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New Fuzzy Logic Based Management Strategy to Improve Hydrogen Production from Hybrid Wind Power Systems

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Abstract- This paper presents a new approach to improve the overall efficiency of the Hydrogen Storage System (HSS). Indeed, the amount of hydrogen produced is strongly influenced by the value of the DC-voltage value, since the operating stack voltage increases with electrolyzer's current increasing. Subsequently, increasing of the DC-voltage value allows electrolyzer to absorb much more current. Then the performance of the water electrolysis process is improved. Fuzzy logic techniques, which are known as a good tool for nonlinear systems applications such as electrolyzers, are used to regulate the surplus power sent to the electrolyzer. To validate the effectiveness of the proposed solution, the system's performances are analyzed by simulation over one month profiles data. The simulation results which are carried out using Matlab/Simulink environment have confirmed the effectiveness of the HSS management strategy.

Keywords- Alkaline Electrolyzer; Buck converter; Fuzzy logic control; Hydrogen Storage System; Hybrid Power System; Energy Management Strategy.

1. Introduction

In the last decades, several development programs of renewable energy sources (RES) have been launched in many countries. Wind power is the renewable energy technology which has the fastest average annual growth rate in the global electricity system [1]. The explanation of this outstanding growth in installed wind power is both in increasing the security of energy supplies and reducing the emission of greenhouse gases (GHG) [1-3].

Due the decoupling time between energy production profiles from renewable energies such as wind power, and power demand, an energy buffer system is required. Indeed, wind power profiles depend mostly on weather conditions, while the load demand profiles are imposed by the users consumption [1].

A hydrogen storage technology included to the Hybrid Power System (HPS) can increase the penetration rate of wind power, and then reduce consumption of fossil fuels such as diesel in remote area applications. The partial structure of a hydrogen storage system (HSS) analyzed in this work is shown in Fig. 1. The main elements of this HHS are: available power from wind farm, diesel generators, alkaline electrolyzers, power conditioning unit and control system. A realistic surplus power profile is used to analyze the performance of HSS, where the power production system composed by diesel generators and wind farm are out of scope of this study.

The major contribution of this paper the improvement of the performance of water alkaline electrolyzer (AE) by size properly the DC-bus voltage at the input of buck converter. Indeed, by increasing the operating DC-voltage, which is usually limited to the 2 V/cell [4] by 15%, the electrolyzer can absorb up its rated power even at low operating temperature. An increase of electrolyzer's current causes higher overvoltage which leads to an increase of operating stack's voltage. Thus, increasing the DC-bus voltage permits to the electrolyzer to absorb much more current. According to the Faraday's law, hydrogen production is proportional to the absorbed current [3-5]. This method contributes to produce more hydrogen. In order to reach the desired performances of the electrolyzer system and its proposed control strategy based on fuzzy logic technique control, a dynamic model of buck converter is used with experimental data of an AE [6].

Moreover, an adequate sizing approach of electrolyzers in the HSS is presented and analyzed. This approach consists to analyze the impact of the size and number of electrolyzers on hydrogen production in HSS. Most of today's commercial alkaline electrolyzers allow to operate down only to 25–50% of their rated power. This means that the electrolyzer must be shut down when the input power is lower than this limit (normally 25–50% of its rated power). This is a serious drawback because once the electrolyzer has been switched off, it takes a while (30–60 min) before it can be switched on again (due to purging with nitrogen). Hence, the hydrogen production during this period of time (if the surplus power is still available) is lost [7]. Indeed, in this case, dump loads are used in order to balance power between production and demand. Then, the overall efficiency of HSS decreases. To achieve this study, an average buck converter model is used to analyze the performances and the effectiveness of this sizing method of HSS through one year surplus power profile.

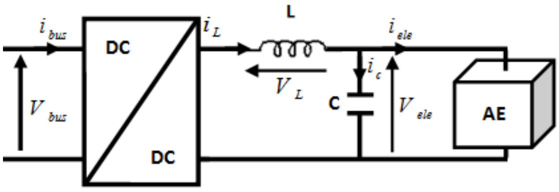

Fig. 1. The structure of hydrogen storage system (HSS)

This paper is organized as follows. An alkaline electrolyzer model and the dynamic model of buck converter are presented in section 2. Section 3 describes the impact of the variation of the DC-bus voltage on the performance of HHS efficiency. The management's strategy of hydrogen production in HSS is presented in section 4. The simulation results are presented in Section 4 and the performance of the new approach to increase the amount of hydrogen production is discussed. Finally, a conclusion about the effectiveness and the performance of the proposed are outlined.

2. Alkaline Electrolyzer System Model

2.1. Alkaline Electrolyzer Model

In this study, water *AE* is used in order to produce hydrogen and oxygen gas using surplus power from HPS. An electrolyzer stack is composed of a number of cells connected in series. The main models which describe the behavior of electrolyzer are both the electrical and thermal models. These ones permit to provide operating stack voltage, current and temperature [3].

The electrical model describes the electrolytic cell current-voltage polarization curve. The semi-empirical correlation proposed firstly by Hug [8], and then modified by Ulleberg [5] by taking into account the temperature variation. A new dynamic model of AE which is presented in [9], is a good tool to simulate its behaviour, but the information on electrical and physical data are required. In this paper we have used an experimental data given in [10] in order to analyze the impact of the DC value of AE performances. To analyze the performance of the new method of energy management in hydrogen storage system, the AE model given in [5] is used since the study is performed around one month. A current–voltage characteristic curve taking into account the operating electrolyzer's temperature has the following expression [5]:

$$V_{cell} = U_0 + \frac{r_1 + r_2 . T_{ele}}{A_{ele}} I_{ele} + s \log\left(\frac{t_1 + t_2 / T_{ele} + t_3 / T_{ele}^2}{A_{ele}} + 1 \right) \tag{1}$$

where

$$s = s_1 + s_2 T_{ele} + s_3 T_{ele}^2 \tag{2}$$

Since the operating temperature influences highly the performance of the electrolyzer [5], the thermal model of the electrolyzer is required to analyze the real state of the HSS. Therefore, a thermal model of alkaline electrolyzer used in this paper is given by Ulleberg [5].

2.2. Modelling of the DC-DC Dynamic Buck Converter

Since *the* electrolyzer has a minimum voltage to start (which is the reversible voltage), and this voltage increases with current increasing, the step-down DC-DC converter so called buck converter is used. The buck converter is chosen to feed the electrolyzer by stepping down the DC-bus voltage and stepping up the current.

The buck converter is controlled in the order to regulate the surplus power which is transmitted to the electrolyzer. Generally, the intersective Pulse Width Modulation (PWM) is the most common strategy used to regulate the power transmitted to the load, is used in this study.

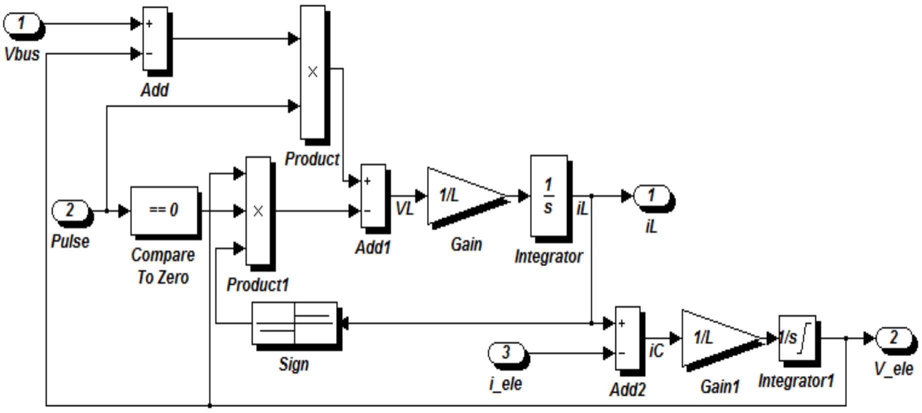

Fig. 2. Dynamic model of buck converter built on Matlab/Simulink

The variation of the current through the capacitor's filter C is give by:

$$i_C(t) = i_L(t) - i_{ele}(t) = C\frac{dV_{ele}}{dt} \qquad (3)$$

where V_{ele} and i_{ele} are the electrolyzer's voltage and current respectively, and i_L is the inductor's current.
The evolution of the voltage through the electrolyzer or the capacitor's filter is expressed as:

$$V_{ele}(t) = \frac{1}{C}\int i_C(t)dt = \frac{1}{C}\int \left(i_L(t) - i_{ele}(t)\right)dt \qquad (4)$$

The variation of the voltage across the inductance which depends on the operating mode is described as:

$$V_L(t) = \left(V_{in}(t) - V_{ele}(t)\right) * S - V_{ele}(t) * \bar{S} * sign(i_L(t)) \qquad (5)$$

where S is the logical variable and its value depends on the comparison between the duty cycle and the value of the carrier. So, S is equal to one when the duty cycle is greater than the carrier, else, S is equal to zero. sign(i_L(t)) is equal to one when the inductor current is positive and it is zero when the inductor current is zero [11]. The dynamic model of buck converter built in Matlab/Simulink software is shown in Fig. 2.

3. Impact of DC bus voltage on Alkaline Electrolyzer Performances

Usually, in the literature survey, the voltage of DC-bus in the electrolyzer system is limited at 2V/cell [4]. Hence, the electrolyzers cannot absorb up its rated power at low temperature. Since the electrolyzers are used generally in HPS with RES such as wind power, which have intermittent nature, the surplus power is not available for a long time. At low operating temperature, electrolyzer cannot absorb all the available power, then a dump load is used to balance power. Therefore, the hydrogen production during this period of time is not optimal.

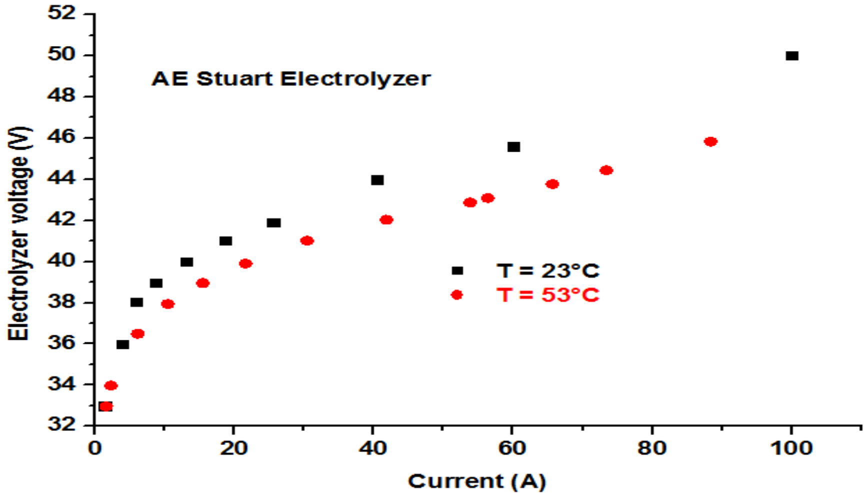

Fig. 3. Experimental data of the Stuart 5 kW AE

In this paper, a new method to increase the amount of produced hydrogen based on DC-bus voltage control is presented and analyzed. The DC-bus voltage varies in a range of 10% around the usual value used in the literature. Dynamic models of buck converter and electrolyzer presented in detail in section 2 are used to show the effectiveness and the performance of the proposed method. Fig. 3 shows the experimental data of the Stuart 5 kW AE presented in this work. Fig. 4 and Fig. 5 illustrate the inputs values and output value of the fuzzy logic controller. Table 1 shows the fuzzy rules.

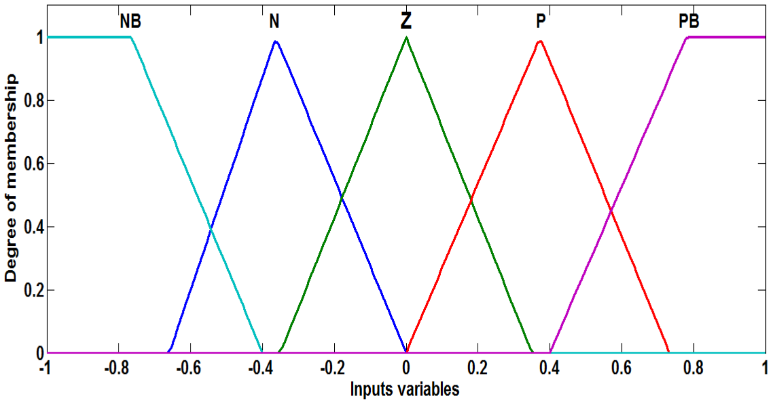

Fig. 4. Membership function of inputs variables of FLC

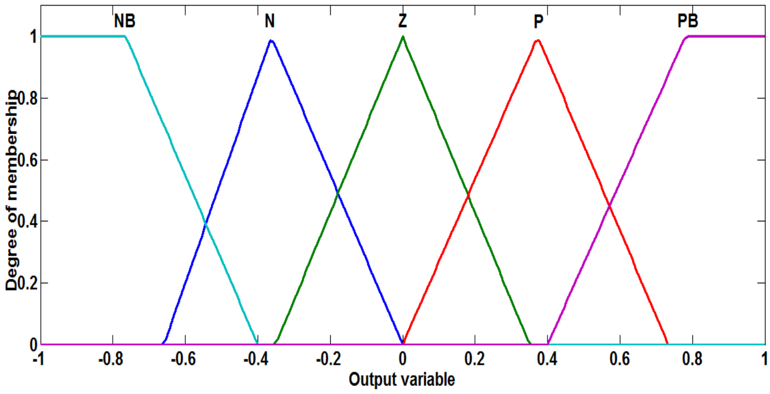

Fig. 5. Membership function of output variables of FLC

Table 1. FLC fuzzy rules

Output		*Δe(t)*				
		BN	*N*	*Z*	*P*	*BP*
e(t)	*BN*	*BN*	*Z*	*BN*	*Z*	*Z*
	N	*Z*	*N*	*N*	*Z*	*Z*
	Z	*BN*	*N*	*Z*	*P*	*BP*
	P	*Z*	*Z*	*P*	*P*	*Z*
	BP	*Z*	*Z*	*BP*	*Z*	*BP*

To achieve properly the control of DC buck converter that feed the electrolyzer, the absorbed current should be known. In our study experimental data for 23°C and 53°C are used. The values represent the low and the medium operating temperature of the AE. A lookup table is used to implement the AE voltage as function of the drawing current.

The Power Management Strategy (PMS) which gives the optimal AE voltage is shown in Fig. 6. The PMS permits to provide the desired stack voltage value which is used by the buck converter's controller based on fuzzy logic technique. Note that the fuzzy logic controller has been programmed in C code using an embedded S-function block in Matlab/Simulink software. Hence, the hardware implementation of the proposed control strategy can be achieved easily using a microcontroller or a DSP.

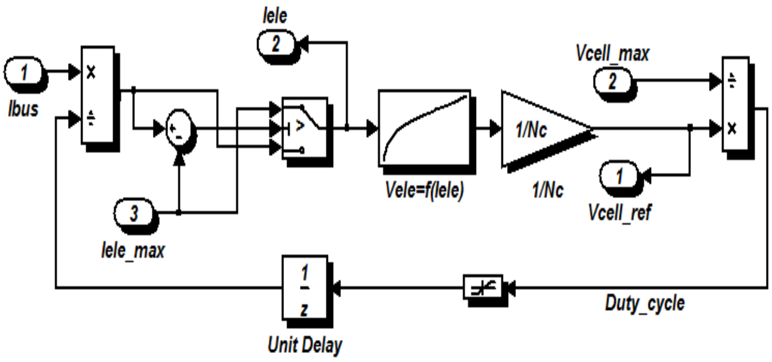

Fig. 6. Scheme of power strategy management (PSM) of surplus power

4. Power Management Strategy to Improve Hydrogen Production

Most of today's commercial AE must be switched off when the available surplus power is less than 25% to 50% of their rated power. Therefore, the electrolyzer is shoot down when the input power is lower than this limit (normally 25–50% of its rated power). This is a serious drawback because once the electrolyzer has been switched off, it takes a while (30–60 min) before it can be switched on again (due to purging with nitrogen) [7]. Hence, if the surplus power is still available, the hydrogen production during this period of time is lost. Therefore, during the switching off time, the available surplus power cannot be absorbed, and then hydrogen production is stopped. The excess power that could be produced during this period is sent to a dump load [12]. Then, the overall efficiency of HSS decreases, since the amount of produced hydrogen decreases. Then, Eq. 6 and Eq. 7 represent the proposed method used for sizing the two AE.

$$P_{ele1} = (1-b) \times P_{available} \tag{6}$$

$$P_{ele2} = b \times P_{available} \tag{7}$$

where P_{ele1} and P_{ele2} represent the rated power of the two AE. $P_{available}$ represents the surplus power in the DC bus, while b is the power limit in (p.u). This limit is fixed at 0.25 in this study.

5. Simulation Results and Discussion

5.1 Impact of the DC Bus Voltage

Fig. 7 depicts the performance of the FLC of the AE voltage. It can seen that the measured voltage tracks with better accuaracy the setpoint value.

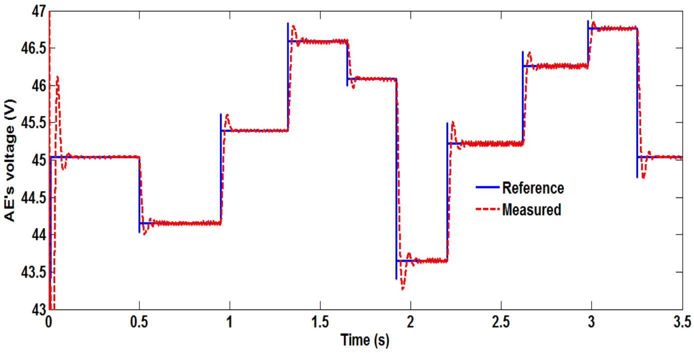

Fig. 7. Performance of the control of the AE voltage

The current absorbed by the AE and the DC bus current are illustrated in Fig 8, while Fig. 9 shows the duty cycle of buck converter.

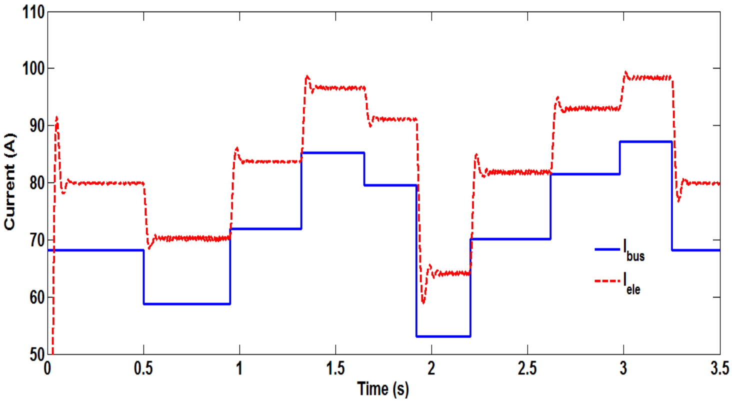

Fig. 8. Currents in the AE system

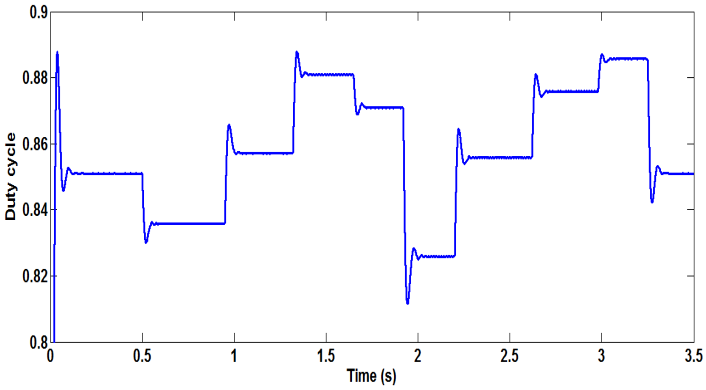

Fig. 9. Variation of the duty cycle of buck converter

The profile of the excess power in the DC bus is illustrated in Fig. 10. Fig. 11 shows the impact of the DC bus voltage on the performance of the electrolyzer for lower temperature (23° C). It can be seen that by increasing the DC bus voltage by only 10%, the AE absorbs up to its rated power (5 kW) even at low operating temperature. The absorbed power is limited at 3.44 kW which represents 69% of the rated power.

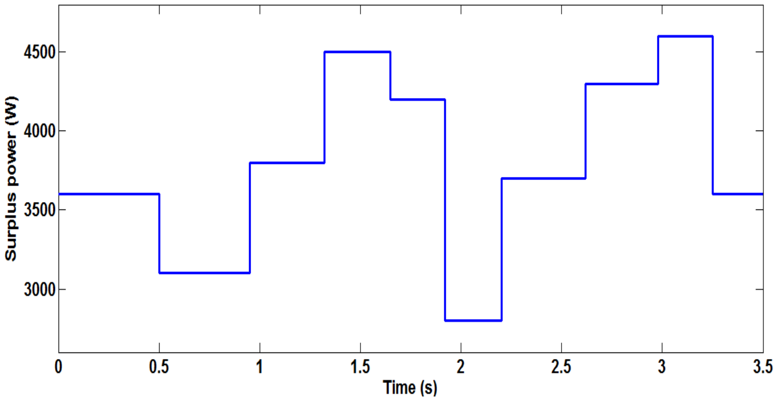

Fig. 10. Profile of surplus power

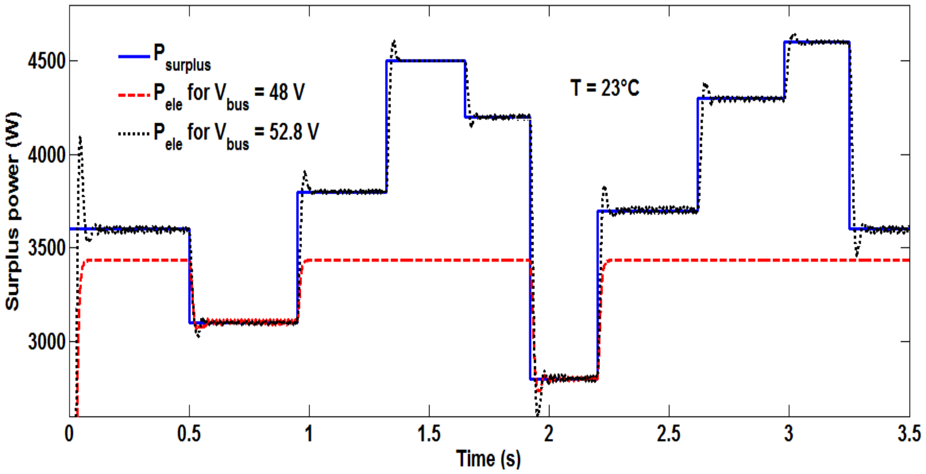

Fig. 11. Comparison of absorbed power for different DC bus voltage

This means that 31% of power is lost with conventional configuration, where a dump load is used to dissipate this power in order to balance the power in the DC bus. Fig. 12 shows that the AE has a good performance at 53°C compared to 23°C with a conventional sized DC bus. Indeed, the electrolyzer absorbs all power at 53°C with a comparison of the low operating temperature. By oversizing a DC bus voltage by 10%, the electroyzer can absorb all surplus power up its rated power even at low operating temperature.

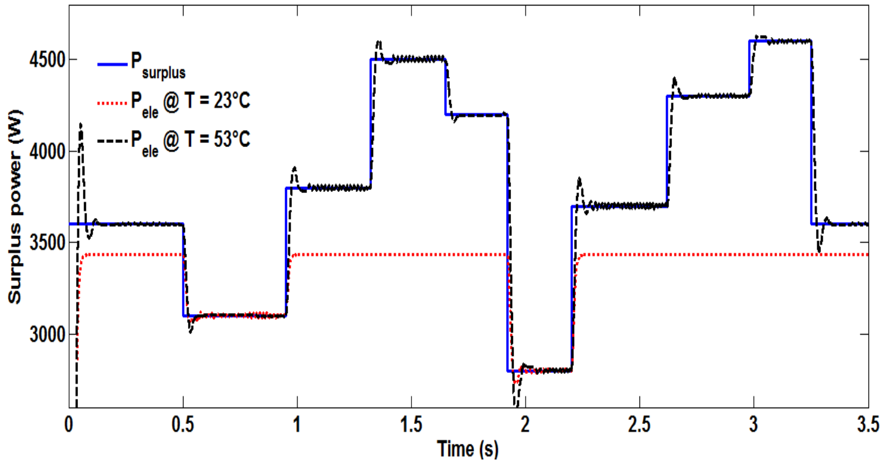

Fig. 12. Comparison of absorbed power for different operating temperature

5.2 Impact of the Size of Electrolyzers on Hydrogen Production

In the order to investigate the performance of the proposed sizing method, the 26 kW AE, its models and parameters are given in [5]. In this study, three cases are analyzed and a one month profile of the surplus power is used.

Case I

In the first case, a 26 kW electrolyzer is investigated. Fig. 13 and Fig. 14 illustrate respectively the voltage and the current of the 26 kW electrolyzer, while Fig. 15 shows its operating temperature. The surplus of power and the power absorbed by the electrolyzer are depicted in Fig 16.

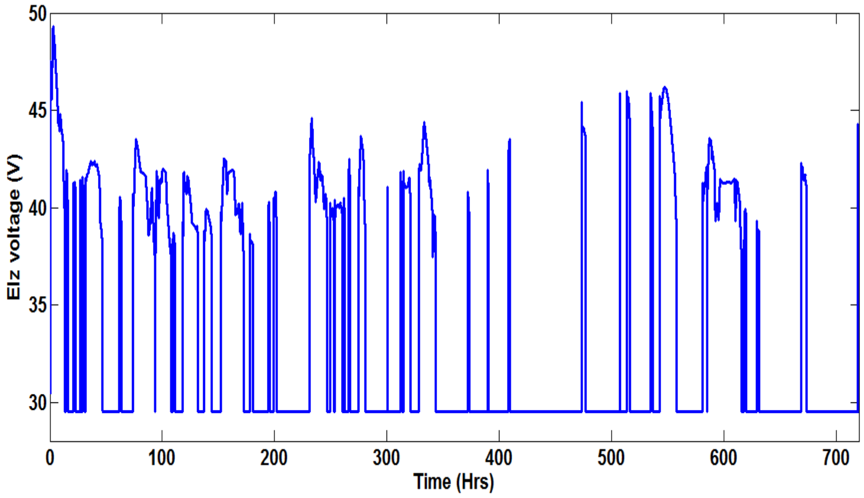

Fig. 13. Voltage of the 26 kW AE

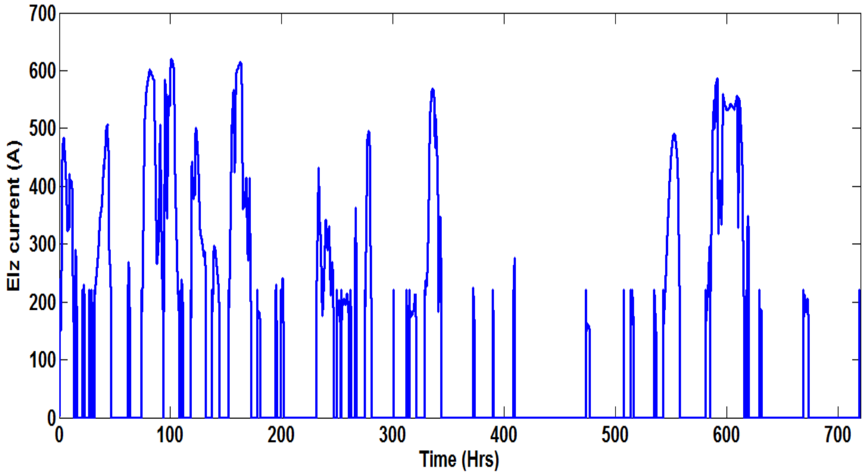

Fig. 14. Current of the 26 kW AE

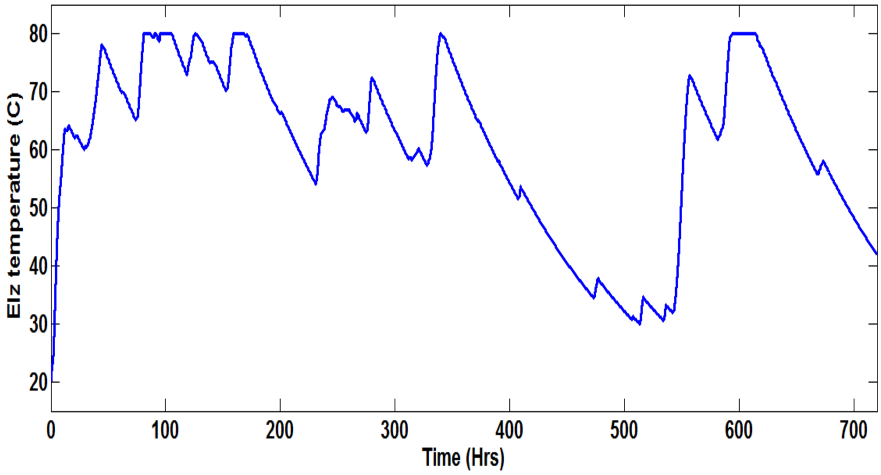

Fig. 15. Operating temperature of the 26 kW AE

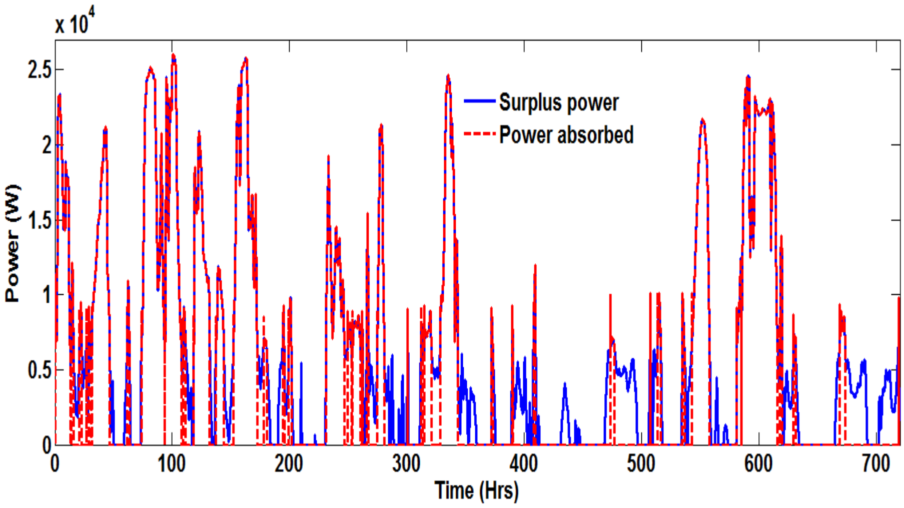

Fig. 16. Surplus power and power absorbed by the 26 kW AE

Case II

In Case II, two 13 kW electrolyzers are used. Fig. 17 and Fig. 18 show respectively the voltage and the current of the both 13 kW electrolyzers, while Fig. 19 shows their operating temperature. The power absorbed by both electrolyzers are depicted in Fig. 20.

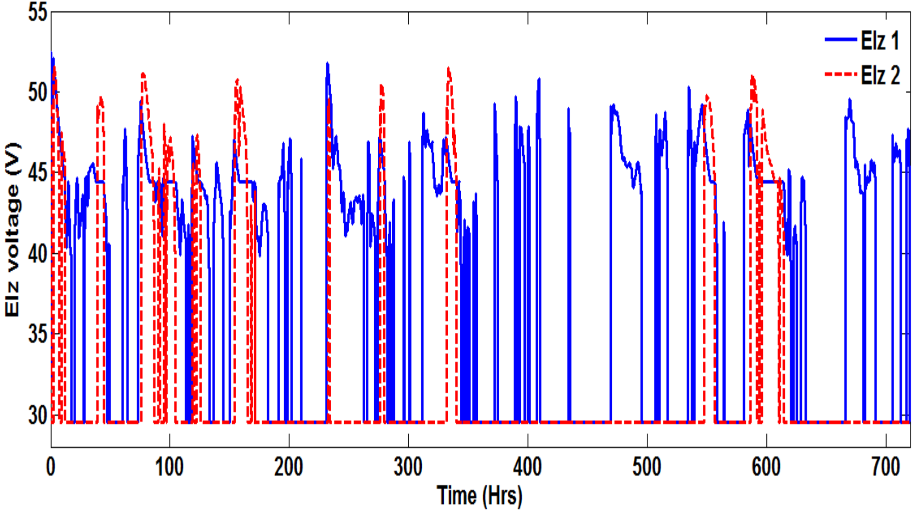

Fig. 17. Voltages of both 13 kW AE

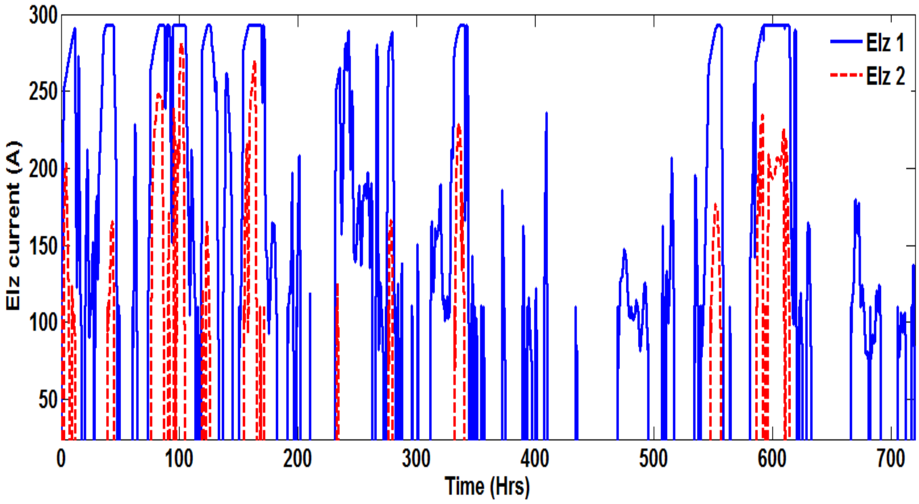

Fig. 18. Currents of both 13 kW AE

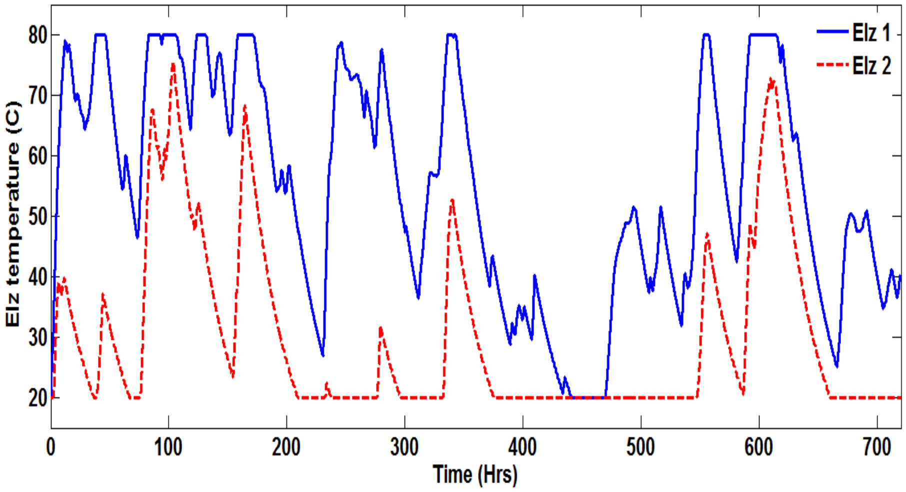

Fig. 19. Operating temperatures of both 13 kW AE

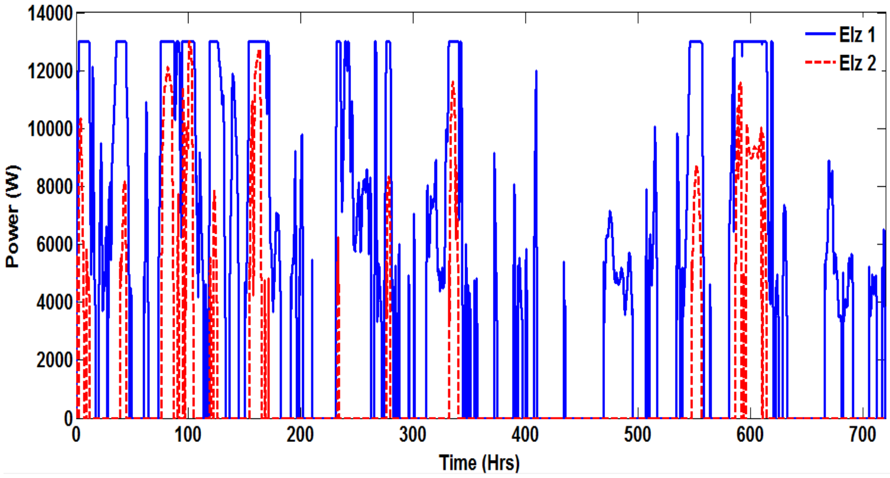

Fig. 20. Power absorbed by the both 13 kW AE

Case III

In the third case, two electrolyzers (19.5 kW and 6.5 kW) are used. Fig. 21 and Fig. 22 depict respectively the voltages and the currents of 19.5 kW and 6.5 kW, while Fig. 23 illustrates their operating temperature. The powers absorbed by both electrolyzers are shown in Fig 24.

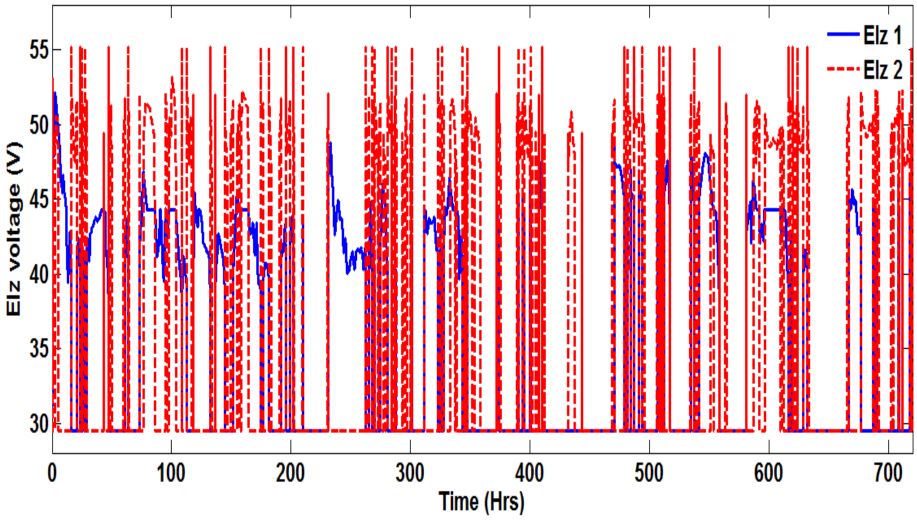

Fig. 21. Voltages of both 19.5 kW and 6.5 kW AE

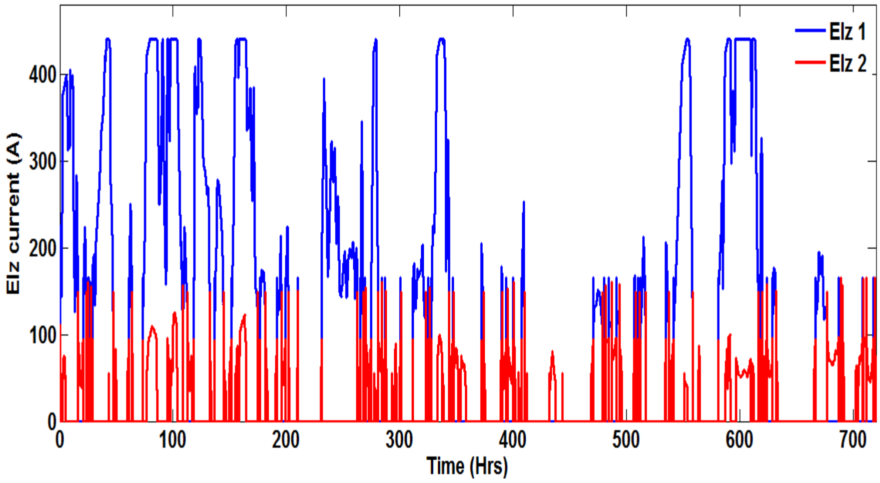

Fig. 22. Currents of both 19.5 kW and 6.5 kW AE

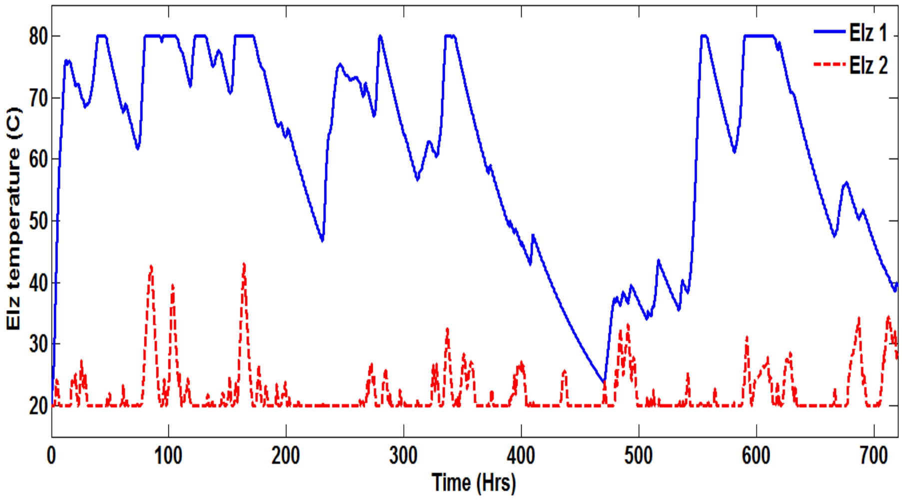

Fig. 23. Operating temperatures of both 19.5 kW and 6.5 kW AE

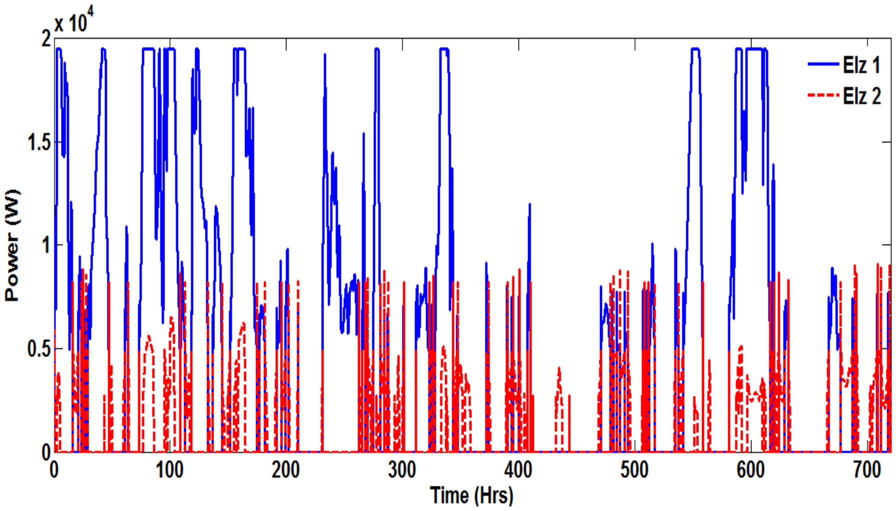

Fig. 24. Power absorbed by the both 19.5 kW and 6.5 kW AE

Fig. 25 shows the comparison of the hydrogen production in the three investigated cases. It can be seen that 815 N.m^3 are produced with one electrolyzer, while 887 N.m^3 are produced with two same 13 kW electrolyzers, and 940 N.m^3 are produced by the two 19.6 kW and 6.5 kW electrolyzers. This means that hydrogen production was increased by 8.84% and 15.34% respectively in case II and case III with comparison to Case I.

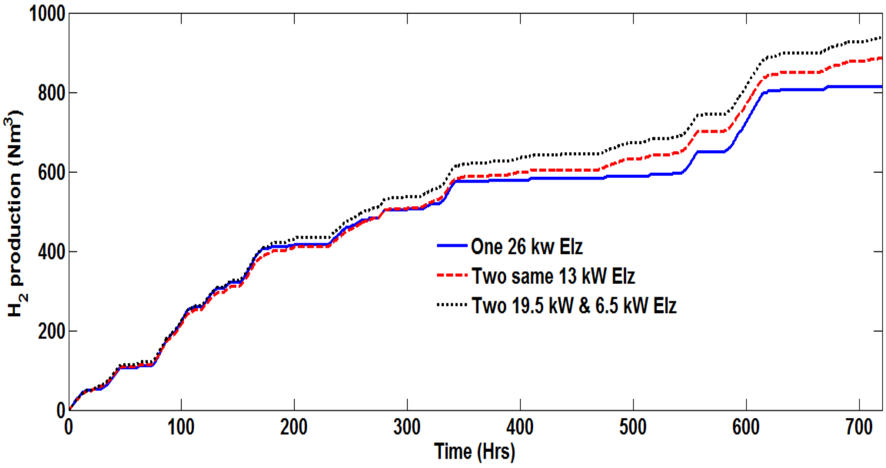

Fig. 25. Comparison of the H_2 production in three cases

6. Conclusion

In this paper, a new strategy to improve the efficiency of the hydrogen production system in a structure integrating renewable energy sources. Indeed, because of the intermittent and the stochastic nature of these renewable energy sources, it is difficult to predict the excess power absorbed by the electrolyzer. Thus, the electrolyzer will be observed several stops and starts, which means that its operating temperature fluctuates between ambient temperature and its optimal Temperature. A new method based on the oversizing of the DC bus voltage was proposed. The study supported by experimental results, showed that the electrolyzer can absorb up to its rated power even at low temperatures.

Thereafter, a new design method of hydrogen storage system was presented in order to increase the amount of produced hydrogen. The study showed that the best approach is using two electrolyzers with 75% and 25% of the maximum surplus power which produces the most amount of H_2. Indeed, with this strategy, the hydrogen production increases by about 15% compared to the case where a single power electrolyzer.

Acknowledgements

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References

[1] F. J. Pino, L. Valverde, and F. Rosa, "Influence of wind turbine power curve and electrolyzer operating temperature on hydrogen production in wind–hydrogen systems," *Journal of Power Sources,* vol. 196, pp. 4418-4426, 2011.

[2] R. Sarrias, L. M. Fernández, C. A. García, and F. Jurado, "Coordinate operation of power sources in a doubly-fed induction generator wind turbine/battery hybrid power system," *Journal of Power Sources,* vol. 205, pp. 354-366, 2012.

[3] T. Zhou and B. Francois, "Modeling and control design of hydrogen production process for an active hydrogen/wind hybrid power system," *International Journal of Hydrogen Energy,* vol. 34, pp. 21-30, 2009.

[4] T. Zhou, "Commande et supervision énergétique d'un générateur hybride actif éolien incluant du stockage sous forme d'hydrogène et des super-condensateurs pour l'intégration dans le système électrique d'un micro réseau," Ecole Centrale de Lille, 2009.

[5] Ø. Ulleberg, "Modeling of advanced alkaline electrolyzers: a system simulation approach," *International Journal of Hydrogen Energy,* vol. 28, pp. 21-33, 2003.

[7] Ø. Ulleberg, T. Nakken, and A. Ete, "The wind/hydrogen demonstration system at Utsira in Norway: Evaluation of system performance using operational data and updated hydrogen energy system modeling tools," *International Journal of Hydrogen Energy,* vol. 35, pp. 1841-1852, 2010.

[8] W. Hug, J. Divisek, J. Mergel, W. Seeger, and H. Steeb, "Highly efficient advanced alkaline electrolyzer for solar operation," *International journal of hydrogen energy,* vol. 17, pp. 699-705, 1992.

[11] C. Batard, F. Poitiers, C. Millet, and N. Ginot, "Simulation of power converters using Matlab-Simulink," 2012.

[12] D. Bechrakis, E. McKeogh, and P. Gallagher, "Simulation and operational assessment for a small autonomous wind–hydrogen energy system," *Energy Conversion and Management,* vol. 47, pp. 46-59, 2006.