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Fuzzy logic control for solar powered hydrogen production, storage and utilisation system

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Abstract—**Climate change concerns, increasing global energy demand, coupled with limited supply of fossil fuels, calls for development of new power source. Solar energy is a very promising renewable energy source to moderate the growth of energy demand. The combination of electrolyser and fuel cell which use hydrogen as an energy carrier extends the utilisation of the solar energy. For this integrated solar powered hydrogen production, storage and utilisation system, one of the problems is to develop an efficient control system to improve the performance of the overall system. This paper presents a power management strategy based on fuzzy logic technology to address such problem. The target of this power management strategy is to meet the power demand, to maximise the hydrogen production and to minimise the usage of battery. Therefore, the overall system's efficiency will be increased and lifetime of the battery pack will be extended. The numerical results based on real solar data for a one year period shown that the proposed fuzzy logic controller behaved as expected, it was able to meet the power demand and to store the hydrogen when possible while maintain the battery's state of charge at desired level.**

Keywords - Hydrogen production and storage, Renewable energy, Power management, Fuzzy logic control

I. INTRODUCTION

The global energy demand is increasing rapidly. The concerns of limited supply of conventional fossil fuels and the emission of green house gases call for new solutions to this energy problem. Renewable energy can be part of the solution to provide clean and sustainable energy supply.

However, the inherent intermittency in most of the renewable sources causes problems for power-on-demand requirements. Hydrogen is considered to be a promising candidate as an energy carrier to compensate this problem.

Renewable powered hydrogen production and utilisation systems can be either standalone or grid connected. Over the past few years, the development and application of such systems has increased significantly. A large body of research work addressed various topics for such systems, including modelling, simulation, control and performance evaluation [1]–[7].

A typical system normally consists of one or several renewable power sources, such as photovoltaic (PV) array, wind turbines, micro-hydro, geothermal, etc. An electrolyser is used to convert excess energy to produce hydrogen as an energy carrier. The fuel cell will be used as power source to convert the chemical energy from hydrogen into electrical energy when the power demand is higher than the supply of renewable sources. Batteries or a battery pack are usually used to maintain a constant DC bus voltage and to store or supply short-term energy. The emphasis of such systems is not only to improve the performance of existing hydrogen production, storage and utilization technologies, but also to integrate various units effectively with renewable energy sources through overall power management strategies [8].

Several researchers addressed power management strategy (PMS) design and applications for such system. However, from above examples [1]–[6], [9], [10], it can be seen that for most of the reported PMS, the state of charge (SOC) level of the battery is the main parameter that governs the operation sequence of the electrolyser and the fuel cell. The start-up and shut-down of the electrolyser and fuel cell is relied on the fixed SOC limits. Reference [11] indicated that the two important shortcomings for this type of algorithm are:

1) it did not take into consideration of the system's state except for the batteries' SOC;
2) it did not allow the control of the production or consumption of the hydrogen, which would help manage the energy in the system.

The fuzzy logic (FL) controller developed by [11] determines the appropriate hydrogen production/consumption rate as a function of the system's power inputs and outputs and the batteries' SOC. However, the authors in [11] have not considered the system sizing that may lead to significant drop of hydrogen storage level in 7-day period. Meanwhile, although the battery SOC was maintained within a reasonable region (i.e., between 40% and 60% as the results demonstrated), the oscillation means that considerable amount of energy may be wasted during charging and discharging process of the battery pack.

This study focuses on developing PMS based on FL control methodology for solar powered hydrogen production, storage and utilisation system to improve the overall system's efficiency. The purpose of proposed FL controller is twofold, one is to maximise the hydrogen production which is a function

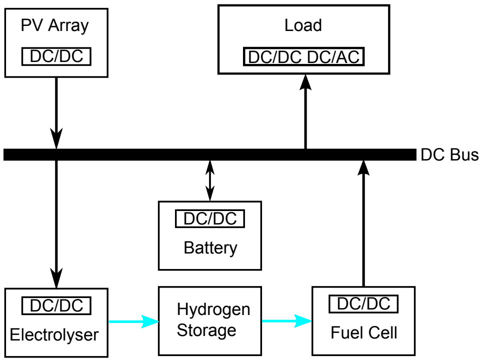

Fig. 1. System configuration of the solar powered hydrogen production, storage and utilisation system

of the battery SOC and the difference of the power flow between available solar power and load demand, the other one is to minimise the usage of batteries. The entire system is modelled with consideration of system sizing and systematic modelling approach. Then the FL controller is designed in order to achieve aforementioned control objectives. Finally, performance of the overall control system is validated over a one-year period using real solar data. The numerical results shown that the designed system has the capability to satisfy the daily load demand as well as produce hydrogen using excessive solar power for future usage, storage, transportation or hydrogen powered car refuelling.

II. SYSTEM CONFIGURATION

The structure of this standalone system is shown in Fig. 1 where the black arrow represents the electricity flow and the blue arrow represents the hydrogen flow.

In this study, a photovoltaic array is considered as the main power source to the system to meet the predefined load demand. Due to the inherent intermittent nature of solar power, a battery pack is included only to smooth the fluctuation of the solar power if necessary. When excess power is available, hydrogen will be produced using an electrolyser. When a power shortage occurs, a fuel cell will be used to convert the chemical energy from hydrogen to electric energy.

The complete model is developed in order to represent the physical system and to design and validate the performance of the proposed controller. The detailed model of DC/DC or DC/AC converter is neglected and they are treated as an ideal device to produce power which is determined by the FL controller.

A. Load profile

The purpose of this solar hydrogen system is to use solar power to satisfy the load demand of the office block of Hydrogen Centre of University of Glamorgan at Baglan Energy Park, Port Talbot, United Kingdom and utilise excess power to produce hydrogen for later use, storage, transportation or for fuel cell car refuelling, therefore, the load profile analysis is essential for determine the size and the control design of the overall system.

Appliance	Power (W)	Duty cycle (hours)	Energy consumption (Wh)
Fridge	23	24	552
Microwave	700	0.3	210
Kettle	3000	0.4	600
Lighting	400	4	1600
Laptops	390	8	3120
Auxiliary devices	1200	24	28800
Total	5713	–	34882

TABLE I
LIST OF APPLIANCES' POWER, DUTY CYCLE AND ENERGY CONSUMPTION

The average energy consumption E_{load} can be estimated by equation

$$E_{load} = \sum_{i=1}^{n} I_{load} V_{load} D_{load} \tag{1}$$

where I_{load}, V_{load}, D_{load} are the current, voltage and duty cycle of each appliance used in one day, respectively. n is the number of the appliances.

The considered office block is utilised between 09:00 and 17:00 and includes 6 laptops, 1 mini refrigerator, 1 microwave, 1 kettle, lighting and several auxiliary devices such as security system, monitor system, phone system, LAN, boiler etc. The list of appliances together with their power, duty cycle is given in Table I. It is reasonable to assume that this daily load will keep constant throughout the year, for weekdays.

B. Battery model

The battery stack creates a linkage between all components in the solar powered hydrogen system, it is used as an energy buffer to compensate the power fluctuation.

The battery state of charge S is the only state variable of the battery system model and is given by

$$S = \frac{\left(Q_{max} - \int_0^t I_b dt\right)}{Q_{max}} \tag{2}$$

where Q_{max} is the battery's maximum capacity [12].

The battery current I_b is defined by

$$I_b = -(I_{pv} - I_{load} - I_{el} + I_{fc}) \tag{3}$$

where I_{pv} is the PV array's current, I_{load} is the load current, I_{el} is the electrolyser current and I_{fc} is the fuel cell current.

When charging the battery, the current is negative and positive current indicates discharging mode of the battery. It is found that in order to lengthen the battery lifetime, overcharging and deep discharging should be avoided.

C. Electrolyser model

The electrolyser operating current is defined by

$$I_{el} = \frac{P_{el}}{V_{el}} \tag{4}$$

where P_{el} is the power of electrolyser.

f_1	269.9112
f_2	1.1013
r_1	9.2434×10^{-5}
r_2	-2.2120×10^{-7}
s	0.1084
t_1	-1.0636
t_2	8.7077
t_3	267.7084
A	0.013
n_c	48

TABLE II
PARAMETERS FOR THE ELECTROLYSER

For a given cell temperature, the operating voltage of the electrolyser is expressed as

$$V_{el} = V_{rev} + \frac{r_1 + r_2 T}{A} I_{el} + s log \left(-\frac{t_1 + t_2/T + t_3/T^2}{A} I_{el} + 1 \right) \tag{5}$$

where V_{rev} is the reversible cell voltage, r_1, r_2, t_1, t_2, t_3 are parameters which can be determined experimentally [13].

The hydrogen production rate is proportional to the electrolyser current, hence, the total hydrogen production for an electrolyser which consists of several series connected cells, can be expressed as

$$\dot{n}_{H_2} = \eta_F \frac{n_c I_{el}}{2F} \tag{6}$$

where η_F is the Faraday efficiency and can be calculated as $\eta_F = \frac{(I_{el}/A)^2}{f_1 + (I_{el}/A)^2} f_2$, n_c is the number of series connected cells, F is the Faraday constant.

The validated parameters used in the electrolyser model are listed in Table II.

D. Fuel cell model

The fuel cell operating current is defined as

$$I_{fc} = \frac{P_{fc}}{V_{fc}} \tag{7}$$

where P_{fc} is the fuel cell power.

The fuel cell model is derived and validated in [14]. A brief detail of the fuel cell model is described here, detailed information can be found in [14]. The fuel cell stack voltage can be calculated by multiplying the cell voltage by the number of cells n_{fc} of the stack, hence

$$V_{fc} = n_{fc} \times (E - V_{act} - V_{ohm} - V_{con}) \tag{8}$$

where

$$E = \frac{1}{2F} \left\{ \Delta G + \Delta S (T - T_r) + RT \left(ln(P_{H_2}) + \frac{1}{2} ln(P_{O_2}) \right) \right\} \tag{9}$$

where E is the open circuit voltage of the fuel cell, ΔG is the change in the free Gibbs energy, ΔS is the change of the entropy, R is the universal constant of the gases, P_{H_2} and P_{O_2} are the partial pressures of hydrogen and oxygen respectively. V_{act} represented the activation over potential at the electrodes; V_{ohm} represents the ohmic over potential caused by electrical and ionic conduction loss; V_{con} represented the concentration over potential caused by mass transport limitations of the reactants to the electrodes.

The activation over potential V_{act}, including anode and cathode can be calculated as

$$V_{act} = -\left\{ \xi_1 + \xi_2 T + \xi_3 T ln \left(\frac{P_{O_2}}{5.1 \times 10^6 e^{\frac{-498}{T}}} \right) + \xi_4 T ln(I_{fc}) \right\} \tag{10}$$

ξ represents parametric coefficient for the cell model.

The ohmic voltage drop V_{ohm} is determined by the following expression

$$V_{ohm} = I_{fc} \left(\rho_m t_m A_{fc}^{-1} + c \right) \tag{11}$$

In this model a general expression for resistance is defined to include all the important parameters of the membrane. The resistance to the transfer of protons through the membrane is assumed to be a constant (c) and included in the equation as an additional term. ρ_m is the specific resistivity of the membrane for the electron flow. t_m is the thickness of the membrane, $A_f c$ is the cell active area.

The voltage drop due to the mass transport can be determined by

$$V_{con} = -B ln(1 - \theta) \tag{12}$$

and

$$\theta = \left(I_{fc} A_{fc}^{-1} \right) \left(\left(I_{fc} A_{fc}^{-1} \right)_{max} \right)^{-1} \tag{13}$$

where B is a parametric coefficient that depends on the cell and its operation state.

The hydrogen consumption rate of the fuel cell stack is given by

$$\dot{n}_{fc} = \frac{n_{fc} I_{fc}}{2F} \tag{14}$$

III. FUZZY LOGIC BASED POWER MANAGEMENT STRATEGY

A. Control objects

The control object is to make full use of the solar power to maximise the hydrogen production and minimise the usage of battery stack, i.e., keep the battery SOC between 50 -60% which will extend its lifespan and increase the overall system's efficiency.

The operating strategies for power management system are listed as follows:

1) The highest priority is to utilise the solar power to satisfy the predefined power demand.
2) If excess solar energy is available, it will be sent to the electrolyser to generate hydrogen for future usage.
3) The electrolyser will keep running as long as the addition power from PV array is available. The electrolyser

maximum power is set to 16kW. The addition power transferred from PV array to the electrolyser will not exceed this limit.

4) If there is still additional power generated by PV array when the load demand is satisfied and the electrolyser is running at its peak limit, extra power will be utilised to charged the battery if the battery SOC is low.
5) Dumping power is only required if the electrolyser is running at its maximum power level and the battery SOC is at desired level.
6) If the power generated by PV array is insufficient to support the electrical demand, the difference is supplied by fuel cell stack which can run up to 4kW.
7) Only when the power demand is higher than the power supply of PV/FC combination, will the battery be used to provide short-term compensation.

B. Fuzzy logic controller

The required control objects are implemented by a two-input-one-output fuzzy logic controller. Two inputs to the controller are the difference power flow (dP) and the battery's SOC. The difference power flow indicates the difference between available solar power and the power demand. The controller will use this information to decide whether excess solar power is available for hydrogen production. The SOC is used to maintain the battery's SOC at desired level in order to prevent overcharge / deep discharge of the battery.

The fuzzy mechanism consists of triangular membership functions for the two inputs and for the output is shown in Fig. 2 and Fig. 3 respectively. The reason for choosing triangular membership function is mainly for the simpler computation of membership value. The dP flow is divided into eight variables. Negative power supply means fuel cell or battery is required to supply the difference and positive power means addition solar power can be used to produce hydrogen or charge the battery. The battery SOC is also described by three variables. It is desired that the SOC will be maintained within the region between 50-60%. Negative power output means fuel cell power is required to compensate the power shortage and positive power output indicates that excess solar power is available for electrolyser to produce hydrogen.

The rules of the FL controller are demonstrated in Table III and the definitions of the linguistic variables are described in Table IV. In Table III, the top row of the table shows the difference of power flow (dP) and the left column is the battery's SOC. The cells of the table at the intersection of rows and columns contain the linguistic value for the output corresponding to the value of the first input written at the beginning of the row and to the value of the second input written on the top of the column. The rule output was defuzzified using a centroid computation.

IV. SIMULATION AND RESULTS

The model of the aforementioned solar hydrogen system is created in MATLAB/Simulink and the proposed fuzzy logic controller is implemented using the Fuzzy Logic Toolbox. The

		dP							
		NL	NM	NS	Z	PS	PM	PL	PEL
SOC	L	NL	NL	NM	NS	Z	PS	PM	PL
	C	NL	NM	NS	Z	PS	PM	PL	PEL
	H	NM	NS	Z	PS	PM	PL	PEL	PEL

TABLE III
FUZZY CONTROL RULE TABLE

Linguistic	Linguistic meanings
PEL	Positive extreme large
PL	Positive large
PM	Positive medium
PS	Positive small
Z	Zero
NS	Negative small
NM	Negative medium
NL	Negative large
L	Low
C	Correct
H	High

TABLE IV
LINGUISTIC VARIABLES IN THE FUZZY INFERENCE SYSTEM

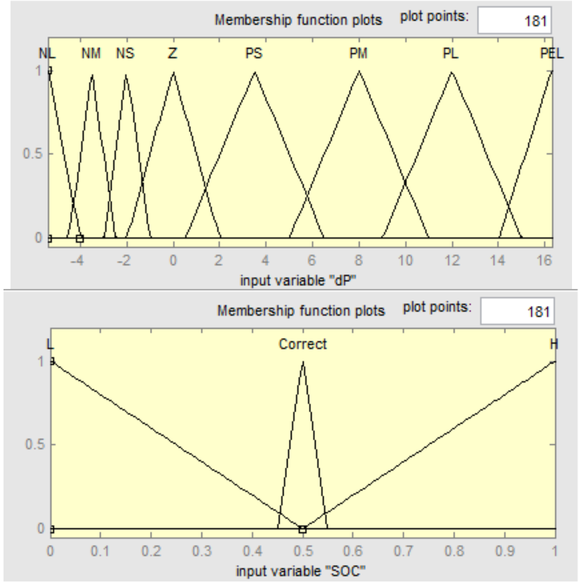

Fig. 2. Membership functions for input variables

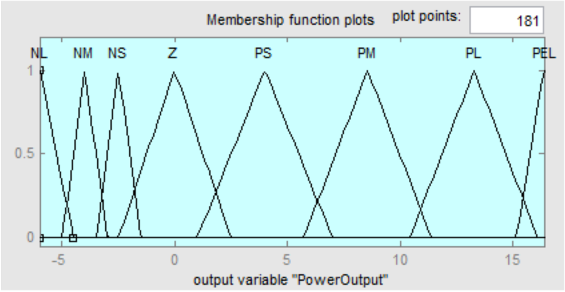

Fig. 3. Membership function for output variable

purpose of the simulation is to observe the performance of proposed system over a period of year including day and night.

The real solar data gathered from the PV panel for entire year of 2010 is utilised in this analysis. The PV array is rated at 18kWp. The annual solar power delivered by the PV array is illustrated in Figure 4. The fluctuation of delivered solar power can be seen from the figure. In summer, the maximum power solar panel can deliver can reach up to 18kW, while during winter and early spring, this value can drop down lower than 0.1kW.

The power generated by the PV array will be used to satisfy the user power demand as stated previously and the difference between available power and the load demand is shown in Figure 5. The negative power indicates that there is insufficient solar power to meet the power demand therefore fuel cell is required to supply the difference. The positive region means that excess solar power is available and can be utilised by electrolyser to produce hydrogen. The figure demonstrated that during winter and spring season, from November to April, due to low solar irradiation and short daylight, the power generated by solar array cannot satisfy the load demand, therefore, the fuel cell has to operate for most of the time to compensate this power shortage. During summer season, the frequency of fuel cell usage is reduced and the electrolyser is running more frequently to convert solar power into hydrogen.

Under the control of the proposed fuzzy logic controller, the hydrogen production rate is shown in Figure 6. The hydrogen consumed by the fuel cell is shown in Figure 7. A more clear demonstration of monthly hydrogen production by electrolyser, hydrogen consumption by fuel cell and the net hydrogen in storage overall this test period are shown in Figure 8. The results fit the seasonal profile demonstrated in the previous figures very well and clearly indicate that by using such system, the load demand can be satisfied and there is an abundance of hydrogen produced which can be used for storage, transportation or fuel cell refuelling.

Figure 9 shows the SOC of battery stack. The initial SOC was set at 50%. From the figure it can be seen that the proposed FL controller can maintain the battery's SOC around 55% during the entire year as desired, which increases the efficiency of overall system and prevents abusive use of the battery and hence contributes to extend the lifespan of the battery pack.

V. CONCLUSION

This paper presented a solar powered hydrogen production, storage and utilisation system. The system uses solar power as a main power source to meet the power demand, and utilises hydrogen as an energy vector to store excess solar power via electrolyser. When required, the produced hydrogen will be converted back to electric energy using fuel cell. The proposed FL controller determines the time to produce hydrogen and to convert it back to electricity. The purpose of the FL controller is to maximise the hydrogen production and minimise the usage of the battery stack to increase the system's efficiency and to extend the lifetime of the battery stack.

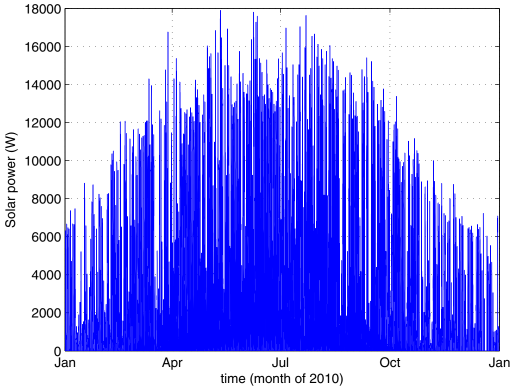

Fig. 4. Annual solar power generation

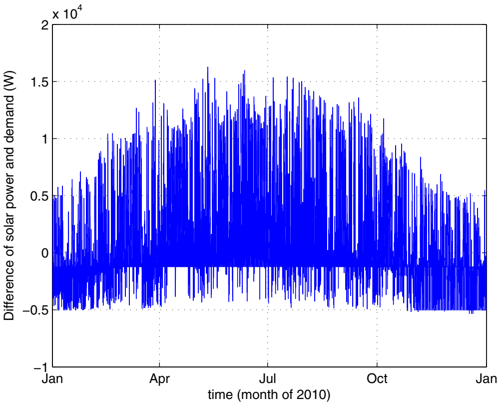

Fig. 5. Annual difference of power

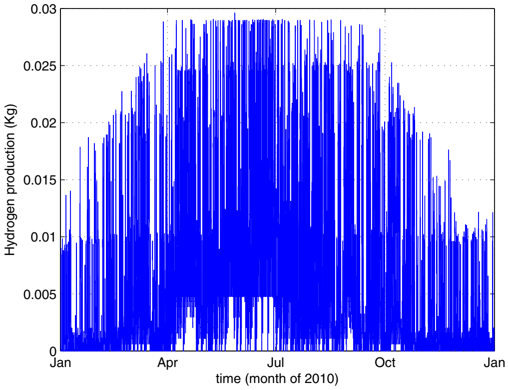

Fig. 6. Electrolyser H_2 production rate

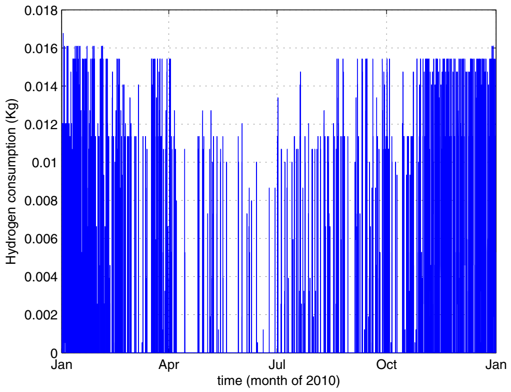

Fig. 7. Fuel cell H_2 consumption rate

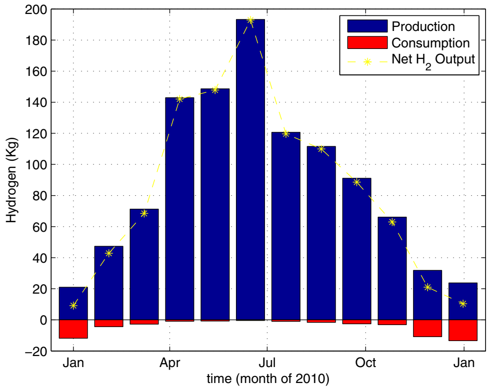

Fig. 8. Monthly variation of hydrogen production, consumption and net hydrogen output

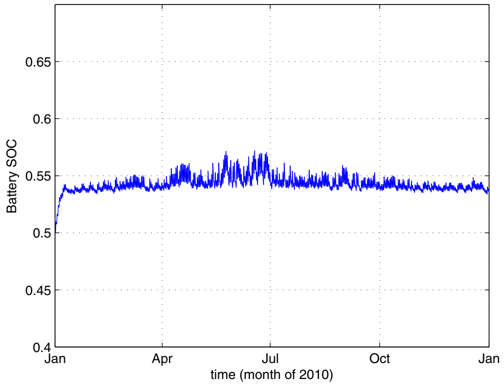

Fig. 9. SOC for entire year

The proposed system is simulated for a complete year with real solar data gathered from University of Glamorgan Hydrogen Centre. The purpose of the simulation is to evaluate the performance of the proposed controller. The numerical results shown that the proposed controller behaved as expected, it was able to satisfy the power demand and to store the hydrogen when possible while maintain the battery's SOC at desired level.

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