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Journal of Power Sources 162 (2006) 757–764
JOURNAL OF POWER SOURCES
www.elsevier.com/locate/jpowsour

Control analysis of renewable energy system with hydrogen storage for residential applications

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Received 19 January 2005; accepted 7 April 2005
Available online 24 August 2005

Abstract

The combination of an electrolyzer and a fuel cell can provide peak power control in a decentralized/distributed power system. The electrolyzer produces hydrogen and oxygen from off-peak electricity generated by the renewable energy sources (wind turbine and photovoltaic array), for later use in the fuel cell to produce on-peak electricity. An issue related to this system is the control of the hydrogen loop (electrolyzer, tank, fuel cell). A number of control algorithms were developed to decide when to produce hydrogen and when to convert it back to electricity, most of them assuming that the electrolyzer and the fuel cell run alternatively to provide nominal power (full power). This paper presents a complete model of a stand-alone renewable energy system with hydrogen storage controlled by a dynamic fuzzy logic controller (FLC). In this system, batteries are used as energy buffers and for short time storage. To study the behavior of such a system, a complete model is developed by integrating the individual sub-models of the fuel cell, the electrolyzer, the power conditioning units, the hydrogen storage system, and the batteries. An analysis of the performances of the dynamic fuzzy logic controller is then presented. This model is useful for building efficient peak power control.

Keywords: Renewable energy; Fuel cell; Fuzzy logic; Electrolyzer; Hydrogen; Energy conversion

1. Introduction

The global energy situation tends to become more complex as the demand grows faster than the offer. With many developing countries lacking the resources to build power plants and distribution networks and the industrialized countries that face insufficient power generation and greenhouse gas emission problems, new solutions to the energy issue are needed. Distributed generation system that use renewable energy resources could be a part of the solution [1–12]. These systems address both the economical and environmental issues of the problem. The Hydrogen Research Institute (HRI) has developed and implemented an autonomous renewable energy systems (RES) that uses wind and solar energy to power a load autonomously (Fig. 1). This is done by storing the excess energy produced by the sources in hydrogen by using an electrolyser and to provide on-peak energy by reconverting this hydrogen into electricity with a fuel cell when the weather is bad. There is also a battery stack that is used to maintain a constant the DC bus voltage and to store short-term energy. A control system was developed to determine when to produce hydrogen and when to convert it back to electricity. The control algorithm is based on the batteries' state-of-charge (SOC) and it relies on fixed SOC limits to determine when to start the electrolyzer or the fuel cell [2,6,12,13]. However, this method presents two important shortcomings: it does not take into account the system's state except for the batteries' SOC and it does not allows for the control of the hydrogen's rate of production or consumption, which could help manage the energy in the system. Vosen and Keller [12] also presented a control method based on neural networks. This controller uses the system's state to control the hydrogen storage loop but it presents an important weakness: the controller must be provided with high quality

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doi:10.1016/j.jpowsour.2005.04.038

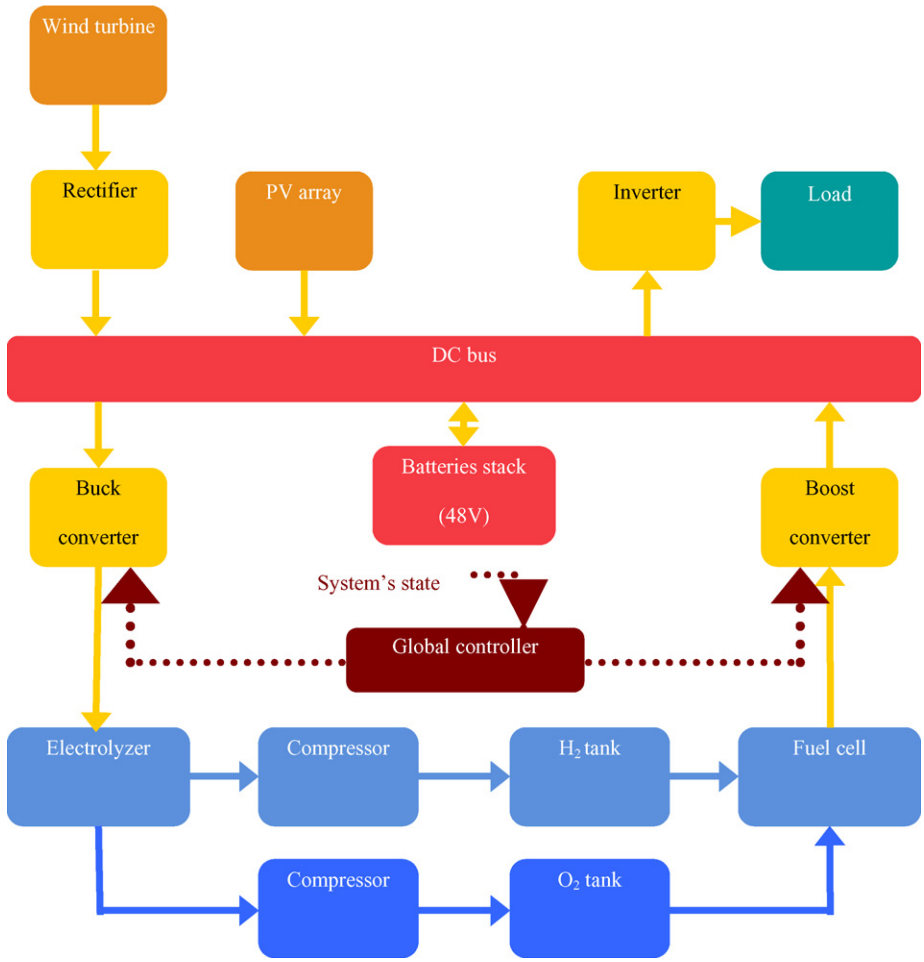

Fig. 1. Renewable energy system.

historical data to be efficient. This paper presents a dynamic controller that overcomes these issues by using fuzzy logic. The proposed fuzzy logic controller (FLC) determines the appropriate hydrogen's rate of production/consumption as a function of the system's power inputs and outputs and the batteries' SOC. The chosen rate is then applied to the electrolyzer or the fuel cell by using local power control loops around these devices. A model of the RES used to design and validate the proposed controller is first presented. The design of the FLC itself is then presented. The simulation parameters that were chosen to test the controller and the results analysis are finally given.

2. System's model

A complete model of the RES was developed in order to design and validate an adequate controller. The model was built using sub-models for each individual component. The model described in [14] was used as a base but a few modifications were made to include the new control system. Among them, the most important is the addition of local power controllers for the electrolyzer and the fuel cell. These controllers are implemented using the buck converter for the electrolyzer and the boost converter for the fuel cell. The power converters' duty cycle were thus eliminated as a variable in the system and then replaced by their output power. Moreover, since the converters' dynamic is considered to be much faster than that of the system, it was neglected and the converters are treated as devices providing a fixed output power (this output power is determined by the set point decided by the FLC).

2.1. Batteries model

The batteries stack is the element linking together each component of the RES. Since it is connected in parallel with the DC bus and it acts as an energy buffer, the current flowing into or from the batteries is defined by (1):

$$I_{\mathrm{B}}(t) = I_{\mathrm{PV}}(t) + I_{\mathrm{Wind}}(t) + I_{\mathrm{Bo}}(t) - I_{\mathrm{Bu}}(t) - I_{\mathrm{Load}}(t) \quad (1)$$

where $I_{\mathrm{PV}}(t)$ is the photovoltaic array's current (A), $I_{\mathrm{Wind}}(t)$ is the wind turbine's current (A), $I_{\mathrm{Bo}}(t)$ is the boost converter's current (A), $I_{\mathrm{Bu}}(t)$ is the buck converter's current (A), and $I_{\mathrm{Load}}(t)$ is the load current (A).

This current is positive when the batteries are charging and negative otherwise. Knowing the current, it is possible to deduce the voltage by:

$$U_B(t) = (1 + \alpha t)U_{B,0} + R_i I_B(t) + K_i Q_R(t) \quad (V) \tag{2}$$

where α is the self-discharge rate (Hz), $U_{B,0}$ is the open-circuit voltage at time 0 (V), R_i is the internal resistance (Ω), K_i is the polarization coefficient ($\Omega\,h^{-1}$), and $Q_R(t)$ is the rate of accumulated charge.

The total energy stored in the batteries is given by:

$$E_B(t) = E_{B,0} + \frac{1}{3600}\int I_B(t)\,dt \quad (Ah) \tag{3}$$

where $E_{B,0}$ is the batteries' initial energy (Ah).

Substituting (1) into (3), it is possible to express the batteries' energy in the Laplace domain using this equation:

$$E_B = E_{B,0} + \frac{I_{PV} + I_{Wind} + I_{Bo} - I_{Bu} - I_{Load}}{3600s} \quad (Ah) \tag{4}$$

Finally, this energy can be expressed as a state-of-charge using the following equation:

$$SOC_B = 100 \times \frac{E_B}{E_{B,max}} \quad (\%) \tag{5}$$

where $E_{B,max}$ is the total capacity of the batteries (Ah).

2.2. Electrolyzer's and buck converter's model

This part of the system can be represented by a power source (the buck converter) feeding the power needed by the electrolyzer. As previously stated, the buck converter dynamic is negligible compared to the electrolyser one. The converter was thus modeled as an ideal power source where the ratio from its output power to its input power is dictated by its efficiency.

$$P_{El} = \eta_{Bu} P_{Bu} \quad (W) \tag{6}$$

where η_{Bu} is the efficiency of the buck converter and P_{Bu} is the buck converter's input power (W).

The converter's output voltage and current are dictated by the electrolyzer. The voltage is first defined by:

$$U_{El} = \frac{P_{El}}{I_{El}} \quad (V) \tag{7}$$

where I_{El} is the electrolyzer's current (A).

This voltage can also be expressed by (8) and is related to the electrolyzer's current and temperature.

$$U_{El} = U_{El,0} + C_{1El} T_{El}(t) + C_{2El} \ln\left(\frac{I_{El}(t)}{I_{El,0}}\right) + \frac{R_{El} I_{El}(t)}{T_{El}(t)} \quad (V) \tag{8}$$

where $U_{El,0}$ (V), C_{1El} (V °C^{-1}), C_{2El} (V), R_{El} (Ω °C) and $I_{El,0}$ (A) are constants that were determined experimentally; and T_{El} (t) is the cells' operating temperature (°C).

Substituting (7) into (8), it is possible to obtain an equation linking the electrolyzer's current to the converter's output power. Since the hydrogen's rate of production is directly proportional to the electrolyzer's current (9), it is possible to control it by varying the buck converter's set point.

$$\dot{V}_{El} = N_{Cell,El} \frac{\eta_{I,El} I_{El}(t)}{C_{H_2}} \quad (l\,s^{-1}) \tag{9}$$

where $\dot{V}_{El}$ is the hydrogen production rate, $N_{Cell,El}$ is the number of cells, $\eta_{I,El}$ is the electrolyzer's utilisation factor, and C_{H_2} is a conversion coefficient (Ah l^{-1}).

2.3. Fuel cell's and boost converter's model

This part of the RES is very similar to the buck converter/electrolyzer group. In the same way, the boost converter is represented as an ideal power source that delivers a chosen power to the dc bus. The ratio from its output power to its input power is also directly related to its efficiency (10).

$$P_{Bo} = \eta_{Bo} P_{FC} \quad (W) \tag{10}$$

where η_{Bo} is the boost converter's efficiency and P_{FC} is the boost converter's input power (W).

Again, the converter's input voltage is fixed by the fuel cell and is described by (11) and (12).

$$U_{FC} = \frac{P_{FC}}{I_{FC}} \quad (V) \tag{11}$$

where I_{FC} is the fuel cell's current (A).

$$U_{FC} = U_{FC,0} + C_{1FC} T_{FC}(t) + C_{2FC} \ln\left(\frac{I_{FC}(t)}{I_{FC,0}}\right) + \frac{R_{FC} I_{FC}(t)}{T_{FC}(t)} \quad (V) \tag{12}$$

where $U_{FC,0}$ (V), C_{1FC} (V °C^{-1}), C_{2FC} (V), R_{FC} (Ω °C) and $I_{FC,0}$ (A) are constants that were determined experimentally, and $T_{FC}(t)$ is the fuel cell's operating temperature (°C).

The substitution of (11) in (12) gives an expression linking the fuel cell's current to the boost converter's input power. This expression is useful to determine the hydrogen's rate of consumption by the fuel cell (13).

$$\dot{V}_{FC} = N_{Cell,FC} \frac{\eta_{I,FC} I_{FC}(t)}{C_{H_2}} \quad (l\,s^{-1}) \tag{13}$$

where $\dot{V}_{FC}$ is the hydrogen consumption rate, $N_{Cell,FC}$ is the number of cells, $\eta_{I,FC}$ is the fuel cell's utilisation factor, and C_{H_2} is a conversion coefficient (Ah l^{-1}).

Using (10) to relate the boost converter's output power to its input power, it is then possible to vary the hydrogen's rate of consumption by changing the converter's set point.

2.4. Hydrogen storage's model

The model for the hydrogen's production and consumption rate allows for the derivation of an expression giving the energy stored as hydrogen:

$$E_{H_2} = E_{H_2,0} + \int (P_{El} - P_{FC})\,dt \quad (kJ) \tag{14}$$

where $E_{H_2,0}$ is the initial energy stored as hydrogen (kJ), P_{El} is the electrolyzer's power production rate (as hydrogen), and P_{FC} is the fuel cell's power consumption rate (as hydrogen).

The following equations relate power production and consumption rates to the hydrogen's production and consumption rates of the electrolyzer and the fuel cells:

$$P_{El} = \frac{\dot{V}_{El}\,\Delta H}{V_T} \quad (kJ\,s^{-1}) \tag{15}$$

$$P_{FC} = \frac{\dot{V}_{FC}\,\Delta H}{V_T} \quad (kJ\,s^{-1}) \tag{16}$$

where ΔH is the hydrogen's enthalpy ($kJ\,mol^{-1}$) and V_T is a conversion constant ($l\,mol^{-1}$).

Combining (14), (15) and (16) in the Laplace domain, the net hydrogen's production can be derived:

$$E_{H_2} = E_{H_2,0} + \frac{1}{s}\left(\frac{\dot{V}_{El}\,\Delta H}{V_T} - \frac{\dot{V}_{FC}\,\Delta H}{V_T}\right) \quad (kJ) \tag{17}$$

The hydrogen's storage level is therefore:

$$HL = 100 \times \frac{E_{H_2}}{E_{H_2,max}} \quad (\%) \tag{18}$$

3. Fuzzy logic controller

The RES' global controller is critical to manage efficiently the energy flow in the system. There are two main objectives that must be considered when designing the controller. The first objective is to reduce the energy transfers from the short-term storage to the long-term storage and vice-versa when possible. Storing energy as hydrogen is very costly in terms of efficiency, it is then preferable to use the long-term storage only when there's a large quantity of excess energy and there's sufficient energy in the batteries to provide for the short-term demand. On the other hand, the fuel cell must be started only when the load consumption is much higher than the power produced by the sources. The second objective is to prevent abusive use of the batteries. Although the batteries are of "deep-cycle" type, they must not be discharged too deeply and for a long time in order to lengthen their lifetime. The controller must then control the batteries' state-of-charge to avoid these situations.

Since, the wanted behaviour is well known and can be described using linguistic variables, the use of a FLC seems appropriate. This type of controllers presents many advantages for this system. First of all, it allows us the use of multiple input variables without increasing the controller's complexity. It also simplifies the controller's design since the wanted behaviour can be described easily in words but it would be difficult to express mathematically. It is more convenient than a classical expert system because the behaviour for the entire range of inputs can be defined by using only a few rules. Finally, there's no need for historical data, which is an important advantage over other types of "intelligent" controllers such as neural networks and genetic algorithms.

3.1. FLC's structure

The wanted behaviour, as described above, was implemented with the help of two input variables: the net power flow (dP) and the batteries' SOC. The net power flow is simply the difference between the power provided by the sources and the power consumed by the loads. This information is useful to determine whether there is excess energy available or not and how much. The batteries' SOC is used to prevent a deep discharge of the batteries and to know how much short-term energy is available. Both values are normalized to simplify their representation in the FLC. The net power flow is also filtered by a low-pass filter with a very low time constant. This filtering is important to avoid running the electrolyzer and the fuel cell for very short period of time. It is effectively more efficient to use these devices for at least a few minutes at a time since they operate more efficiently at high temperatures and their temperature rise only when they are in operation [15,16]. Moreover, the electrolyzer stores its hydrogen production in a small buffer tank and it transfers this hydrogen in the main tank only once it is full. Since this buffer tank is emptied in the atmosphere when the electrolyzer starts up, it is easy to figure that most of the production would be lost if the electrolyzer is started up frequently for very short period of time.

The FLC output variable is a power set point. When the output is positive, the set point is sent to the boost converter and the fuel cell is started. On the other hand, when the output is negative the set point is sent to the buck converter and the electrolyzer is started. It is important to note that the minimum set point was fixed to 500 W since their efficiency is too low below this threshold [15,16]. If the FLC's output is below this value, both the electrolyzer and the fuel cell are stopped.

3.2. Membership functions

In order to keep the controller simple, only three membership functions for each input were used. The linguistic variables positive (P), zero (Z) and negative (N) along with triangular functions were used for the net power flow and the power set point (Fig. 2).

The batteries' SOC input was divided using the variables low (L), normal (N) and high (H), as shown on Fig. 3. In this case, trapezoidal functions were preferred to triangular functions because these functions are more appropriate to obtain the wanted behaviour. It is desirable, per example, that the controller starts the fuel cell at high power when the batteries are mostly discharged. The SOC must then be considered as "fully" low when it is below a minimum threshold.

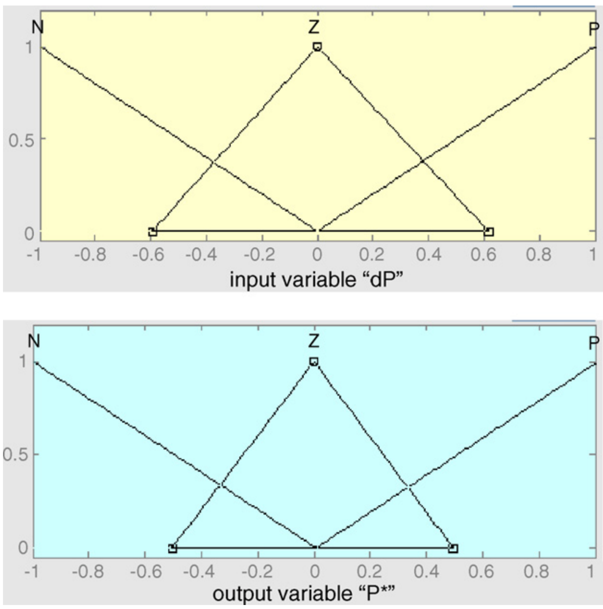

Fig. 2. Membership functions for the net power flow (dP) and the power set point (P^*).

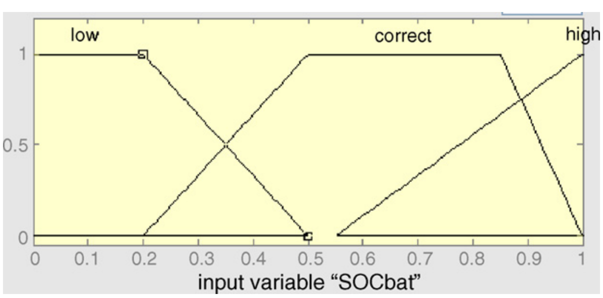

Fig. 3. Membership function for the batteries' SOC.

This behaviour is easily obtained with the use of trapezoidal functions.

The exact shape of each membership function was determined using the control surface (Fig. 4) to produce the wanted behaviour. The control surface shows that the power set point will be more positive (the fuel cell will be started) if the SOC is lower and/or the net power flow is more negative. On the other hand, the power set point will be negative (the electrolyzer will be started) if the SOC is sufficiently high and the net power flow is more positive.

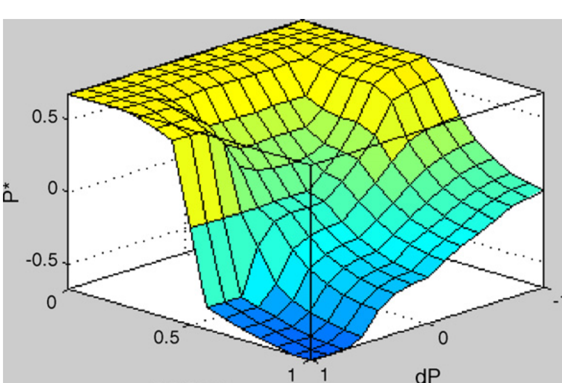

Fig. 4. Control surface.

3.3. Rules

The controller's behaviour is also defined by the FLC's rules. Always in the sake of simplicity, the number was minimized. The rules were chosen very intuitively following the guidelines previously enounced:

- if the net power flow is negative then the power set point is positive;
- if the net power flow is zero then the power set point is zero;
- if the net power flow is positive and the SOC is high then the power set point is negative;
- if the SOC is low, then the power set point is positive;
- if the SOC is high, then the power set point is negative.

It is important to specify that the implication operator is MIN and the aggregation operator is MAX. The output is defuzzified using the centroid method.

4. Simulation

In order to simulate the system, the model described in Section 2 was implemented in Matlab/Simulink (Fig. 5) and the designed fuzzy logic controller was defined using the Fuzzy Logic Toolbox. What was wanted is an overview of the system's behaviour over a long period of time. To achieve this, the system was simulated for a complete week using an integration step of 60 s. While this value is high, this has no significant impact on the precision of the results because there's no fast dynamics in the model. Moreover, the real controller will be implemented using similar time constants. The model needs three inputs: the wind turbine power, the photovoltaic array (PV) power and the loads power. Real data was used to represent the reality more closely. The wind turbine and PV array power data come from a database containing measures from the HRI's wind turbine and PV array. The data for a typical July week was used. The load data was kindly provided by Hydro-Québec and it represents power consumption data for a typical residence, also for a week in July.

Since the controller makes sure that the electrolyzer and the fuel cell are not used for less than a few minutes at a time, the effect of the temperature was neglected. The temperatures were assumed to be the nominal values.

Finally, all the model's parameters were determined experimentally by Kélouwani et al. [14]. They are presented in the Table 1.

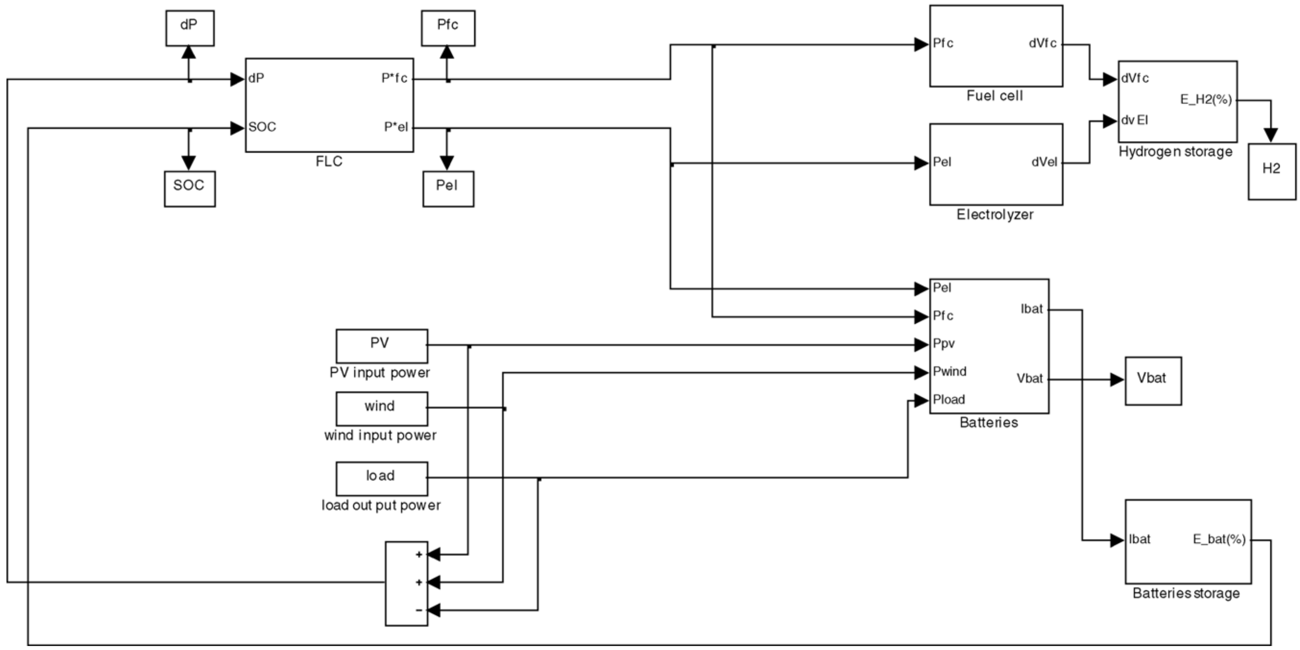

Fig. 5. System's Simulink model.

Table 1
Measured and known parameters

Section	Parameter	Value	Parameter	Value
Batteries	α (Hz)	~0	R_i (Ω)	0.076
	$U_{B,0}$ (V)	48	K_i	~0
Electrolyzer	$U_{El,0}$ (V)	22.25	R_{El} (Ω °C)	−3.3189
	C_{1El} (V °C^{-1})	−0.1765	C_{2El} (V)	5.5015
	$I_{El,0}$ (A)	0.1341	$N_{Cell,El}$	24
	$\eta_{I,El}$	0.7	C_{H_2} (Ah l^{-1})	8604
	η_{Bu}	0.95		
Fuel cell	$U_{FC,0}$ (V)	33.18	R_{FC} (Ω°C)	−2.04
	C_{1FC} (V °C^{-1})	−0.013	C_{2FC} (V)	−1.57
	$I_{FC,0}$ (A)	8.798	$N_{Cell,FC}$	35
	$\eta_{I,FC}$	0.45	C_{H_2} (Ah l^{-1})	8604
	η_{Bo}	0.95		
Hydrogen storage	ΔH (kJ mol^{-1})	286	VT (l mol^{-1})	22.4

5. Results

The model was simulated under the conditions described above. Fig. 6 shows the net power flow in the system and the power exchanges with the hydrogen storage sub-system and Fig. 7 shows the energy storage's state during the entire simulation.

The first remarkable characteristic is that the FLC is able to keep the batteries' SOC above 50% during the entire week, thus helping to increase the batteries' lifetime. It is effectively known that deep discharges of the batteries could be very damageable [17]. The second characteristic is that the batteries really act as a short-term energy buffer and their SOC varies very slowly. This avoids many charge-discharge cycles to the batteries, thus again contributing to extend their lifetime.

Fig. 6 clearly shows that when the net power flow is positive in the system, the electrolyzer is started to store hydrogen. On the other hand, the fuel cell is started when there is not enough energy available to power the load. This way, the energy stored as hydrogen increases on the first and the seventh days and it decreases on the other days. These results are not surprising since the chosen site for the wind turbine is not very windy. However, this situation could be improved

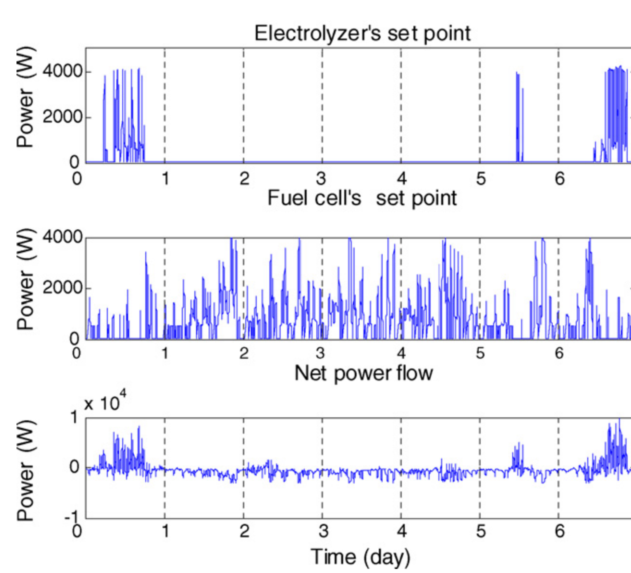

Fig. 6. System's power flow.

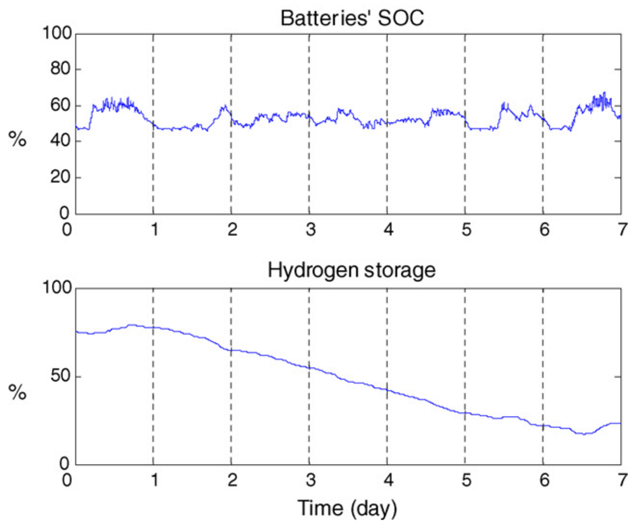

Fig. 7. System's energy storage.

by installing the system on a better site or by adding PV arrays to the system. However, these results illustrate very well the usefulness of the hydrogen storage system. Powering the load continuously from the second day to the sixth day required about 66 kWh of energy storage. Stored in batteries, this means seven supplementary batteries stacks (56 batteries), thus increasing substantially the storage space, the initial cost of the system and the required maintenance. Moreover, the extrapolation of these results for a complete month demonstrates clearly that the batteries are inadequate to store long-term energy. Providing sufficient power for a similar month would effectively require the addition of 224 batteries, whereas a slight increase of the hydrogen tank size would be sufficient.

The analysis of these results thus shows that the fuzzy logic controller behaves as expected. It is able to keep the batteries from being discharged too deeply, to keep the load powered continuously and to store energy as hydrogen when possible. Moreover, the fuel cell and the electrolyzer are always started for a few minutes each time, thus increasing their efficiency.

6. Conclusion

This paper presented a dynamic controller for a renewable energy system that uses a wind turbine and a PV array to feed power to a load, store excess energy in batteries or in hydrogen via an electrolyser. The stored hydrogen is used for electricity generation by using a fuel cell. The proposed controller uses fuzzy logic to decide when to produce hydrogen or convert it back to electricity and at what rate. The use of fuzzy logic is interesting for this application since it allows to easily use multiple inputs and to describe the controller's behaviour with only a few rules defined by a few linguistic variables. This way, the designed controller uses the net power flow (the difference between the power provided by the sources and the power consumed by the loads) and the batteries' state-of-charge as inputs to determine a power set point for the electrolyzer and a power set point for the fuel cell.

In order to design and validate the controller, a complete model of the renewable energy system was elaborated. This model is composed of a sub-model for each individual component of the system. All the model's parameters were determined experimentally to obtain results that are closer to the real system.

The system was simulated for a complete week with real sources power data collected at the HRI and load data provided by Hydro-Québec to observe the controller's behaviour. It was possible to determine that the controller effectively behaves as expected, meaning that it was able to maintain an adequate SOC while powering the load continuously and storing hydrogen when possible. Although this simulation results showed that the system would 'not provide enough input energy to power a typical residential load in July for a very long time, this situation illustrated very well the need for the hydrogen storage sub-system. Storing 1 week of energy only in batteries would be very costly and would imply a lot of maintenance.

Acknowledgements

This work has been supported by the LTE Hydro-Québec, the Natural Resources Canada and the Natural Sciences and Engineering Research Council of Canada.

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