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Control of Renewable Energy System with Hydrogen Storage

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Abstract: Present world rely on conventional non renewable energy resources which are now closer to depletion. Time has come to switch on to the renewable energy resources to meet the demands of increasing human population. Though the above case compels us to switch on, the practical difficulties regarding the renewable energy resources remain a problem. Intermittent nature of renewable energy resources and its cost in practical implementation slow down any change from conventional methods. The problem of intermittent energy can be solved by using a backup system such as battery, super capacitor etc. In this paper, a renewable energy system is presented with hydrogen storage. The system consists of a photovoltaic panel, an electrolyzer, hydrogen storage tank and a fuel cell. Each model is then integrated in MATLAB simulink environment. A suitable power management system is designed in order to solve the problem of intermittent nature of renewable energy sources such that an electrolyzer is activated during the time of excess power. Thus, power is stored in the form of hydrogen. During deficit power, fuel cell is activated and the stored hydrogen is converted into electricity to meet the load demand. Model Predictive Controller is designed over electrolyzer and fuel cell in a decentralized manner inorder to control hydrogen generation and storage by rectifying the slow power response time of hydrogen.

Keywords: MPC, MPPT, photovoltaic, renewable.

I. INTRODUCTION

Environmentally friendly power generation technologies are expected to play an important role in future owing to the depletion of conventional non-renewable energy resources. Although these technologies are improving in various aspects, drawbacks such as their intermittent nature and high capital costs, remain obstacles to their utilization.

In order to ensure continuous power, a storage medium or energy carrier is required. Hydrogen is an attractive energy carrier since it is one of the cleanest, lightest and most efficient tools, but it has a slow power response time. This disadvantage can be compensated by implementing a suitable power management tool.

Most of the studies that have dealt with renewable energy systems have been performed in the simulation mode [1][2], with only a few dealing with real time application due to high capital cost associated with design and implementation. The optimal integration of hydrogen storage with renewable energy sources and the power management of such system have also received considerable attention [3]-[5].

Here, the comprehensive model for the pv/electrolyzer/fuel cell system and its control using Model Predictive Controller is described. Maximum Power Point Tracking (MPPT) on PV system is applied to ensure optimal power generation by the source. Subsystems are integrated and evaluated in MATLAB simulink environment.

II. MODEL

System consists of PV array, electrolyzer, storage tank and fuel cell

A. Solar energy conversion

The equivalent one diode model of a solar cell is shown in figure.

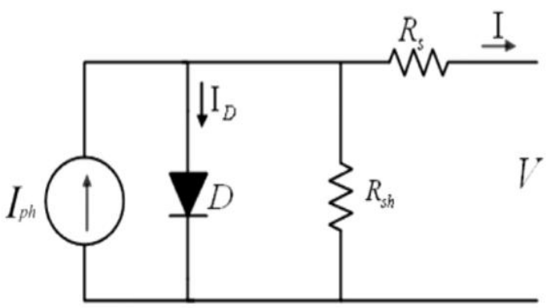

Fig. 1 Equivalent circuit model for a PV cell

The model consists of a short circuit current Isc, a diode and a series resistance Rs and the resistance Rp inside each cell and in the connection between the cells. The correlation between the output voltage and the current is expressed as

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$$I = I_{pv} - I_0\left[\exp\left(\frac{V + IR_s}{aV_T}\right) - 1\right] - \frac{V + IR_s}{R_{sh}} \quad (1)$$

$$V_T = \frac{N_s kT}{q} \quad (2)$$

$$I_{pv} = \frac{G}{Gn}[I_{pvn} + K_I(T - T_n)] \quad (3)$$

$$I_0 = I_{0n}\left(\frac{T}{T_n}\right)^3 \exp\left[\frac{qE_g}{aK}\left(\frac{1}{T_n} - \frac{1}{T}\right)\right] \quad (4)$$

$$I_{on} = \frac{I_{scn}}{\exp(V_{ocn}/aVT_n) - 1} \quad (5)$$

Where k is the Boltzman constant, q is the charge of electron, Iscn nominal short circuit current, Vocn nominal open circuit current, kv temperature voltage constant, ki temperature current constant, Ns number of series connected cells, T operating temperature, Tn nominal temperature, Gn nominal irradiance, a diode ideality constant,and Eg band gap of Si at 25 degree celcius.

B. Electrolyzer

Polymer Electrolyte Membrane (PEM) electrolyzers are very simple and compact and have demonstrated higher current density capability than conventional alkaline water electrolyzers. Electrolysis of water using PEM is a very efficient method of producing hydrogen.

$$H_2O + electrical\,energy \rightarrow H_{2(gas)} + \frac{1}{2}O_2 \quad (6)$$

The water supplied at anode is decomposed into oxygen gas, hydrogen protons and electrons. The hydrogen protons are transported through the proton conductive membrane to cathode. At the same time, the electrons supply the driving force for the reaction whereas at the cathode side the hydrogen protons and the external electrons recombine to form hydrogen gas.

The rate of hydrogen reacting is proportional to the electrical current in the equivalent electrolysis current

$$N_{H_2}^{gen} = \frac{n_{ele}\, i_e}{2F}\eta_F \quad (7)$$

The relation between the real hydrogen flow rate and the theoretical one is defined as the Faraday's efficiency. It is expressed by

$$\eta_F = 96.5e^{(0.09/i_e - 75.5/i_e^2)} \quad (8)$$

C. Hydrogen storage system

The amount of hydrogen required by the PEM fuel cell is sent directly from the electrolyzer system based on the relationship between the output power and the hydrogen requirement of the PEM fuel cell system. The remaining amount of hydrogen is sent to the storage tank.

The dynamic of the storage is obtained as follows

$$P_b - P_{bi} = Z\frac{N_{H_2}RT_b}{M_{H_2}V_b} \quad (9)$$

Auxillary power requirements such as pumps, valves were ignored in the model

D. Fuel cell

Chemical energy of the hydrogen fuel is converted into electricity through a chemical reaction with oxygen. The byproducts of this reaction are water and heat. The proportional relationship of the molar flow of gas through a valve with its partial pressure can be expressed as

$$\frac{qH_2}{pH_2} = \frac{RT}{V_{an}}(q_{H_2}^{in} - q_{H_2}^{out} - q_{H_2}^{r}) \quad (10)$$

The relationship between the hydrogen flow and the fuel cell system current can be written as

$$q_{H_2}^{r} = \frac{N_0 I}{2F} = 2K_r I \quad (11)$$

the hydrogen partial pressure can be rewritten in the s domain as

$$pH_2 = \frac{\frac{1}{kH_2}}{1 + \tau H_2 s}\left(q_{H_2}^{in - 2K_r I}\right) \quad (12)$$

where

$$\tau_{H_2} = \frac{V_{an}}{K_{H_2}RT} \quad (13)$$

the fuel cell output voltage is obtained from the sum of three effects, the Nernst potential, the cathode and anode activation overvoltage and the ohmic overvoltage due to internal resistance

$$V_{cell} = E + \eta_{act} + \eta_{ohmic} \quad (14)$$

Where

$$\eta_{act} = B\ln(CI) \quad (15)$$

$$\eta_{ohmic} = R^{int}I \quad (16)$$

$$E = N_0\left[E_0 + \frac{RT}{2F}\log\left(\frac{pH_2 pO_2^{0.5}}{pH_2O}\right)\right] \quad (17)$$

III.CONTROL

The energy system consists of photovoltaic as power generation and load as power consumption components. The net power is calculated as the difference between photovoltaic power and load demand.

The generated power from renewable source can be either used directly to meet the load demand or transferred to the

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hydrogen production process. Because of the intermittent nature of solar energy as well as the load demand, net power can have zero, positive or negative values. When there is excess power generated, the electrolyser is activated and fuel cell is activated in case of deficit power.

A. Solar energy system controller

It is important to extract maximum possible power to ensure efficient system operation. The characteristic curves for a photovoltaic array gives a unique operating point at which maximum power is delivered. There are several Maximum Power Point Tracking (MPPT) techniques, of which current perturbation and observation method is applied in this paper[7].

B. Electrolyzer and fuel cell

Model Predictive Control over electrolyser and fuel cell can improve the efficiency of the system. The advantage of MPC is its ability to deal with constraints in a systematic manner. This is important in electrolyser and fuel cell operation, where abrupt changes in the load produce more water distribution and in turn decreases the overall efficiency and working life of these units.

The non linear models of electrolyser and fuel cell were linearized and discretized. The resulting state space model has the form

$$x(k+1) = Ax(k) + Bu(k)$$

$$y(k) = Cx(k) \qquad (18)$$

where k is the sampling time, and A, B, D, and C are matrices of appropriate dimensions. x, u, d, and y are the model states, manipulated variables, disturbances, and model outputs, respectively.

The model predictive controller is designed to minimize the following finite horizon control and performance index:

$$\min J(x(t),u(t),t) = \sum_{k=1}^{Hp} W_y\left[y(k) - y(k)_{ref}\right]^2$$

$$+ \sum_{k=1}^{H_c} W_u\left[u(k) - u(k)_{ref}\right]^2 + \sum_{k=1}^{H_c} W_u\left[\Delta u(k|k+1)\right]^2 \quad (19)$$

where Wy and Wu are input and output weight factors for each variable, and HP and HC are the prediction and control horizons, respectively.

TABLE I PARAMETERS

notation	parameter	value
K	Boltzman constant	1.38065e-23
q	Charge of electron	1.602e-19
Ki	Temperature current constant	0.0032
a	diode ideality constant	1.3
Eg	Band gap of silicon at 25 degree	1.12
T	operating temperature	35+273
Gn	Nominal irradiation	1050
F	Faraday's constant	96484600
T_{H2}	Hydrogen time constant	3.37
K_{H2}	Hydrogen valve constant	4.22*10^-5
B	Activation voltage constant	0.04777
C	Activation voltage constant	0.0136
R_{int}	Internal resistance	0.00303

The objective function was subjected to a set of constraints, consisting of the fuel cell and electrolyzer output power upper and lower limits (yub, ylb), current upper and lower limits (uub, ulb), and the rate of change in the electrolyzer and fuel cell current. The output power upper and lower limits (yub, ylb) are defined by the fuel cell and electrolyzer power operating range.

IV. RESULTS AND DISCUSSION

The presented simulation results are based on the weather data of June 24th in Trivandrum, Kerala, India. The data was obtained from the weather panel of India Meteorological Department lab, Pune.

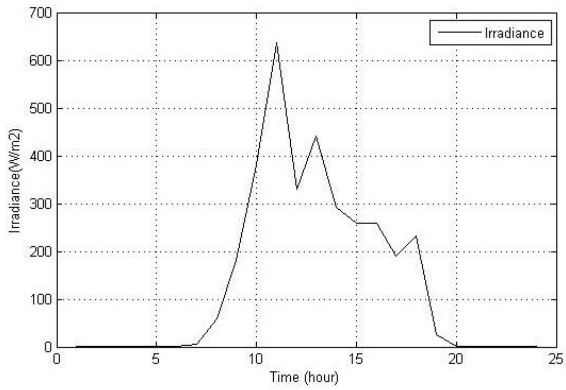

Fig.2. solar data

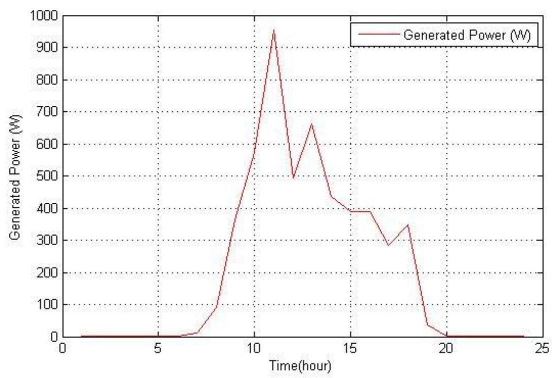

Fig. 3. Generated Power

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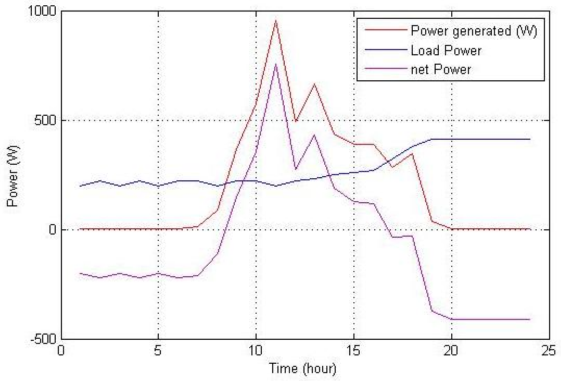

Fig. 4. Power trends including net power, load power and renewable power

Fig 2 shows the solar data of irradiance with time. MJ/m^2 is converted into W/m^2 and then applied to the calculations. V-I-P characteristics of solar energy are obtained and power delivered is shown in Fig 3.

The model predictive controller was designed for the electrolyser and fuel cell and then integrated with the nonlinear model of the plant. The length of the prediction horizon affects both the computational time and the performance time of the system. A variable sampling time with maximum size of 1s was used for data measurement. Figs. 5 and 6 show the performance of the MPC implemented for the electrolyser and fuel cell respectively. The slow power response time of hydrogen is overcome by power management tool applied.

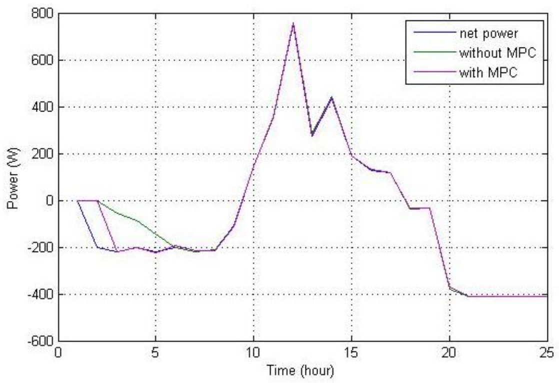

Fig. 5 Electrolyzer MPC

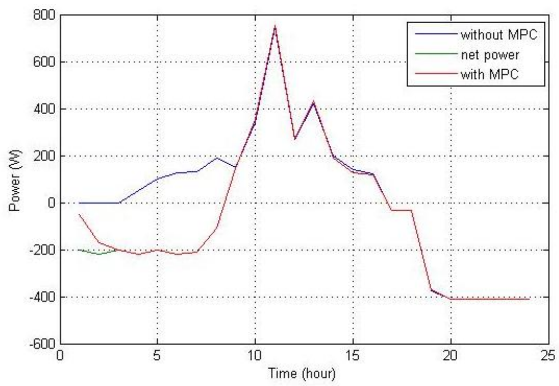

Fig. 6. Fuel cell MPC

V. CONCLUSION

A model for a system with solar energy conversion, electrolyzer, fuel cell and hydrogen storage system was developed. A model predictive controller was designed for optimal operation of the electrolyzer and fuel cell. The controller could track the net power by decreasing the slow power response time.

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