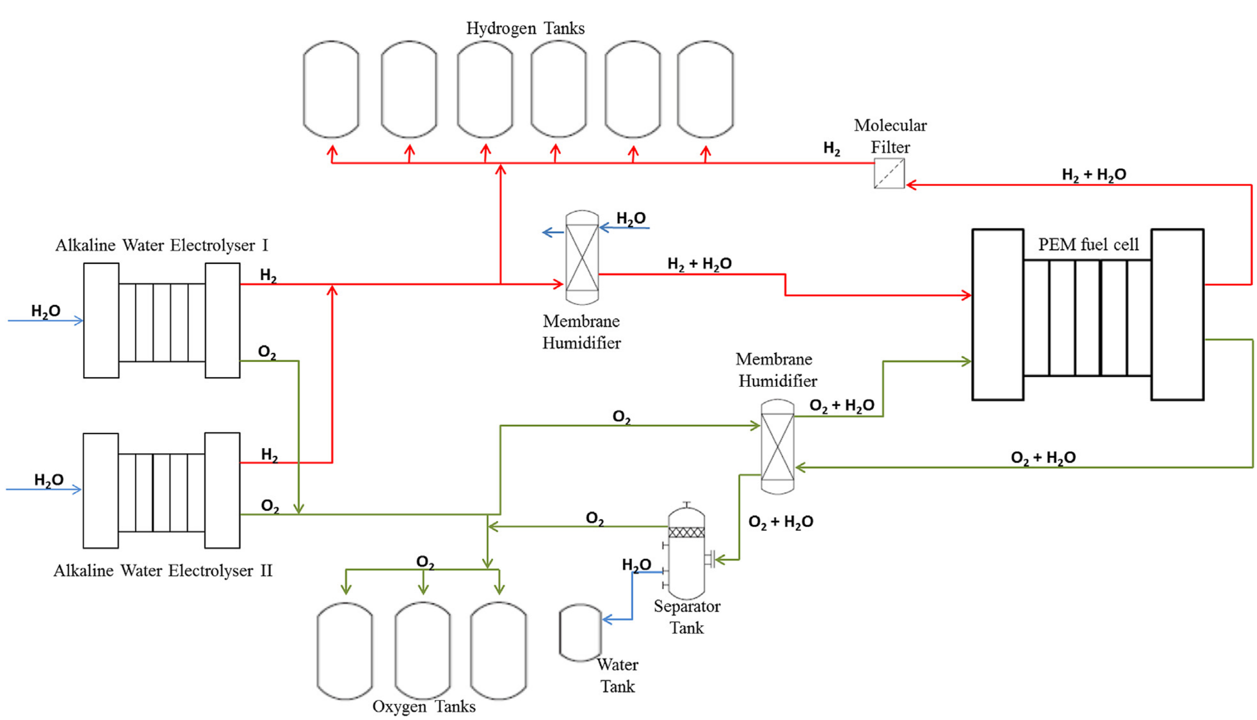

Fig. 6 – Process flow diagram of the integrated renewable power system. Flows of hydrogen appear in red, flows of oxygen appear in green and the flows of water appear in blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

cells are needed. In view of electrolyser monopolar configuration, the electrodes are connected in parallel. The integrated power system proposed offers a 16-hour-autonomy. In order to produce the necessary quantity of hydrogen to confer autonomy, two electrolysers have to work during 8 h. Energy consumption is 6.26 kW/Nm^3.

3.3. *Storage tanks*

Two different types of storage tanks were analyzed. The first one is a metal hydride based-storage tank and the second is a cylindrical tank for hydrogen that could store the gas at atmospheric pressure. Conducting a search for metal hydride tanks available in the market, we found that the one providing a 10 m^3 was that with the largest capacity and for the cylindrical tank we chose one with 150 m^3 capacity. The number of tanks need to confer autonomy are 74 in the case of metal hydride and 5 for cylindrical tanks. The cost of metal hydride tanks represents the fifth part of a cylindrical one, so to save costs, it is advisable to install the cylindrical one. The investment on storage is limited to 35% of the total cost for that purpose. Apart from that it is important to evaluate the operational cost because in order to be able to store hydrogen in the metal hydride tank, compression is needed which increases capital (for compressors) and operational cost.

3.4. *Design of the integrated renewable power system*

An integrated power system was studied to offer a 16-hour-autonomy, for remote communities. This integrated system is comprised by two alkaline water electrolysers, five cylinders tanks and a PEM fuel cell. The 53 kW of generated power is intended to be used to supply 10 families in remote areas with electrical energy. Fig. 6 shows the process flow diagram of the integrated renewable power system. The membrane humidifiers have the function of supplying the relative humidity to the fuel and the oxidant, 120% of relative humidity for hydrogen and 70% of relative humidity for oxygen [12].

4. Conclusions

An integrated power system is proposed. For the selection of the equipment a laboratory PEM fuel cell is scaled to be compared with the energy efficiency of a phosphoric acid fuel cell. From this study it was observed that with the same structural characteristic, the PEM fuel cell presents higher performance (more than 43% compared with the phosphoric acid fuel cell). To satisfy the quantity of fuel and oxidant, two alkaline water electrolyser were needed consisting of 66 unit cells but they have to be improved because they have an energy consumption of 6.26 kW/Nm^3 when those in the market have 4.5–5 kW/Nm^3. Efforts will be focused on the design of zero gap electrolysers. The technology of metal hydride storage tanks is 3 times more expensive (capital cost) than cylindrical tanks and an additional fact to be taken into account is that a compressor is needed which has an operational cost.

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