Wind Turbine Driven by Permanent Magnet Synchronous Generator

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ABSTRACT

A permanent magnet synchronous generator (PMSG) variable speed wind turbine connected to an electrolyzer and a battery model system is presented in this paper. Hydrogen gas could be produced from the model system, when a variable wind speed is applied to the PMSG driven variable wind turbine. The simulation results presented shows the nature of some of the variables of the PMSG wind driven turbine and the hydrogen gas produced as the wind speed varies with time.

(Keywords: PMSG, wind energy, wind turbine, hydrogen gas, electrolyzer, battery)

INTRODUCTION

Variable speed operation of modern wind turbine enables an optimization of the performance, reduces the mechanical loading, and at the same time delivers various options for active power plant control [1, 2]. Megawatt class wind turbines equipped with a permanent magnet synchronous generator (PMSG) have been announced by Siemens Power Generation and GE Energy. In this concept, the PMSG can be directly driven or have smaller gearboxes or even gearless and is connected to the AC power grid through the power converter [3, 4].

In PMSG, the excitation is provided by permanent magnets instead of field windings. Permanent magnets machines are characterized as having large air gaps, which reduce flux linkage even in machines with multi-magnetic poles [5, 6]. As a result, low rotational speed generators can be manufactured in relatively small sizes with respect to their power ratings. Moreover, a gearbox can be omitted due to the low rotational speed in PMSG wind generators resulting in low cost.

Various control strategies have been proposed in recent works on the three-level PWM (pulse width modulation) converter control of the PMSG. A well known method of indirect active and reactive power control is based on current vector orientation with respect to the line voltage vector [7-10].

One of the applications of the wind energy is in the production of hydrogen gas. A considerable amount of hydrogen gas could be produced if an electrolyzer system is connected to the terminals of a fixed speed with turbine with an energy capacitor system (ECS) as reported in [11 and 12]. This paper presents the variable wind turbine driven by PMSG with an electrolyzer connected to the terminal of the machine to produce hydrogen gas. Simulations were run in PSCAD/EMTDC (Power System Computer Aided Design/Electromagnetic Transient including DC) [13].

WIND TURBINE DRIVEN GENERATORS

There are three main types of wind turbines currently in use: the fixed speed wind turbine with Squirrel Cage Induction Generator (IG), the variable speed wind turbine with Doubly Fed Induction Generator (DFIG), and the variable speed wind turbine with Permanent Magnet Synchronous Generator (PMSG) [14]. A brief distinction of the 3 types of wind turbine driven generators is given below.

Fixed Speed Squirrel Cage Induction Generator

This generator consumes reactive power and cannot contribute to voltage control. For this reason, although static capacitor control may allow wind farms with this type of generators are doomed to disappear from wind turbines. Below are the schematic diagram and the equivalent circuit of the fixed speed squirrel cage induction generator used in wind turbine technology as shown in Figures 1 and 2, respectively. Details and nomenclature of the equivalent circuit of this type of generator can be found in [1, 15].

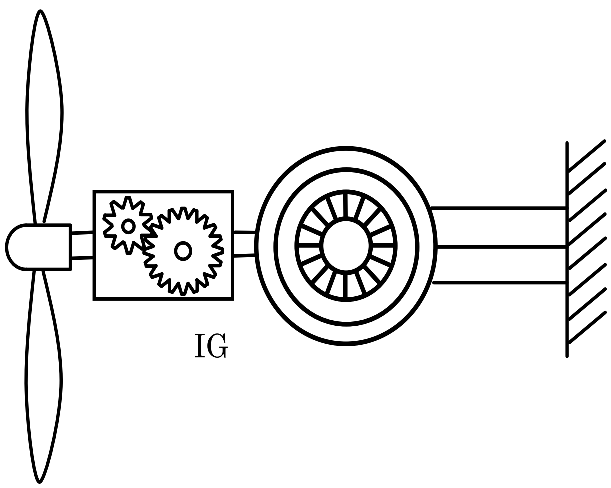

Figure 1: Induction Generator Schematic Diagram.

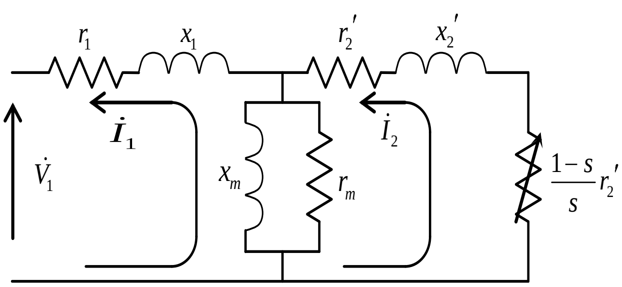

Figure 2: Induction Generator Equivalent Circuit per Phase.

Variable Speed Wind Turbine with Doubly Fed Induction Generator (DFIG)

This generator can be controlled to provide frequency and voltage control with a back-to-back converter in the rotor. This type of generator presents some difficulties to ride-through voltage dips, because voltage dip generate high voltages and currents in the rotor circuit and the power converter could be damaged. This is the most extended variable speed wind turbine technology and manufacturers already offer this type of wind turbines with fault ride-through capabilities. The schematic diagram and the equivalent circuit of the DFIG are shown in Figures 3 and 4, respectively. The equivalent circuit details and nomenclature of this generator can be found in [15].

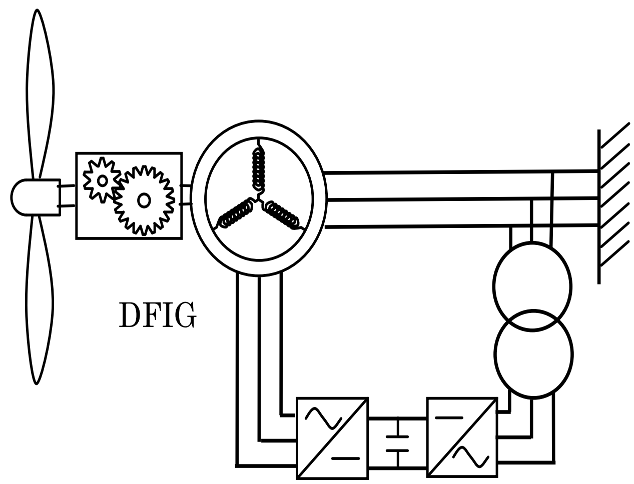

Figure 3: DFIG Schematic Diagram.

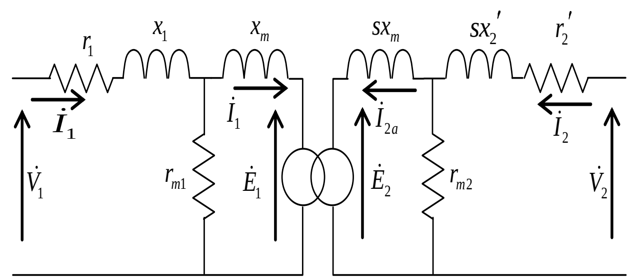

Figure 4: DFIG Equivalent Circuit.

Variable Speed Wind Turbine with Permanent Magnet Synchronous Generator

This generator is connected through a back-to-back converter to the grid. This provides maximum flexibility, enabling full real and reactive power control and fault ride-through capability during voltage dips. The schematic diagram and the equivalent circuit of PMSG are shown in Figures 5 and 6, respectively. The equivalent circuit nomenclature and details can be found in [1 and 4].

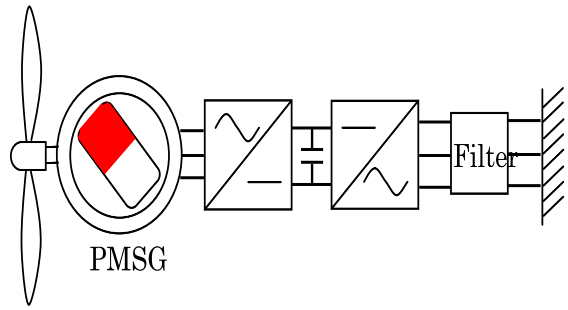

Figure 5: PMSG Schematic Diagram.

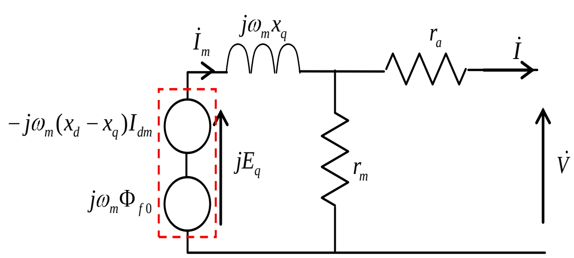

Figure 6: PMSG Equivalent Circuit.

WIND TURBINE AND SYSTEM OF STUDY

Wind Turbine Concept

The wind effect is very important in modeling wind turbines. Wind models describe wind fluctuations in wind speed which causes power fluctuation in generator. Four components are considered in describing a wind model [16] as shown below:

$$V_{wind} = V_{bw} + V_{gw} + V_{rm} + V_{nm} \quad \textbf{(1)}$$

Where, $V_{bw}, V_{gw}, V_{rm}, V_{nm}$ are the Base wind, Gust wind, Ramp wind and Noise wind components respectively in (m/s). The base component is a constant speed; wind gust component could be described as a sine or cosine wave function or combination; a simple ramp function and a triangular wave may describe the ramp and the noise components respectively. The wind speed in this study is shown in the simulation results for the dynamic analysis of the system during wind speed change.

For electrical analysis, a simplified aerodynamic model of wind turbine is normally recommended as described by the set of equations below where the aerodynamic torque (Nm) extracted from the wind is given by [16,17]:

$$T_w = \frac{P_w}{\omega_{rotor}} = \frac{\rho \pi R^3 C_p(\lambda, \theta) V_{wind}^{\ 2}}{2\lambda} \quad \textbf{(2)}$$

$$P_w = \frac{\rho \pi R^2 C_p(\lambda, \theta) V_{wind}^{\ 3}}{2} \quad \textbf{(3)}$$

$$\lambda = \frac{R\omega_{rotor}}{V_{wind}} \quad \textbf{(4)}$$

Where ρ is the air density in (kg/m^3), R is the wind turbine rotor radius in (m), V_{wind} is the equivalent wind speed in (m/s), θ is the pitch angle of the rotor in *(deg.)*, λ is the tip speed ratio, ω_{rotor} is the mechanical speed of the generator in *(rad/s)* and C_p is the power coefficient which can be expressed as a function of the tip speed ratio and pitch angle given by:

$$C_p(\lambda, \theta) = 0.22\left(\frac{116}{\lambda_i} - 0.4\theta - 5\right)e^{\frac{-12.5}{\lambda_i}} \quad \textbf{(5)}$$

$$\lambda_i = \frac{1}{\left(\frac{1}{\lambda + 0.08\theta} - \frac{0.035}{\theta^3 + 1}\right)} \quad \textbf{(6)}$$

Model System of Study

The simulation model of the system under study is shown in Figure 7, where the wind turbine is connected to the hydrogen generator model with an electrolyzer and a battery system. The rated capacity of the PMSG is 3MVA.

From Figure 7; W represents the rotor speed of the PMSG; Wopt represents the optimum rotor speed of the PMSG; Pref represents the maximum power point tracking (MPPT) reference active power of (Figure 8); Vw represents the input wind speed; and the voltmeter and the power meter takes the root mean square (r.m.s) voltage, the active and reactive power at the PMSG terminals, respectively.

WIND TURBINE AND SYSTEM OF STUDY

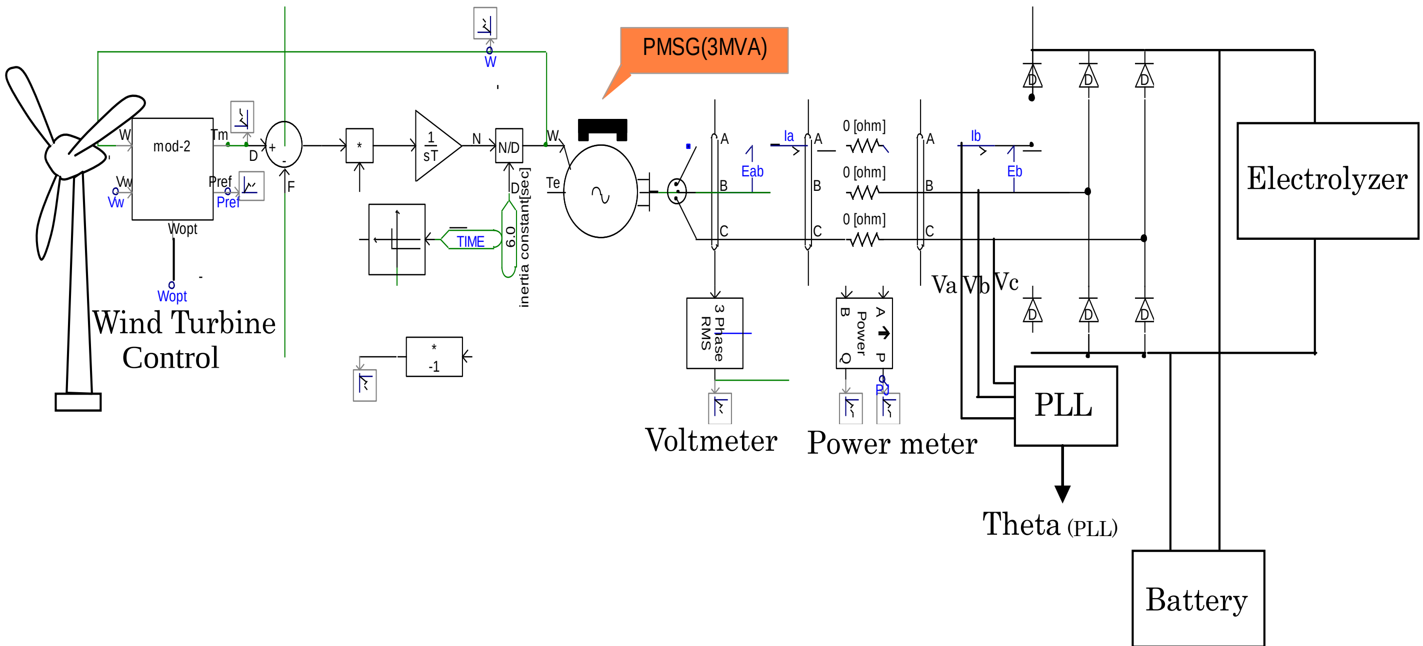

Figure 7: Simulation Model System.

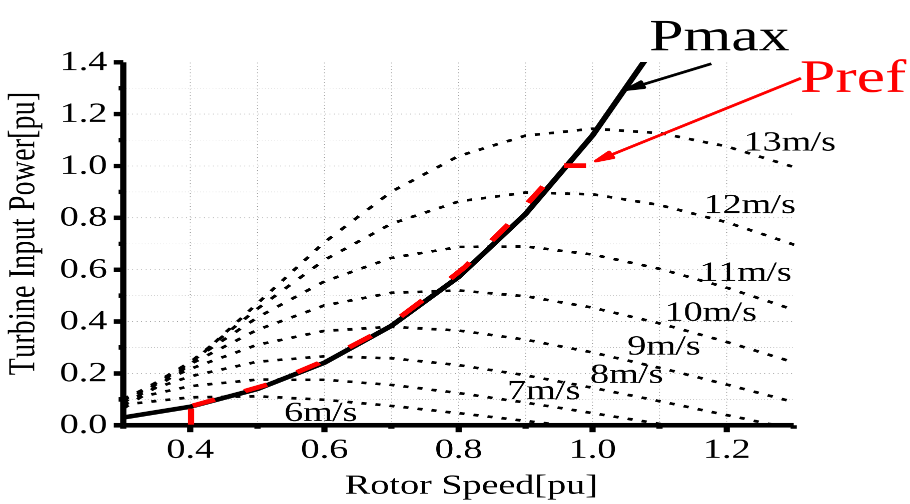

Figure 8: Wind Turbine Characteristic of the Variable Speed PMSG.

The battery is used to provide real power to the system. The schematic diagram of the hydrogen generator is composed of a rectifier and an electrolyzer as shown in Figure 7. Some portion of the wind farm output is rectified and then the DC current enters the electrolyzer directly to generate hydrogen gas. The voltage fluctuation at the hydrogen generator connection point can influence the volume of hydrogen generated. Therefore, constant hydrogen cannot be generated from this hydrogen generator if the voltage at the connection point cannot be maintained constant. This type of hydrogen generator model is quite cheaper and more efficient than the other type of hydrogen generator model that involves a power conversion step of DC-to-DC chopper [1]. The PMSG has the ability to provide reactive power to keep the voltage of the hydrogen generator terminal constant, hence enabling the production of constant hydrogen gas.

Figure 8 shows the PMSG variable wind turbine characteristics, where Pmax represents the maximum power point tracking (MPPT) that the PMSG can track from the wind energy; Pref is the reference active power of the MPPT controller. The red line shows the range of operation of the rotor speed of the PMSG variable wind turbine from 0.4pu to 1.0pu at lowest and highest wind speed respectively.

The control structure of the grid side frequency converter for reactive power control of the PMSG is shown in Figure 9, where dq to abc transformation are done from the direct and quadrature components of the reference signals. The source voltages V_a, V_b, and V_c of the grid, are used to calculate the phase lock loop (PLL) angle for the dq/abc transformation. These transformed dq quantities are passed through proportionate integral (PI) controllers. The resultant signals are then compared with a carrier signal of frequency 1.08 kHz. The effective signals are used to control and produce the reference currents I_a', I_b', and I_c' for the insulated bipolar gate transistors (IGBTs) switching. The grid side converter maintains the DC-link voltage to 1.0pu.

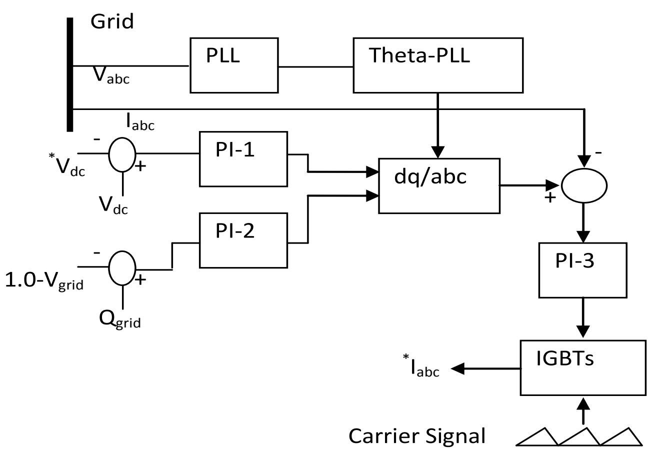

Figure 9: Control Structure of the VSWT-PMSG Grid side Frequency Converter.

SIMULATION RESULTS

Simulations were run in power systems computer aided design/electromagnetic transient including DC (PSCAD/EMTDC), for 700sec with natural wind speed data obtained from Hokkaido Island, Japan. Some of the responses of the model system variables are shown below.

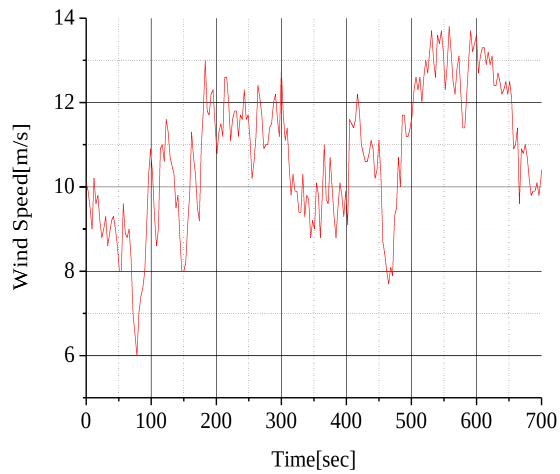

Figure 10: Natural Wind Speed Data.

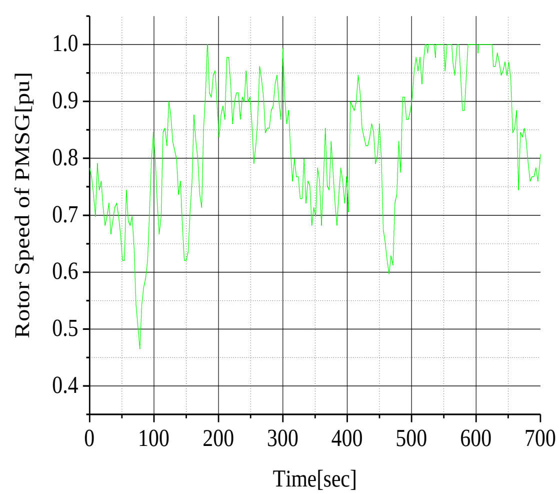

Figure 11: Rotor Speed of VSWT-PMSG.

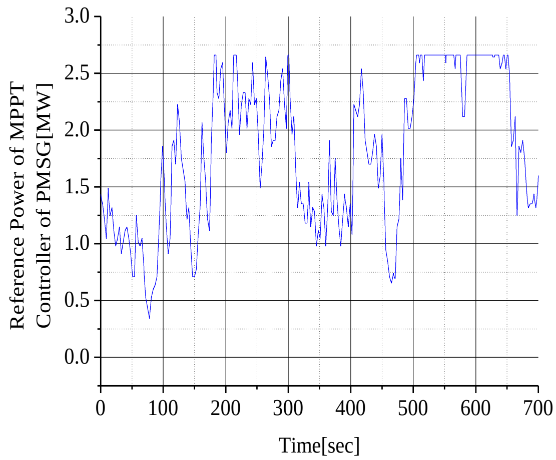

Figure 12: MPPT Reference Active Power (Pref) of VWST-PMSG.

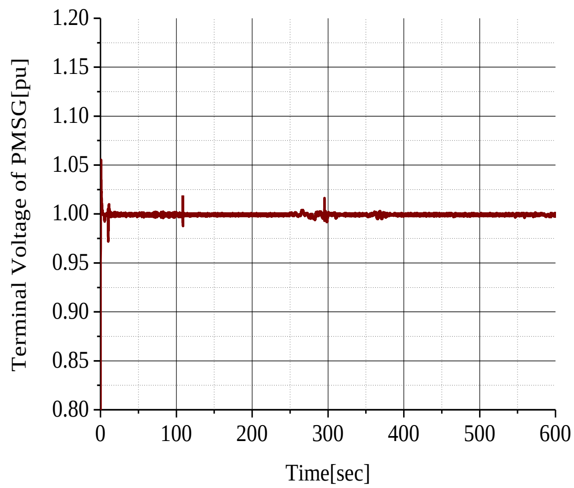

Figure 13: Terminal Voltage (V_t) Generated by PMSG (zoomed).

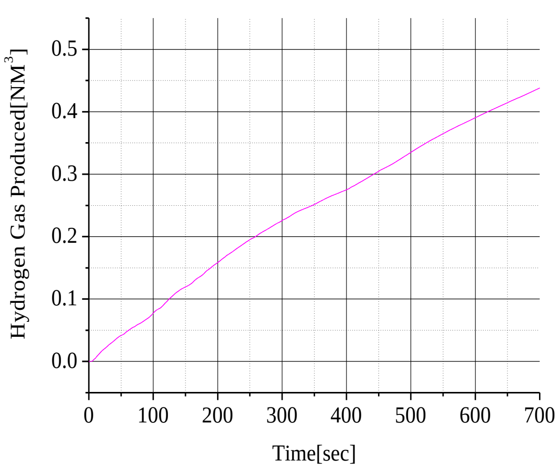

Figure 14: Volume of Hydrogen Gas Generated.

The simulation results are based on the dynamic behavior of the PMSG variable speed wind turbine (VSWT) during wind speed change, as well as the production of hydrogen gas for source of fuel when an electrolyzer is connected to the PMSG VSWT.

Figure 10 shows the natural wind speed data used for the simulation study, for duration of 700sec, the timing step of the simulation is chosen to be 0.00001sec. The varying wind speed (stochastic in nature) is been captured by the blades of the wind turbine and through the dynamics of the wind turbine conversion, electrical energy is been generated by the variable speed wind turbine permanent magnetic synchronous generator (VSWT-PMSG) driven.

The response of the mechanical rotor speed of the VSWT-PMSG is shown in Figure 11, where it can be observed that the rotor speed varies as the nature of the wind speed captured. Also, the limit of the range of operation of the rotor speed of the VSWT-PMSG which is 0.4pu to 1.0pu from the turbine characteristics earlier discussed in Figure 8 is not exceeded despite the high or low value and nature of the input wind speed to the wind turbine. This shows the effectiveness of the control topology that is adopted in the design of the VSWT-PMSG.

Also, the effectiveness of the control strategy of the VSWT-PMSG can be seen in Figure 12, where the maximum power point tracking (MPPT) reference active power follows the nature of the wind speed and not exceeding its rated design value despite the high and low value of the input wind speed to the wind turbine.

Figure 13 shows the terminal voltage generated by the VSWT-PMSG from the variable wind speed input to the wind turbine. It can be seen that despite the variable and stochastic nature of the wind energy, the terminal voltage generated by the generator remains constant. This is one of the advantages of the VSWT-PMSG driven, because the control system of its frequency converter is able to absorb or supply reactive power to the network system. This cannot be achieved in the fixed speed wind turbine induction generator (FSWT-IG) driven, where the terminal voltage generated by the fixed speed generator varies with the nature of the wind speed, because it does not have the ability to provide reactive power to the network system, unless it is supplied reactive power from an external reactive power compensation device like the static synchronous compensator, etc.

The volume of hydrogen gas generated from the system through the electrolyzer in the hydrogen model is shown in Figure 14. It can be seen that, despite the variable wind speed nature, the volume of hydrogen gas generated is kept constant and increasing also with time because the voltage at the hydrogen generator is maintained constant through the provision of sufficient reactive power from the PMSG frequency converters, thus demonstrating the effectiveness of the control strategy of the converter used in this study.

CONCLUSION

The paper presented the modeling and control design of the variable speed wind turbine (VSWT) driven by a permanent magnetic synchronous generator (PMSG). The modeling of the wind turbine maximum power point tracking is also described. The modeling and control strategy for the generator rotor side frequency converter are presented.

The control topologies are suitable for improving the dynamic analysis of the VSWT-PMSG driven, to be able to generate a constant voltage despite the stochastic nature of the input wind energy. Hydrogen gas for fuel purpose can also be generated, when an electrolyzer is connected via a hydrogen generator to the VSWT-PMSG system as shown by the simulation results in PSCAD/EMTDC. The hydrogen gas production in the system is possible because the VSWT-PMSG driven has the ability to provide and absorb reactive power to the network system, through its high frequency converter controls despite the varying nature of the wind energy, thus maintaining a constant voltage supply.

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