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DYNAMIC ANALYSIS OF A WIND ENERGY STORAGE SYSTEM IN REMOTE OFFSHORE AREAS

Pan Zhao
Institute of Turbomachinery,
Xi'an Jiaotong University
Xi'an, Shaanxi, China

Yiping Dai*
Institute of Turbomachinery,
Xi'an Jiaotong University
Xi'an, Shaanxi, China

Jiangfeng Wang
Institute of Turbomachinery,
Xi'an Jiaotong University
Xi'an, Shaanxi, China

Danmei Xie
School of Power and Mechanical Engineering,
Wuhan University
Wuhan, Hubei, China

ABSTRACT

Due to the increasing oil and gas demand, the shortage of fossil fuel resources, serious global greenhouse effect and extremely environmental deterioration, the renewable energy sources are more and more attractive. The energy storage is a vital problem for the intermittent and seasonal renewable energy sources. In this paper, a wind energy storage system consideration of chlorine production which is located in remote offshore area is proposed. The detailed dynamic models are established and simulations are also carried out. The proposed system stores the surplus energy generated from wind farm as a form of hydrogen via the electrolyzer array, and uses the stored hydrogen to generated electrical energy at poor wind condition through a PEM fuel cell array. The simulation results show that the proposed system could not only absorb the wind power maximally, but also produce sufficient electric energy to meet the load power demands. Moreover, the proposed system could tolerate the frequently impulses because of the variations of wind energy on the small stand-alone power system effectively.

1 INTRODUCTION

In recent years, increasing amounts of renewable energy sources are joined in electrical power systems for alleviating the environmental deterioration and conventional fossil fuels shortage. Wind energy is the fastest growing renewable energy source all over the world, at an expanding rate of 25~35% annually over the last decade [1]. However, the power output of wind farm is fluctuant due to the variations of wind speed which flows through the farm field. This is the main difference between conventional power generations and wind power. If wind power is to supply a significant portion of the demand, the energy storage system is required to smooth the wind farm output power to meet sustained load demands during varying natural conditions. Actually, lots of wind farms are located in remote areas because of the higher wind power density and expansive land space; on the other hand, the capacity of power consumption at remote areas is normally limited. Hence, it has always been an important problem to store the surplus energy of wind farm output for utilizing in the low wind speed period at remote area [1, 2].

Hydrogen as an energy carrier can play an important role as a storage medium for intermittent and seasonal renewable technologies [3]. Hydrogen can be produced by electrolyzing water, which is abundantly available in nature. For the wind energy case, an energy storage system (a small stand-alone power system) translates the surplus energy into hydrogen when the wind energy is sufficient, and uses the stored hydrogen to produced electric energy through fuel cells at poor wind condition. This kind of energy storage system could not only extract the wind power maximally, but also supply adequate electric energy to meet the load power demand. It also could decrease the concussion effect to power system due to the unstable wind power output.

Some studies have been presented in the literatures to model hybrid energy system, hydrogen energy system and other relevant areas over the past few years. Onar [1] presented

* Professor and author of correspondence

a dynamic model of a wind/fuel cell/ultra-capacitor based hybrid power generation system by using a novel topology to alleviate the effects of wind speed variations. Khan [2, 6] introduced the model of a small wind-fuel cell hybrid energy system which was suited for remote isolated communities and analyzed the life cycle of this integrated system, and found that this system had an expected transient under different conditions and had an environmental friendly feature. Gorgun [4] reported a PEM electrolyzer dynamic model which contained a hydrogen storage system model. Battista [5] presented a novel controller for a wind-hydrogen production system to match the input wind power to the electrolyzer requirements. Nelson [7] introduced a method for unit sizing and cost analysis of stand-alone hybrid wind/PV/fuel cell power generation systems. Kalantar [8] reported the dynamic behaviors of a stand-alone hybrid power system combined with wind turbine, micro-turbine, solar array and battery storage.

Most investigations on the wind-fuel cell hybrid energy system with hydrogen production and storage for stand-alone use have focused on the dynamic behaviors analysis, life cycle analysis, controller design, unit sizing and other related areas. However, the present literatures lack the consideration of chlorine production in the process of splitting sea water by using electrolyzer. Chlorine is commonly used in water treatment and in the manufacture of PVC. Hence, it's valuable to take chlorine production into account in the simulation of the hybrid energy storage system.

In this paper, a wind energy storage system (a small stand-alone power system) which is suited for the remote offshore area by considering of chlorine production and storage is proposed. The dynamic model of wind energy storage system is built by integrating the wind turbine model, the PEM fuel cell model, the hydrogen storage model and a modified electrolyzer model. In the modified electrolyzer model, the production of chlorine is considered. For the offshore area, there have plenty wind energy resource and inexhaustible sea water for the proposed system operating. The usage of energy storage equipments could provide reliable and stable electric power to stand-alone power system with high wind energy utilization efficiency.

The rest of this paper is structured as follows: next section describes the configuration and detailed dynamic model of components for the proposed system. Section 3 presents the energy management strategy which is used in the proposed system operation. Section 4 presents the principle of unit sizing and parameters selection for the proposed system simulations. Section 5 shows the simulation results and section 6 closes the paper with some conclusions.

2 SYSTEM DESCRIPTIONS AND MODELLING

The system overall configuration schematic diagram of the proposed wind power storage system in remote offshore areas is shown in Figure 1. From Figure 1, the proposed system consists of a wind energy conversion system (WECS), an electrolyzer array, a proton exchange membrane fuel cell array, a hydrogen tank, an oxygen/chlorine tank, a water storage tank, a control unit and power management unit.

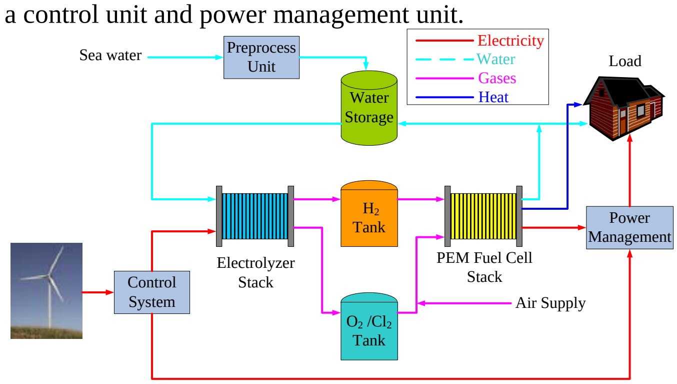

Figure 1. Schematic diagram of proposal wind energy storage system

Sea water is disposed through preprocess unit to filter the solid grains and other impurities, and then filled up the water tank. When energy generated from the wind power conversion system is larger than the load power requirements, the surplus energy of wind farm output should be stored in the form of hydrogen, which produced by splitting the sea water from the water tank via the electrolyzer array. The hydrogen flow would feed into the hydrogen storage tank by the help of some gas compressors. At the same time, the electrolysis of sea water should produce chlorine or oxygen (decided with the electrodes material in electrolyzer array) which stored in the chlorine/oxygen tank. On the contrary, when the wind energy conversion system output power is insufficient to meet the consumption load requirement, the stored hydrogen and the compressed air would be supplied to the PEM fuel cell array to produce more electrical energy, some heat also is generated as byproduct in this process. All of these actions are determined automatically by the power management unit.

The following assumptions are used to simplify the analysis and simulations:

(1) In the wind energy conversion system, all the wind turbines have good talent on the yaw system to adjust the wind rotor according to the wind direction. The wake effect between wind turbines and the induction generators are not considered in this model.

(2) The power electronics devices such as the AC/DC rectifier, DC/AC inverter and DC/DC boost converter are not include in this model.

(3) In the hydrogen storage system, the compressors, gases pressure regulator, pumps and valves are ignored.

2.1 WIND ENERGY CONVERSION SYSTEM MODEL

For horizontal-axis variable pitch wind turbine, the power extraction from the wind which flows through the wind rotor blades is given by [9]

$$P_{wind} = 0.5\rho A v^3 C_p\left(\lambda, \beta\right) \tag{1}$$

where ρ denotes the air density (kg/m^3), A is the area swept by the wind rotor blades(m^2), v is the wind speed(m/s). C_p is named the power coefficient, which is a function about the tip speed ratio λ and pitch angle β .

According to the Betz Theory, the limit of power coefficient is 0.593 approximately. The actual power coefficient is smaller than the Betz limit. Figure 2 shows the power coefficient-tip speed ratio characteristics of the wind turbine at different pitch angles. As can been seen from Fig 2, the power coefficient could be adjusted by changing the pitch angle. It means that the wind turbine output power could be regulated through the pitch angle controller.

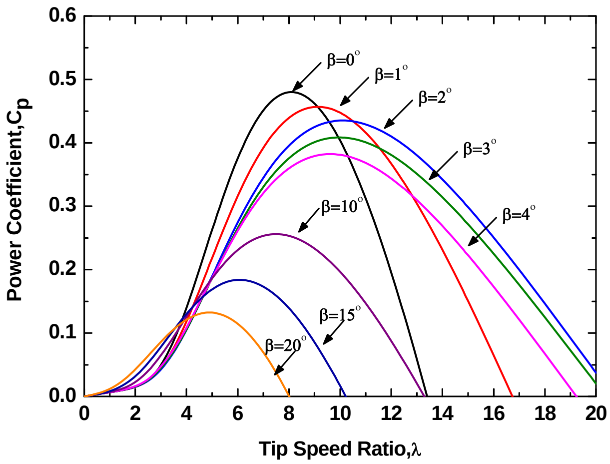

Figure 2. Power coefficient-tip speed ratio characteristics of wind turbine at different pitch angle

For the variable pitch wind turbine, a proportional-integral (PI) controller is designed for controlling the blade pitch angle in order to limit the wind turbine output power to its rated power. Usually, the blade pitch angle is kept constant at zero degree when the measured output power is less than its rated power. When the output power increases above the rated value, the pitch angle controller would increases the pitch angle to adjust the output power to the rated value. Figure 3 shows the principle diagram of pitch angle control system.

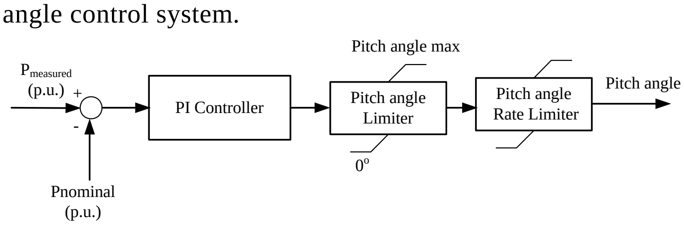

Figure 3. Principle diagram of wind turbine pitch angle control system

2.2 PROTON EXCHANGE MEMBRANE FUEL CELL ARRAY MODEL

Fuel cells are electrochemical devices that convert the chemical energy of a reaction into electrical energy directly. This type of electrical energy could be used for power vehicles, electronic devices, houses, or be delivered to power grid as a distributed generation [10]. Fuel cells are classified into several types according to the difference of electrolytes used in the fuel cells, including the alkaline fuel cell (AFC), phosphoric acid fuel cell (PAFC), proton exchange membrane fuel cell (PEMFC), molten carbonate fuel cell (MCFC) and solid oxide fuel cell (SOFC). The different types of fuel cells have slightly different chemical reaction in their electrodes.

PEM fuel cells have been widely recognized as the most promising candidates for future power generating devices recently [18]. For the PEMFC, it employs a solid polymer which is an excellent conductor of protons and an insulator of electrons, as electrolyte [10]. Hydrogen and air (or pure oxygen) are fed to the electrodes as reactants to produce electricity, water, and heat. The detailed chemical equations are shown as follows:

Anode reaction: $H_2 \Rightarrow 2H^+ + 2e^-$

Cathode reaction: $2H^+ + 2e^- + 0.5O_2 \Rightarrow H_2O + heat$

Overall reaction: $H_2 + 0.5O_2 \Rightarrow H_2O$

Figure 4 shows the schematic and chemical reactions of individual PEM fuel cell. At the anode, the hydrogen molecules are broken into hydrogen protons and electrons with the help of catalyst. Then the hydrogen protons pass though the electrolyte internally and reach the cathode surface, the electrons flow though the externally load and get to the cathode. At the cathode, the hydrogen protons combine with electrons and oxygen molecules to produce the water and heat.

Actually, lots of similar individual PEM fuel cells are connected in series or in parallel to form the PEM fuel cell array. Therefore, dynamic model of single PEM fuel cell is effective for dynamic characteristics research of PEMFC array subsystem. The detail model of PEM fuel cell is presented below [10].

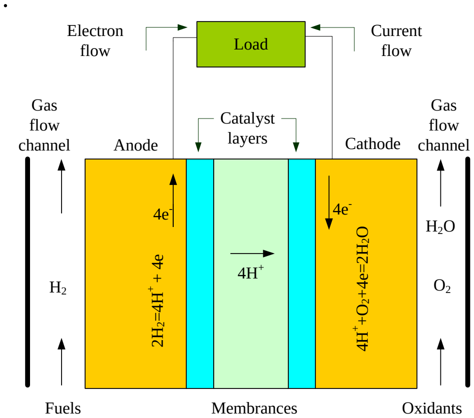

Figure 4. Schematic diagram and chemical reaction of individual PEM fuel cell [10]

Gas Diffusion at the Electrodes

According to Stefan-Maxwell formulation, the effective partial pressures of hydrogen and oxygen are calculated to determine the PEM fuel cell output voltage. The effective partial pressures of hydrogen at anode and oxygen at cathode could be written as follows [11, 12]:

$$p_{H_2} = 0.5 \cdot p_{H_2O}^{sat} \cdot \left[\frac{1}{x_{H_2O}^{anode} \cdot \exp(\frac{1.653 \cdot i}{T_k^{1.334}})} - 1 \right] \quad (2)$$

$$p_{O_2} = p_{H_2O}^{sat} \cdot \left[\frac{1}{x_{H_2O}^{cathode} \cdot \exp(\frac{4.192 \cdot i}{T_k^{1.334}})} - 1 \right] \quad (3)$$

where p_{H_2} and p_{O_2} are the effective partial pressure of hydrogen and oxygen (atm), $x_{H_2O}^{cathode}$ and $x_{H_2O}^{anode}$ are mole fraction of water at cathode and anode respectively, i is current density (A/m^2), T_k is the temperature in Kelvin (K) and $p_{H_2O}^{sat}$ is the saturation pressure of water (atm), is calculated by [12]:

$$p_{H_2O}^{sat} = 10^{-2.1794+0.02953T_c-9.1837\times10^{-5}T_c^2+1.4454\times10^{-7}T_c^3} \quad (4)$$

where T_c is the temperature in Celsius（℃).

Nernst Equation

The thermodynamic potential of reaction in a hydrogen oxygen fuel cell could be defined by Nernst equation as below:

$$E = E_0 + \frac{RT_k}{2F} \ln\left[p_{H_2} \cdot \left(p_{O_2} \right)^{0.5} \right] \quad (5)$$

where E_0 is the ideal standard potential of an hydrogen/oxygen fuel cell (V), R is ideal gas constant ($8.314 J/mol \cdot K$) and F is Faraday's constant ($96487 C/mol$).

Further expansion of equation (5) yields that the ideal voltage is [11, 17]:

$$E = 1.229 - 0.85\times10^{-3}(T_k - 298) + 4.3085\times10^{-5} \cdot T_k \left[\ln(p_{H_2}) + 0.5\ln(p_{O_2}) \right] \quad (6)$$

PEMFC Voltage Losses

In general, due to some irreversible losses such as the activation polarization, ohmic polarization and concentration polarization inside the PEM fuel cell, the voltage measured outside the PEM fuel cell is smaller than the ideal voltage calculated inside the fuel cell, which is obtained from the Nernst equation. Hence, the actual output voltage of a single PEM fuel cell V could be presented as:

$$V = E - V_{act} - V_{ohm} - V_{conc} \quad (7)$$

where V_{act}, V_{ohm} and V_{conc} are the activation polarization, ohmic polarization and concentration polarization(V) respectively.

The activation polarization can be expressed as:

$$V_{act} = \eta_0 + (T_k - 298) \cdot a + T_k \cdot b \ln(I) \quad (8)$$

where η_0 (V), a, b (V/K) are empirical constants and I is the current (A).

The ohmic polarization can be written as:

$$V_{ohm} = I \cdot R_{ohm} = I \cdot \left(R_{ohm,0} + k_{RI} I - k_{RT} T_k \right) \quad (9)$$

where R_{ohm} is a function of current and temperature (Ω) [10], $R_{ohm,0}$ is the constant part (Ω) of R_{ohm}, k_{RI} (Ω/A)and k_{RT} are empirical constants (Ω/K).

And the concentration polarization could be:

$$V_{conc} = -\frac{RT_k}{2F} \ln(1 - \frac{I}{I_{limit}}) \quad (10)$$

where I_{limit} is the current limit of PEM fuel cell (A).

Thermodynamic Energy Balance

Heat is generated from the chemical reaction inside the PEM fuel cell array, which would result in an increase or decrease in the array temperature. The formula can be written below [10]:

$$Q_{fc} = Q_{ch} - Q_e - Q_{s,l} - Q_{loss} \quad (11)$$

where Q_{fc} is the net heat energy(J), Q_{ch} is the chemical energy(J), Q_e is the electric energy(J), $Q_{s,l}$ is the sensible and latent heat, and Q_{loss} is the heat which loss to ambient(J).

The chemical power released by chemical reaction is achieved by [10]:

$$Q_{ch} = n_{H_2,con} \cdot \Delta H \quad (12)$$

where $n_{H_2,con}$ is hydrogen consumption rate (mol/s), ΔH is the enthalpy change of the chemical reaction inside the PEM fuel cell(J/mol).

The electrical energy can be calculated by [10]:

$$Q_e = V \cdot I \quad (13)$$

The sensible and latent heat absorbed during the process could be calculated approximately as follow [10]:

$$Q_{s,l} = n_{H_2,out}(T - T_{amb}) \cdot C_{H_2} + n_{O_2,out}(T - T_{amb}) \cdot C_{O_2} + n_{H_2O,gen} \cdot (T - T_{amb}) \cdot C_{H_2O,l} + n_{H_2O,gen} \cdot H_V \quad (14)$$

where n_i is flow rate of species i (mol/s), C_i is specific heat capacity of species i ($J/molK$), H_V is vaporization heat of water(J/mol), and T_{amb} is ambient temperature(K).

The loss energy is estimated as follow [10]:

$$Q_{loss} = h(T - T_{amb}) n_{fc} A_{fc} \quad (15)$$

where h is the convective heat transfer coefficient (W/m^2K), n_{fc} is the number of cells in array and A_{fc} is the reaction area of each cell(m^2).

2.3 ELECTROLYZER MODEL

Electrolysis of water to produce hydrogen and oxygen has a long history [13]. Electrolysis is a process for breaking water into its constituent elements hydrogen and oxygen by supplying electrical energy [14]. Due to the water is a very stable molecule compared with the hydrogen and oxygen, the outside added energy is necessary to ensure this reaction occur. From the view of a chemical insight, the electrolysis of water can be considered a reverse reaction that happens in fuel cells.

The overall chemical reaction equation and for splitting water can be written as:

Overall: $H_2O + electrcity \Rightarrow H_2 + 0.5O_2$

Anode: $OH^- \Rightarrow 0.25O_2 + 0.5H_2O + e^-$

Cathode: $H_2O + e^- \Rightarrow 0.5H_2 + OH^-$

At the offshore area, the sufficient sea water or brine could replace the fresh water to attend in the reaction. Due to sodium chloride and other impurities in the sea water, electrodes voltage of electrolyzer cell is higher than the electric potential of producing chlorine. In this way, the electrolysis of sea water would yield chlorine instead of oxygen, which is an important industrial chemical [15]. The reaction equations are as follows:

Anode: $Cl^- \Rightarrow 0.5Cl_2 + e^-$

Cathode: $H_2O + e^- \Rightarrow OH^- + 0.5H_2$

Normally, because of the strong toxicity of chlorine, the production of chlorine in the process of splitting sea water should be avoided. It's an available method by using manganese or manganic compound as electrodes material to produce pure oxygen instead of chlorine through the sea water electrolysis [16]. The production at anode of electrolzyer cell is decided by system operating requirements and users.

Like the PEM fuel cell array, a water electrolyzer array can also be organized by connecting the single water electrolyzer cells in series or in parallel. The operation temperature is a crucial factor for the efficiency and current-voltage characteristics of a single electrolyzer cell. According to the Faraday's law, the hydrogen production rate in a single electrolyzer cell is proportional to the transfer rate of electrons at the electrodes [2], could be written as:

$$n_{H_2} = 0.5\eta_F n I_{el} F^{-1} \tag{16}$$

where I_{el} is the elctrolyzer current(A), η_F is the Faraday efficiency, and n is the number of elctrolyzer cells.

Faraday efficiency is the ratio between the actual maximum amount of hydrogen production and the theoretical hydrogen production. Assuming that the electrolyzer array has an independent cooling system to keep the temperature at desired value which is 40℃ in this paper. Then the Faraday efficiency can be expressed as:

$$\eta_F = 96.5\exp(0.09 I_{el}^{-1} - 75.5 I_{el}^{-2}) \tag{17}$$

2.4 HYDROGEN STORAGE SYSTEM MODEL

Hydrogen production by electrolyzer can be stored in a hydrogen tank. Constant hydrogen flow fills up the tank until the pressure of tank is equal to the electrolyzer cathode pressure. Of course, a compressor could be arranged before the hydrogen tank, to ensure the hydrogen flows into hydrogen storage tank at higher pressure level. The dynamic of hydrogen storage can be expressed as follow [1]:

$$P_{t,H_2} \hat{=} P_{t,init} = z\frac{n_{H_2} R T_t}{m_{H_2} V_t} \tag{18}$$

where $P_{t,init}$ is the initial hydrogen pressure in tank(Pa), n_{H_2} is hydrogen moles per second delivered to tank(mol/s), m_{H_2} is molar mass of hydrogen(g/mol), R is universal gas constant, and T_t , V_t is the tank operation temperature(K) and tank volume (m^3) respectively.

3 THE ENERGY MANAGEMENT STRATEGY

An energy management strategy is needed for dealing with the power flows among different energy sources and loads. The block diagram of energy management strategy for the proposed system is shown in Figure 5.

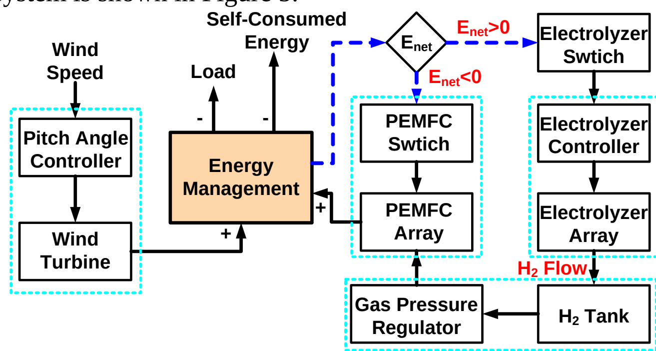

Figure 5. Block diagram of energy management strategy for proposal system

From Figure 5, in the proposed system, the wind energy conversion system is controlled by the pitch angle controller to extract the maximum energy from the wind flow through the wind rotor at different wind speed. The net energy of the proposed storage system is the difference between the produced power by WECS and consumption power. The sign of net energy is the decided condition for operating the PEMFC-electrolyzer system. That is expressed as below:

$$E_{net} = E_{generated} - E_{consumption} = E_{wind} - E_{load} - E_{s,cons} \tag{19}$$

Where $E_{s,cons}$ is the self-consumed energy, namely the consumption power by the auxiliary components such as control systems, compressors and water cooling system.

The detail energy management strategy is: If the net energy is a positive value, it means that there has sufficient energy generated by wind energy conversion system, and then supply the surplus energy is delivered to electrolyzer array to produce hydrogen, which is the energy storage carrier in this paper. If the net energy is a negative value, it means that there has a poor wind speed flow through wind rotor and the generated energy is deficient, and the PEM fuel cell array would start to transfer the stored hydrogen to electrical energy in order to compensate the energy insufficiency.

4 SYSTEM SIZING AND PARAMETERS SELECTION

The size configuration of the proposed hybrid wind energy storage system is needed for simulation. Because the hybrid system is designed for remote offshore village, the mean load demand is lower than other places. We assuming that the peak load demand, mean load demand and lowest load demand of a small village are 280kW, 200kW and 120kW for the simulation purposes respectively.

The capacity factor of renewable energy is defined for estimating the availability of the renewable source, and it is a ratio between actual average output power over a period of time T and nominal output power of the renewable energy system [10]. The period T is usually taken as one year. In this paper, the capacity factor of wind turbines is chosen as 30% [7], which is mostly used in hybrid power system.

According to the given wind turbine capacity factor and mean load demand, the size of the wind energy conversion system is calculated to be 667kW. Therefore, a 700kW installed capacity wind farm is composed of fourteen wind turbines with 50kW rated power each.

The PEM fuel cell array provides the urgency energy for the proposed system. It needs to supply the peak load demand at poor wind condition, thereby the size of PEMFC array should be equal to peak load demand, which is 300kW if there has a safe margin. Therefore, the number of PEMFC in the fuel cell array is 600, and each cell is the Ballard Mark IV PEM fuel cell [11, 17]. The PEMFC array consists of 25 PEMFC stacks connected in parallel, and each PEMFC stack is connected with 24 single PEM fuel cells in series.

The electrolyzer array should deal with the maximum surplus power from the WECS. It can be calculated at the wind turbines operating at rated condition and there has lowest load demand meanwhile, so the electrolyzer array size is 580kW. Therefore, the array is composed of twelve 50 kW electrolzyer cells connected in series.

The detail components parameters are listed in Table 1 ~ 4.

Table 1. Parameters of the H_2 storage system

Parameter	Value
Tank volume	20m^3
Operating temperature	20℃
Initial pressure	1kPa

Table 2. Parameters of the WECS system

Parameter	Value
Total capacity	700kW
Wind turbine number	14
Rated power	50kW
Rated speed	14m/s
Cut in speed, cut out speed	3m/s,25m/s
Blade diameter	15m
Air density	1.225kg/m^3
Blade swept area	177m^2

Table 3. Parameters of the PEMFC array

Parameter	Value
Total capacity	300kW
PEMFC number	600
Connected mode	25 stacks in parallel, each stack connected with 24 single cells in series
Rated power per cell	0.5kW
Anode pressure per cell	152kPa
Cathode pressure per cell	152kPa

Table 4. Parameters of the electrolyzer array

Parameter	Value
Total capacity	580kW
Electrolyzer cell number	12
Connected mode	In series
Rated power per cell	50kW
Operating voltage per cell	60V

5 SIMULATIONS AND DISCUSSION

To observe and validate the proposed system's behavior over a period of time including the low wind speed condition, high wind speed condition versus different load power requirement conditions, some simulations are presented in this section. The simulation time is set to 300 seconds. With variations in load power requirement, we assuming that the end user's power demands changes are from 120kW (at lowest power demand condition) to 280kW (at peak power demand condition) at 100 second and from 280kW to 200kW (at mean power demand condition) at 150 second, the load demands is shown in Figure 6. The detail simulation results are presented below.

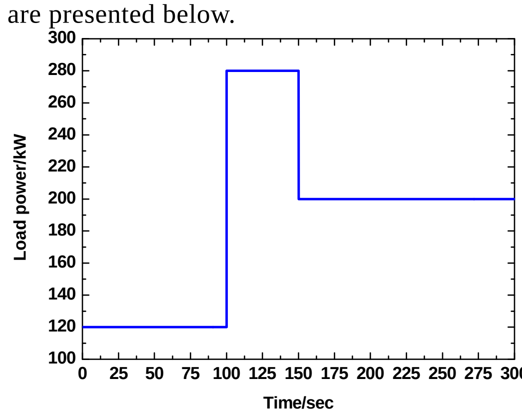

Figure 6. Load power demands from the end users

5.1 WIND ENERGY CONVERSION SYSTEM PERFORMANCE

Wind speed profile used for system simulation is plotted in Figure 7, the wind speed data were measured by the meteorological tower in a wind farm named "Lingyang", which located at the eastern coastal areas of Nantong city in Jiangsu province of China. The original measured wind speed data are 10-minute average values for a continuous 3000 minutes period, otherwise, the unit of time for this wind speed profile has been changed from "10-minute" to "second" intentionally for evaluating the performance of proposed system conveniently. These wind speed data cover a large range between the cut-in speed and the rated speed. The corresponding wind power output produced by wind farm is shown in Figure 8. As can be seen, the power generated from wind farm varies because of the wind speed fluctuating, and the wind power is limited below 700kW due to the actions of wind turbine's pitch angle controller.

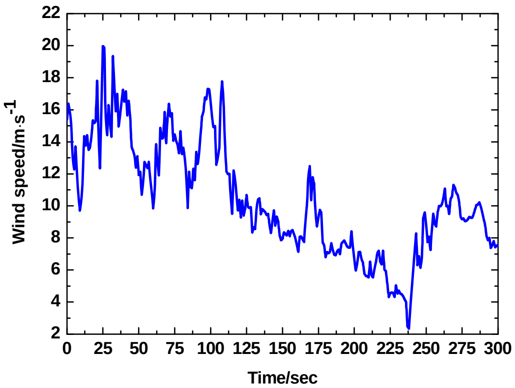

Figure 7. Wind speed profile used for simulation

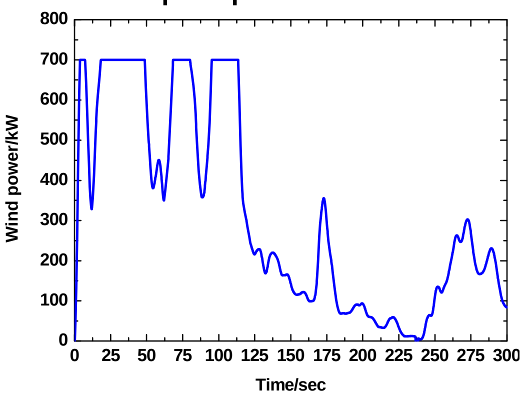

Figure 8. Wind power produced by WECS

5.2 ELECTROLZYER ARRAY PERFORMANCE

The net energy is positive at the beginning period (0~125s) due to the load power demand at the lowest condition but the wind energy at the rated condition. According to the energy management strategy, the surplus energy would be supplied to electrolyzer array to produced hydrogen. The net energy (electrolyzer array consumption power) is plotted in Figure 9. Because the single electrolzyer cell is operating at constant voltage mode (60V), the current flow through the electrolyzer array is proportional to the consumption (net) power, which is showed in Figure 10. And the hydrogen or chlorine production rate of electrolyzer array is presented in Figure 11, which has the same variations trend with the electrolyzer current.

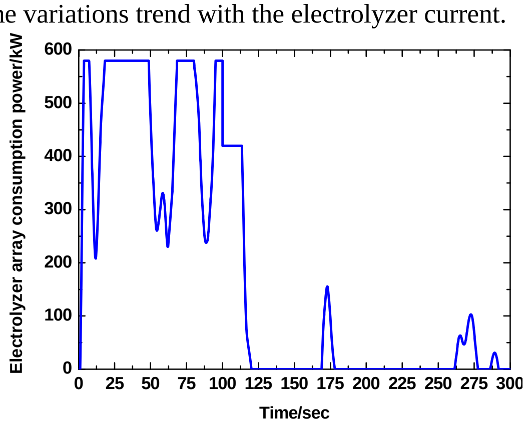

Figure 9. Electrolyzer array consumption power

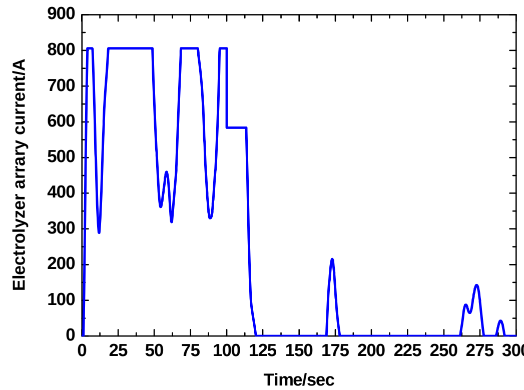

Figure 10. Electrolyzer array current

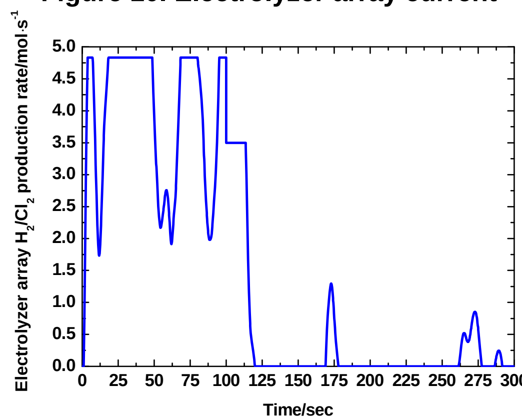

Figure 11. H_2/Cl_2 production rate of electrolyzer array

5.3 PEM FUEL CELL ARRAY PERFORMANCE

At the posterior stage of this simulation (126s~300s), the power generated from wind farm is under the rated power and the end user's demand is getting larger, at the peak load and mean load conditions. Therefore, the wind power could not satisfy the load requirements, the net power is negative. At this situation, the PEM fuel cell array would be tuned on to supply power for compensating the power gap. The current and voltage of PEMFC array are showed in Figure12 and Figure 13 respectively. The energy generated from the PEMFC array is obtained by multiplying the current and voltage, which is plotted in Figure 14.

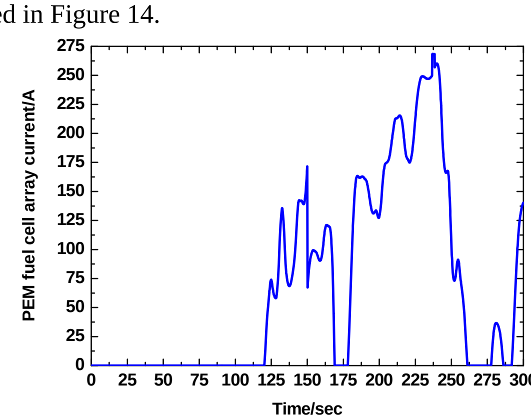

Figure 12. PEM fuel cell array current

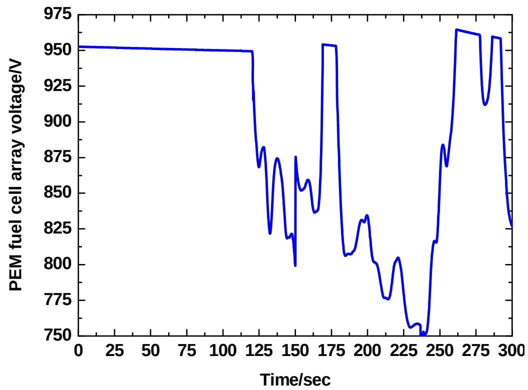

Figure 13. PEM fuel cell array voltage

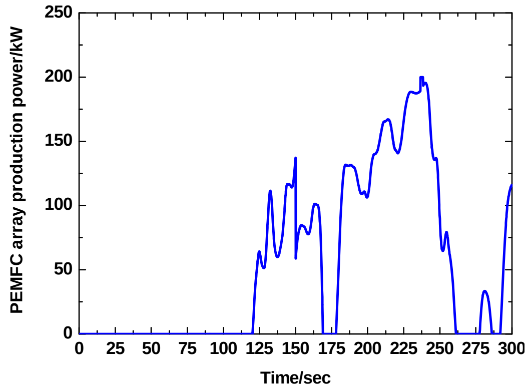

Figure 14. PEM fuel cell array production power

5.4 HYDROGEN STORAGE SYSTEM PERFORMANCE

At the whole simulation, the hydrogen mole flow rate changes according to the sign of net energy. The hydrogen produced by the electrolyzer array and consumed by the PEMFC array causes the pressure variations of the hydrogen storage tank as shown in Fig. 15. The pressure of the storage tank increases when the electrolyzer array produces hydrogen (net energy is positive), and the tank pressure decreases when the PEMFC array uses the stored hydrogen (net energy is positive). In Figure 15, the region A represents a small time scale of electrolzyer array operating, the tank pressure has a small rise.

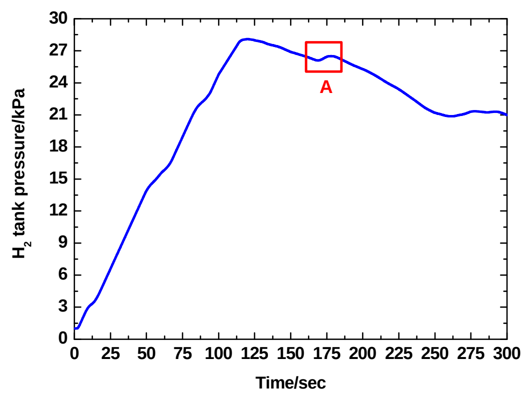

Figure 15. The pressure of H_2 storage tank

6 CONCLUSIONS

A wind energy storage system which considers the chlorine production is developed in this paper. The proposed system is aimed to supply reliable and stable electric energy to meet the load requirements for remote offshore area by integrating with a wind farm, a PEM fuel cell array, an electrolyzer array, an energy management unit and some gas storage tanks. The wind energy storage system stores surplus energy in the form of hydrogen via electrolzyer array to splitting sea water when wind power is plenteous, and uses the stored hydrogen to generate electricity through PEM fuel cell array at the poor wind speed period. Meanwhile, chlorine as a production would be produced in the process of splitting sea water.

Simulation results show that the proposed system gives an approximate energy variation trend in the system components under variable wind speed and load power requirements conditions. The extra stored hydrogen due to the high wind energy density and low load power demands in remote offshore areas, could be used for the mobile fuels or some other areas. The production chlorine is also useful for industrial production. The proposed system could be used for the non-connected remote offshore areas to produce energy self-sufficiently. However, the simulation results are just qualitative analysis due to the assumptions mentioned in previous section, further studies on improving the dynamic models must be carried out. But the simulation is useful for a conceptual study and cognizance the value of a hybrid wind-hydrogen system.

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