A Study of Hydrogen Production in Stand-alone Wind Farm

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Abstract- Hydrogen production using wind power generation system is very effective for solving the energy supply problem in the future. Many strategies have been proposed for the operation of a grid-connected wind farm. But operation method of stand-alone wind farm has not been studied sufficiently so far. There are many places with good wind condition but without connectable grid, where stand-alone wind farm can be very attractive. This paper proposes a control method for the operation of a stand-alone wind farm with a hydrogen generator.

Keywords- Wind energy conversion, Stand-alone system, Hydrogen production, Power converters.

1. Introduction

Hydrogen has attracted much attention as an alternative energy to oil due to the problems of global warming and exhaustion of fossil fuel, because it does not emit any greenhouse gas (CO_2 etc) during combustion. Normal method to produce hydrogen is presently the reforming of fossil fuel. However it is clear that electrolysis of water using the electricity generated from fossil fuel is not a good way. On the other hand, it can be expected to be a good way to produce hydrogen using electricity from wind power generation. However, wind power generation has some problems, that is, generated power varies due to wind speed variations which can cause frequency fluctuations in the connected power grid. On the other hand, even if suitable place for wind power generation with good wind condition is available, wind farm cannot be installed at the place if there is no power grid near there.

Hydrogen production in a stand-alone wind farm which is not connected to a power grid can have a possibility to solve above serious situations. This system can be installed at any place where good wind condition is available without a need to think about power grid connection, and can produce hydrogen without usage of fossil fuel and emission of greenhouse gas. Therefore it can be a very useful method to solve the problems of global environment. Though some researches about hydrogen production system with a stand-alone wind farm have been reported so far, only the case of a wind farm is analyzed which is composed of single generator with a battery installed. There is a few reports analyzing a wind farm which is composed of single wind generators and a battery [1]-[2]. This paper proposes a hydrogen production system composed of a hydrogen generator and multiple wind generators connected in parallel through power converters of boost chopper. Hydrogen production system composed of multiple wind generators has merit. For example, multiple generators supply the total power to the hydrogen generator, and thus the smoothing effect can be obtained. Therefore, this system can be operated without battery producing hydrogen gas stably. On the other hand, some researches have been reported in which multiple wind generators are connected in parallel through power converters [3]-[4]. But, the DC distribution grid with various types of power sources including wind generators is considered there. There is few report in which the system is composed of only wind generators connected in parallel. In addition, natural wind speed data is not considered in individual wind generator in these reports [3]-[4].

In this paper, a new type of hydrogen production system composed of a hydrogen generator and multiple wind generators connected in parallel through power converters is proposed, in which each wind generator is operated based on MPPT (Maximum Power Point Tracking) controlled by boost chopper and the total wind generator output is supplied to the hydrogen generator. Validity of the system is evaluated by simulation analyses using PSCAD/EMTDC.

2. Model System

Fig.1 shows the model system used in this paper, which is composed of three PMSG (Permanent Magnet Synchronous Generator) wind generators with variable speed control. Because the hydrogen generator is operated in DC power, AC output of PMSG is converted to DC power by using 3 phase diode bridge rectifiers, and then the boost chopper circuit controls the DC power according to MPPT strategy for PMSG. Finally DC power from each generator is summed through parallel connection of the boost chopper circuits and the total DC power is supplied to the hydrogen generator. The hydrogen generator in this paper is composed of modules [5] connected in 34 series and 2 parallel, which is expressed by an internal resistance and voltage source. The detail of the control system will be described later. Table I shows parameters of the system.

3. Variable Speed Wind Power Generation System

3.1. Wind Turbine Model

Wind turbine model is expressed by the characteristic equations (1)~(4) [6], where P_w is captured wind power [W], λ is tip speed ratio, ω is wind turbine angular speed [rad/s], β is blade pitch angle [deg], ρ is air-density [kg/m^3], v is wind speed [m/s], R is radius of rotor blade [m], and C_1~C_9 are constants, C_1=0.73, C_2=151, C_3=0.58, C_4=0.002, C_5=2.14, C_6=13.2, C_7=18.4 C_8=-0.02 and C_9=-0.003.

$$P_w = \frac{1}{2} Cp(\beta, \lambda) \rho v^3 \pi R^2 \tag{1}$$

$$Cp(\beta, \lambda) = C_1\left(\frac{C_2}{\lambda_i} - C_3\beta C_5 - C_6\right)\exp\left(-\frac{C_7}{\lambda_i}\right) \tag{2}$$

$$\lambda = \frac{\omega R}{v}, \quad \frac{1}{\lambda_i} = \frac{1}{\lambda + C_8\beta} - \frac{C_9}{\beta^3 + 1} \tag{3}$$

$$\omega_{op} = 0.0819v \ \ [\mathrm{pu}] \tag{4}$$

Variable speed wind generator can achieve high energy efficiency operation and its output can be controlled to be maximum output according to the maximum power coefficient with respect to the wind speed. Fig. 2 shows the characteristics of wind turbine input power for rotor speed and wind speed. The dotted line shows the Maximum Power Point Tracking (MPPT) line (ω_{op} vs. P_{MAX}), and the wind generator output follows this line.

In variable speed wind turbine system, the rotor speed of wind turbine (ω) is measured in order to achieve the MPPT operation. Since it is difficult to measure the wind speed accurately, in general, the MPPT operation should be performed without measuring the wind speed as expressed in (5), where P_{MPPT} is the maximum power, P_{wn} is wind turbine rated output (2[MW]), and λ_{opt} is the optimal value of λ. The maximum power (P_{MPPT}) is limited within the rated power of generator.

$$P_{MPPT} = 0.5\rho\pi R^2\left(\frac{\omega R}{\lambda opt}\right)^3 Cp\_\max \Big/ P_{wn} \tag{5}$$

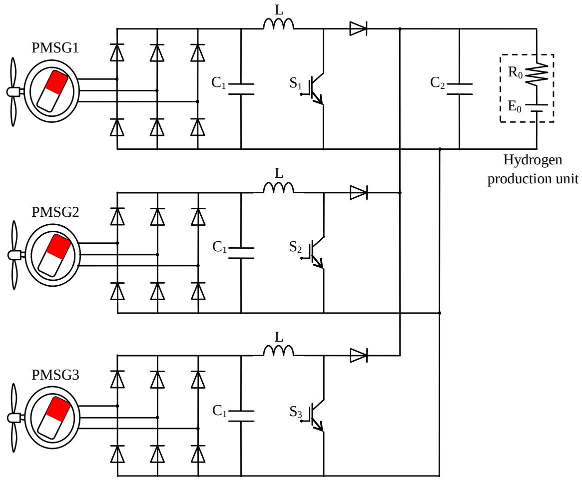

Fig. 1. System model

Table 1. System parameter

Wind turbine	
Rated Power P_{wn}	2[MW]
Rated Rotational speed	23.33[rpm]
Rated Wind speed	12.205[m/s]
Radius of Wind turbine R	36[m]
Maximum Power Coefficient C_{p_max}	0.441
PMSG	
Rated Output	1[MVA]
Rated Voltage	1000[V]
d axis reactance	0.9[pu]
q axis reactance	0.7[pu]
Winding resistance	0.01[pu]
Frequency	20[Hz]
Magnetic strength	1.43[pu]
Chopper	
Reactor L	100[mH]
Capacitor C_1	40000[μF]
Capacitor C_2	50000[μF]
Electrolyzer	
Rated Power	3[MW]
Internal Voltage E_0	3196[V]
Internal Resistance R_0	0.559[Ω]

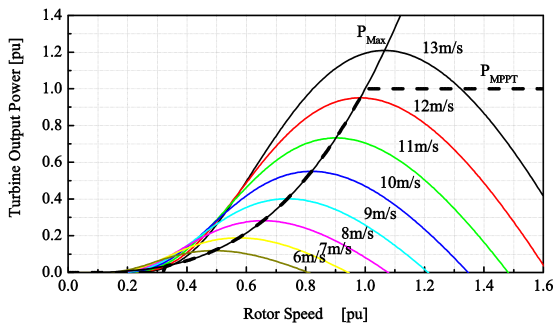

Fig. 2. Wind turbine output characteristics

Though the rated power of wind turbine is different from that of PMSG as shown in Table I, there is no problem because the simulation analyses in this paper are performed based on the per unit system.

3.2. Permanent Magnet Synchronous Generator:PMSG

In this study, PMSG wind generator is adopted because it does not need excitation supply and then it is suitable for the stand-alone operation. Though details of the control system will be described later, generator output is controlled by the boost chopper according to MPPT operation. In addition, three PMSG wind generators with same parameters are used.

4. System Control

4.1. Principle of the Control

In the proposed system, generator AC output is rectified to DC power by using 3 phase diode bridge rectifiers, and then each DC power is controlled by the boost chopper circuit as described before. In order to explain the principle of control system analytically, a simple model is used in which the generator and 3 phase diode bridge rectifier are replaced by a DC voltage source and internal resistance. On the other hand, the hydrogen generator is expressed by an internal resistance and voltage source. Fig.3 shows the simple expression of the model system where n parallel circuits each composed of DC power source and the boost chopper are connected to the hydrogen generator.

We derive relationship between duty ratio of the chopper and current flowing from each voltage source. It is assumed that the values of reactors and condenser in the circuit are large enough so that ripples in reactor current and condenser voltage are negligible. In addition, average values of voltage and current for averaging period of one switching cycle are shown in Fig.3. On the other hand, on-resistances of the IGBTs are r_{igbt1}, r_{igbt2}, ,r_{igbtn}, and on-resistances of the diodes are r_{d1}, r_{d2}, ,r_{dn}.

Considering the first circuit with voltage source E_1, on-time of S_1 is T_{on1}, off-time of S_1 is T_{off1}, and $T_p = T_{on1} + T_{off1}$. Then, energy form voltage source E_1 for T_p is $\bar{i}_1 E_1 T_p$ [J], energy consumption of internal resistance r_1 is $(\bar{i}_1)^2 r_1 T_p$ [J], energy consumption of r_{igbt1} is $(\bar{i}_1)^2 r_{igbt1} T_{on1}$ [J], energy consumption of r_{d1} is $(\bar{i}_1)^2 r_{d1} T_{off1}$ [J], and energy supplied to the condenser and load (resistance R and voltage source E) is $\bar{i}_1 \bar{e} T_{off1}$ [J]. The following equation holds about these components.

$$\bar{i}_1 E_1 T_p = (\bar{i}_1)^2 r_1 T_p + (\bar{i}_1)^2 r_{igbt1} T_{on1} + (\bar{i}_1)^2 r_{d1} T_{off1} + \bar{i}_1 \bar{e} T_{off1} \quad (6)$$

Dividing equation (6) by $\bar{i}_1 T_p$ yields equation (7).

$$E_1 = \bar{i}_1 r_1 + \frac{T_{on1}}{T_p} \bar{i}_1 r_{igbt1} + \frac{T_{off1}}{T_p} \bar{i}_1 r_{d1} + \frac{T_{off1}}{T_p} \bar{e} \quad (7)$$

Defining $T_{on1}/T_p = \alpha_1$ (duty ratio) and $T_{off1}/T_p = \beta_1 = 1-\alpha_1$, current $\bar{i}_1$ can be expressed as follows:

$$\bar{i}_1 = \frac{E_1 - \beta_1 \bar{e}}{r_1 + \alpha_1 r_{igbt1} + \beta_1 r_{d1}} \quad (8)$$

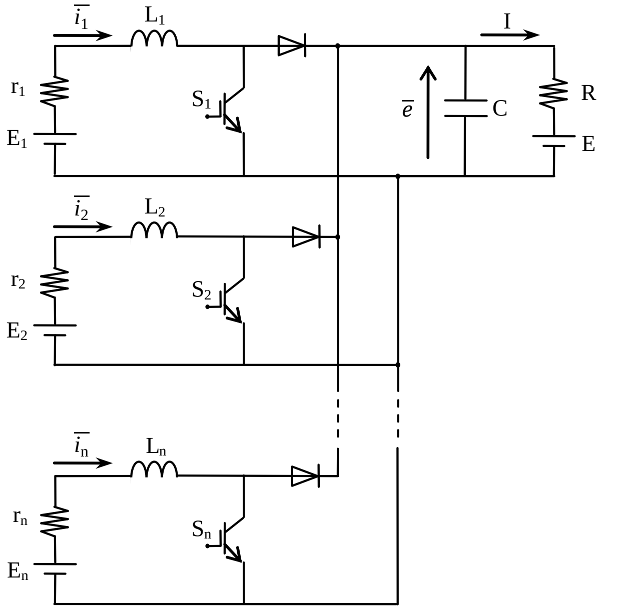

Fig. 3. Parallel connection of multi boost choppers

Similar results can be obtained for other circuits with voltage sources E1, E2, ,En. Then, the following equation (9) can be obtained for currents $\bar{i}_1, \bar{i}_2,\ \ , \bar{i}_n$, where on-time of the choppers are T_{on2}, T_{onn}, off-time are T_{off2} , , T_{offn}, $T_{on2}/T_p = \alpha_2, \alpha_3,\ \ , \alpha_n$, and $T_{on2}/\ T_p = \beta_2, \beta_3,\ \ , \beta_n$.

$$\bar{i}_2 = \frac{E_2 - \beta_2 \bar{e}}{r_2 + \alpha_2 r_{igbt2} + \beta_2 r_{d2}}, \bar{i}_3 = \frac{E_3 - \beta_3 \bar{e}}{r_3 + \alpha_3 r_{igbt3} + \beta_3 r_{d3}},$$
$$, \bar{i}_n = \frac{E_n - \beta_n \bar{e}}{r_n + \alpha_n r_{igbtn} + \beta_n r_{dn}} \quad (9)$$

It seems from equations (8) and (9) that current of each circuit can be controlled by the chopper duty ratio of that circuit without interference from other circuits. As the currents $\bar{i}_1, \bar{i}_2,\ \ , \bar{i}_n$ from each voltage source affect condenser voltage $\bar{e}$, however, interference between each circuit may occur.

Next we derive relations between condenser voltage $\bar{e}$, duty ratio, and currents $\bar{i}_1, \bar{i}_2,\ \ , \bar{i}_n$. Energy supplied to the condenser and load (resistance R and voltage source E) from each voltage source during T_{off1}, T_{off2}, , T_{offn} in T_p is $\bar{i}_1 \bar{e} T_{off1} + \bar{i}_2 \bar{e} T_{off2},\ \ , \bar{i}_n \bar{e} T_{offn}$, and it is equal to the summation of energy charged to the condenser, energy discharged from the condenser, and energy consumed in the load ($I^2 R T_p + I E T_p$). Assuming here (the energy charged to the condenser) + (energy discharged from the condenser) ≒0, following equation (10) can be obtained.

$$\bar{i}_1 \bar{e} T_{off1} + \bar{i}_2 \bar{e} T_{off2} + \quad \bar{i}_n \bar{e} T_{offn} \approx I^2 R T_p + I E T_p \quad (10)$$

On the other hand, substituting $I=(\bar{e}-E)/R$ into equation (10). $\bar{e}$ can be expressed as follows.

$$\bar{e} = R(\beta_1\bar{i}_1+\beta_2\bar{i}_2+\cdots+\beta_n\bar{i}_n)+E \qquad (11)$$

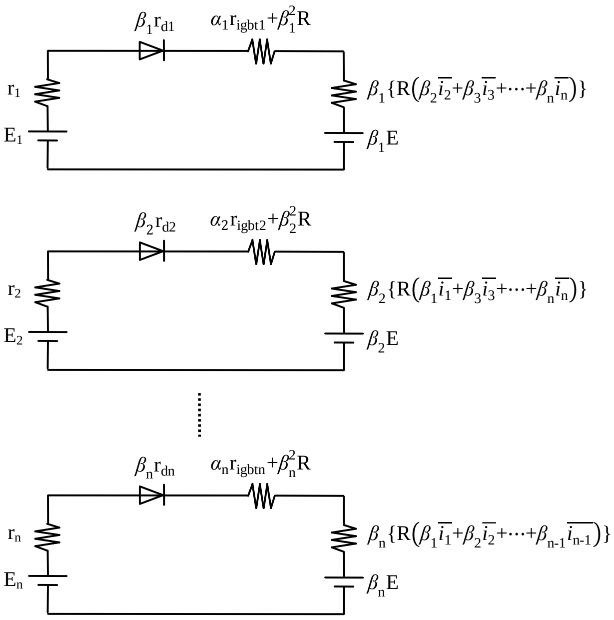

Fig. 4. Equivalent circuit for average values

Table 2. Circuit parameters

Source	
Voltage source E_1~E_3	1000[V]
Internal resistance r_1 ~ r_3	0.1[Ω]
Chopper	
On-resistance of IGBT r_{igbt1} ~ r_{igbt3}	0.01[Ω]
On-resistance of Diode r_{d1} ~ r_{d3}	0.01[Ω]
Reactor L	100[mH]
Capacitor C	50000[μF]
Load	
Voltage source E	3000[V]
Resistance R	0.5[Ω]

Substituting equation (11) into equations (8) and (9) yields following equation (12), where $\bar{i}_1, \bar{i}_2, \cdots, \bar{i}_n \geq 0$ due to the diodes.

$$\bar{i}_1 = \frac{E_1-\beta_1\{R(\beta_2\bar{i}_2+\beta_3\bar{i}_3+\cdots+\beta_n\bar{i}_n)+E\}}{r_1+\alpha_1 r_{igbt1}+\beta_1 r_{d1}+\beta_1^2 R},$$

$$\bar{i}_2 = \frac{E_2-\beta_2\{R(\beta_1\bar{i}_1+\beta_3\bar{i}_3+\cdots+\beta_n\bar{i}_n)+E\}}{r_2+\alpha_2 r_{igbt2}+\beta_2 r_{d2}+\beta_2^2 R}, \quad \cdots,$$

$$\bar{i}_n = \frac{E_n-\beta_n\{R(\beta_1\bar{i}_1+\beta_2\bar{i}_2+\cdots+\beta_{n-1}\bar{i}_{n-1})+E\}}{r_n+\alpha_n r_{igbtn}+\beta_n r_{dn}+\beta_n^2 R} \qquad (12)$$

From equation (12), Fig.4 can be obtained, which is an equivalent circuit for average values viewing from each voltage source. Although the current control of one chopper influences currents of other choppers as can be seen from equation (12) and Fig. 4, current of each chopper can be determined when duty ratio of each chopper is obtained.

4.2. Numerical Calculation

Numerical calculations have been performed in order to evaluate the validity of the derived equations above, where three voltage sources are used in Fig. 3 (n=3) and duty ratios of the choppers are α_1=0.8, α_2=0.79, and α_3=0.78. The parameters shown in Table II were used in the calculations. Fig.5 shows simulation results of the currents flowing from each voltage source, where exact values simulated based on Fig.3 and approximate values calculated from equation (12) are shown. Fig.6 shows simulation results of the condenser voltage where approximate value was calculated from equation (11). Fig.7 shows simulation results of supplied power from each voltage source, where approximate values were calculated based on Fig.4. Fig.8 shows simulation results of the total power consumed in the load, where approximate value was calculated based on Fig.4.

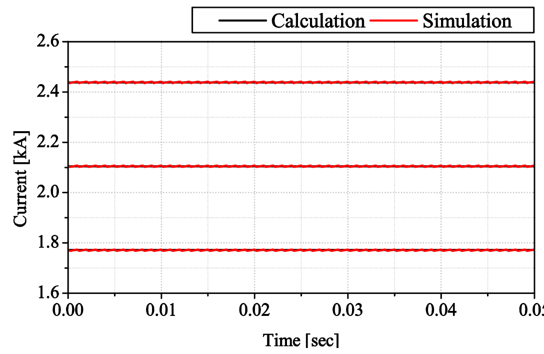

Fig. 5. Responses of currents

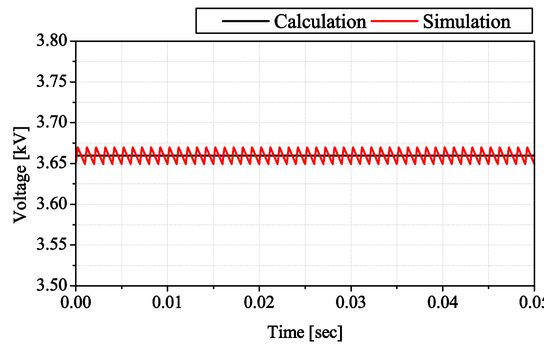

Fig. 6. Responses of condenser voltage

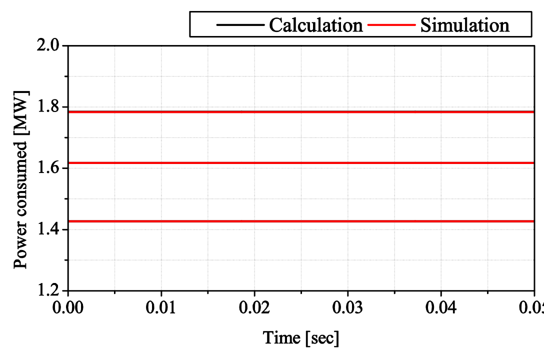

Fig. 7. Power supplied from voltage source

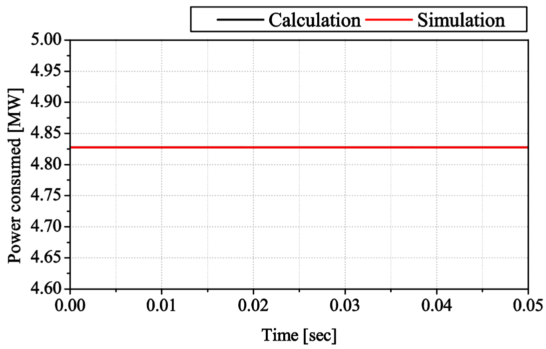

Fig. 8. Total power consumed in the load

It is clear from the simulation results of Figs.5 and 6 that, though slight difference can be seen between the simulated and calculated values, good agreement can be obtained with respect to average values. It is also seen from Figs.7 and 8 that very good agreement can be obtained with respect to supplied power from the sources and consumed power in the load. In addition, the total of the supplied power from the sources is equal to the power consumed in the load. Therefore it is concluded that the derived equations are sufficiently accurate. As a result, it can be said that supplied power from the voltage sources can be controlled by the duty ratio of each boost chopper in the system shown in Fig.3.

5. Wind Generator Control System

5.1. Power Controller

Power control system using boost choppers for parallel connected wind generators is described in this chapter. Fig.9 shows the control system of each boost chopper which controls each generator output to follow P_{MPPT} of each wind generator. It is necessary for the wind generators to operate at MPPT point determined by equation (5). As shown in Fig.9, generator output P_1 can follow the reference value P_{MPPT} by the feedback control with PI controller. And, all wind turbines has similar control system. Therefore each wind generator can keep its MPPT operation.

5.2. Pitch Angle Controller

Wind turbine power depends on the wind speed, and thus, the output power of a wind generator always fluctuates due to the wind speed variations. In order to maintain the output power of generator under the rated level, a pitch controller is considered as shown in Fig.10 [7]. The transfer function of the pitch actuator is represented by a first-order transfer function with an actuator time constant of 5sec and the pitch rate limiter of 10deg/s. A PI controller is used to manage tracking error. In PMSG the pitch controller is used to regulate rotational speed of PMSG under its rated value (1pu).

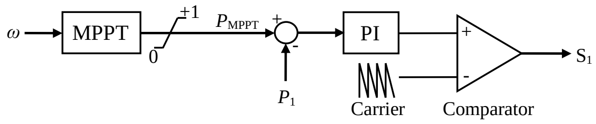

Fig. 9. Power controller

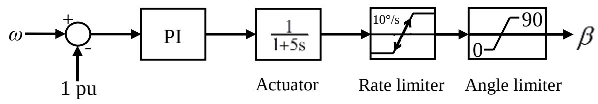

Fig. 10. Pitch angle controler

6. Simulation Results

Simulation analyses have been performed to evaluate the effectiveness of the proposed system shown in Fig.1 for producing hydrogen from parallel connected wind generators. Three different wind speed data have been used in each wind generator in the analyses and Fig. 11 shows each wind speed data. Simulation time is 600s. Fig.12 shows responses of each wind generator output. Fig.13 shows power consumed in the hydrogen generator. Fig.14 shows rotor speed of each generator. Fig.15 shows duty ratio of each boost chopper. Fig.16 shows the amount of produced of hydrogen gas. It is seen that each generator output is following the reference value well as shown Fig.12 due to the suitable control of the boost chopper system. It is also seen from Fig.14 that rotor speed of each wind generator can follow its reference value well based on the MPPT operation. The total power from each generator is consumed in the hydrogen generator as shown Fig.13, and the produced hydrogen gas for 600s is 38.4[Nm^3] as shown in Fig.16.

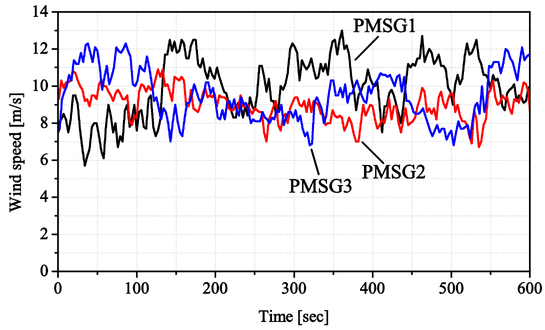

Fig. 11. Wind speed

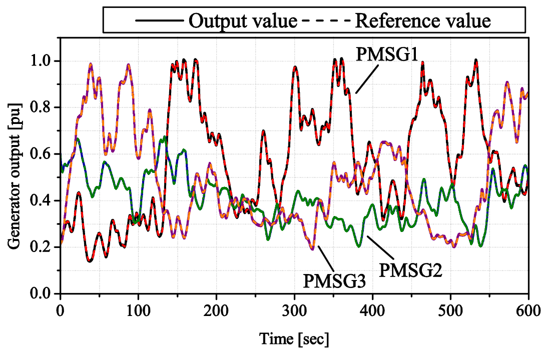

Fig. 12. Generator output

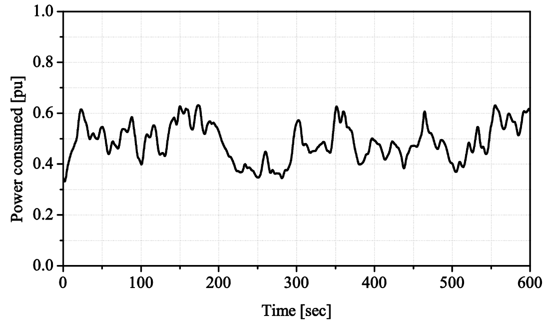

Fig. 13. Consumed power of hydrogen generator

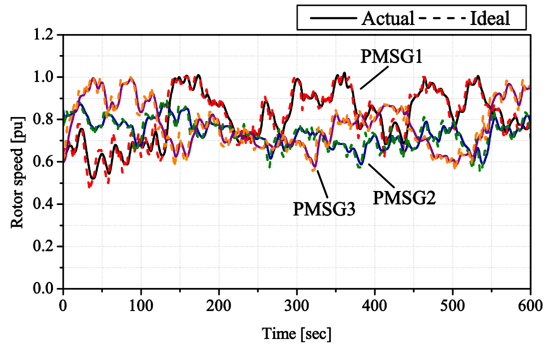

Fig. 14. Rotor speed

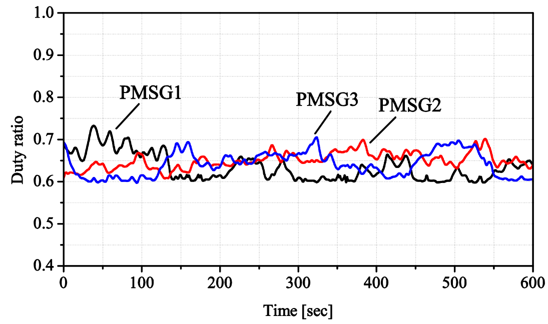

Fig. 15. Duty ratio

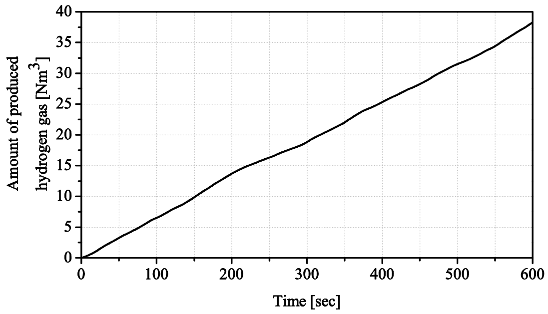

Fig. 16. Amount of produced hydrogen gas

7. Conclusion

This paper proposes a hydrogen production system with a stand-alone wind farm composed of multiple parallel connected wind power generators, where each generator is controlled by a boost chopper to follow the MPPT operation. The chopper control system for parallel connected generators is analyzed and designed firstly based on the simple parallel circuit with voltage sources and then applied to the practical wind farm model. It is shown by the simulation analyses that each wind generator in the stand-alone wind farm can be controlled well in the MPPT condition and the total generated power can be consumed in the hydrogen generator effectively producing hydrogen gas stably.

As a result, the proposed system is very effective as a hydrogen production system which can be installed without connection to a power grid.

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