HYDROGEN GAS PRODUCTION AND STORAGE FROM RENEWABLE ENERGY IN STATIONS OF NATURAL GAS TRANSPORTATION LINES

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ABSTRACT

This paper presents a hydrogen energy technology, especially technology for hydrogen production and storage. This wind farm can be situated on natural gas transportation lines; in the gas pressure increasing stations and we can produce hydrogen gas beyond gas transportation. On this paper, the design and modelling of a wind system which uses, permanent magnet synchronous generators (PMSG) to provide the required power of a hydrogen gas electrolyzer system, is discussed. The electrolysis is considered an internal resistance and a DC voltage source connected To the wind farm system via a DC/DC boost converter, having a fuzzy system control tracking of Maximum power point MPPT, which allows the maximization and control of the power transferred to the electrolysis. In this research, you do not need to measure wind speed and use any batteries that these are the advantages of this research. The desired system is modelled and studied using MATLAB software.

1. INTRODUCTION

Today, the production of hydrogen from wind power has been extensively developed and there are many stations in Iranian natural gas pipe line that is far from residential area and have good wind conditions. We can store produced hydrogen gas from renewable sources in tanks or blend it with natural gas and deliver it via natural gas line network at end users systems. Various topologies have been proposed for hydrogen production in which the hydrogen electrolyzer is connected to dc link frequency converter and the battery is generally used in all these cases [1],[2]and[3]. There is little 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. Using the battery in the long-term period is inappropriate due to losses and low energy density of batteries and makes it undesirable in high powers. In most of these studies a wind system has been used which lowers the reliability of the system [4] and [5.In this paper we propose a WECS that has multi-input/multi-output DC/DC boost converters [6] with hydrogen production system shared between converters.

In this system we connect two variable speed wind turbines, two permanent magnet permanent magnet synchronous generators (PMSG), two boost converters and a Hydrogen electrolyzer together. We can use more or less than two blocks. 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 [3]. Some papers have been reported in which multiple wind generators are connected in parallel through power converters. But generators output voltage delivered through a power converter to the load [7]. We use multi input DC/DC converter in this work. The paralleling of switching converters based on power supply contributes many advantages when compared with a single high power centralized power supply [8]. The connection of multi-input/multi-output DC-DC converters in parallel, with the load shared between modules reduces current stress on the switching devices and increases system reliability [9]. For the reason that conventional PI controller generally does not work well for nonlinear systems, high-order systems and complex systems that have no precise mathematical models, fuzzy logic is chosen to overcome these difficulties due to its flexibility and facility to apply in real time control. With this proposed method, wind generator gives maximum power without any knowledge about generator's characteristic or ambient condition. Control algorithm is independent, achieving the fast dynamic responses for the complex nonlinear system [10].

2. WIND ENERGY CONVERSION SYSTEMS

the overall schematic of our wind system shown in Fig. 1. As it can be seen in Fig.1, the proposed system consists of two sets of wind turbines, permanent magnet synchronous generator, AC-DC full-wave bridge rectifier, DC boost converter and a control system with a hydrogen production and storage unit. In this system, each of the wind turbines converts the wind energy into mechanical energy to move the generator. Three-phase Ac voltages are produced by the rotation of the generator and a full-wave diode rectifier converts it into DC voltage and DC power (Pdc) is produced.

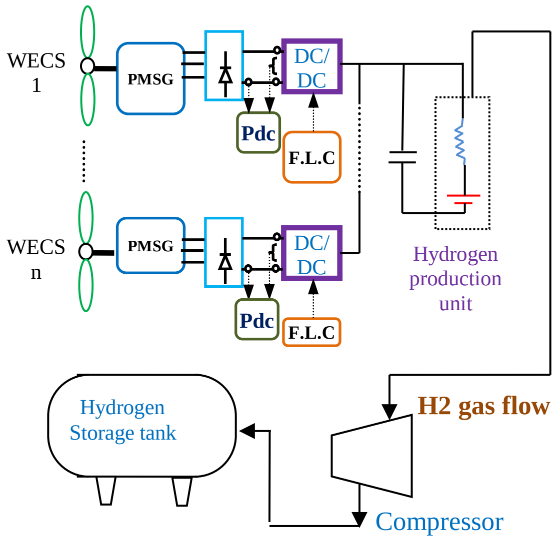

Fig. 1. System overview

2.1 Wind Turbine Model

Power obtained from the wind turbines is defined as follows:

$$P_m=\frac{1}{2}c_p\rho A v^3 \quad (1)$$

P_m: Mechanical power in the moving air (watt)
ρ □: air density (kg/m3)
A: area swept of the rotor blades (m2)
V: velocity of the air (m/sc)
c_p: The power coefficient

In equation 1, c_p is a function of pitch angle β and tip speed ratio λ. The pitch angle β is determined by the shape of the wind turbine blade. The tip speed ratio λ is a controllable parameter that is influenced by the wind turbine rotation speed. The tip speed is defined with equation below:

$$\lambda=\frac{v_m}{v}=\frac{\omega_m R}{v} \quad (2)$$

ω_m: Rotor angular velocity rad / s
R: Turbine blade radius m
V: The average wind velocity m / s

Several kinds of equations are used to express turbines c_p (β, λ). The following equation is based on the modeling of the wind turbine features and is used for the wind turbine in our study [11]:

$$c_p\,(B,\lambda)= c_1\left(\frac{c_2}{\lambda_i}- c_3\beta c_5-c_6\right)\exp\left(-\frac{c_7}{\lambda_i}\right) \quad (3)$$

$$\frac{1}{\lambda_i}=\frac{1}{\lambda+c_8\beta}-\frac{c_9}{\beta^3+1} \quad (4)$$

c_1 to c_9 are C1=0.73, C2=151, C3=0.58, C4=0.002, C5=2.14, C6=13.2, C7=18.4 C8=-0.02 and C9=-0.003.

Fig.2 shows the curve of the power factor in λ according to different values of β for the turbine.
It can be observed that firstly the highest power factor is obtained for β = 0. Second, the highest power factor occurs due to a certain amount of tip speed ratio. Therefore, the controller should set λ at its optimal value to absorb maximum power in different wind velocities.

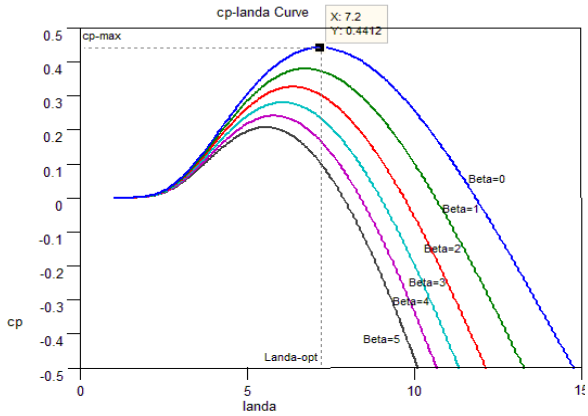

Fig. 2. Cp curves as function of tip-speed-ratio with different pitch angle.

The amount of c_{P_max} is obtained by replacing λopt in equation 3.

c_{P_max}= 0.4412

Replacing λopt in equation 2 results in:

$$\omega_{op}=0.2v \rightarrow \quad \lambda opt=\frac{\omega_{op}R}{v} \qquad (5)$$

This equation indicates that we can obtain wind velocity using turbine rotor angular velocity in a range of variable speed wind turbine operation and no need to measure the wind velocity. measuring the wind velocity is difficult and costly, then the MPPT function, without measuring wind velocity, can be generally expressed by the following equation:

$$P_{MPPT}=0.5\rho\pi R^2[\frac{\omega R}{\lambda opt}]^3 c_{P\_max} \qquad (6)$$

P_{MPPT} : The maximum of the turbine power (W)
λopt : The optimum of tip speed ratio

2.3. Wind turbine pitch angle control

Wind speed versus the desired turbine rpm determines blade pitch. There is a specific pitch angle for any given wind speed to optimize output power. Pitch angles greater or less than this value reduce power output. The calculation of pitch angel is difficult and often is obtained by experimental methods. Fig. 3 shows pitch angle and produced power variation of turbine with the wind speed which is between 12 m/s and 30 m/s to avoid over-rated power of the turbine.

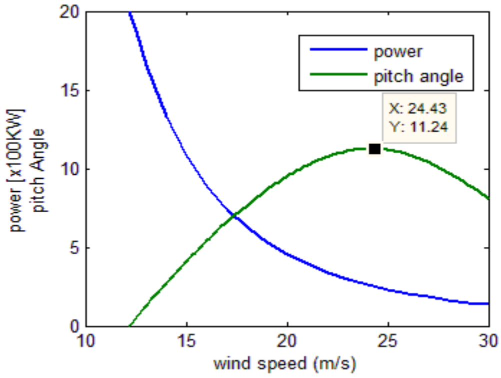

Fig. 3. Variation of power and pitch with wind speed

We express an estimated function to correct the output power. In this method, ratio correction function is used instead of changes in the value of pitch angel.

$$ratio = 1 - [X * [(V_w - 12.205)^{0.2}]/V_w\text{^}2)*1763] \qquad (7)$$

The X expressed as below:

$$X=\tan\left((-0.18) * \left(1 - \frac{V_w}{12.205}\right)\right) \qquad (8)$$

$$12.205 \text{ m/s} < V_w < 25 \text{ m/s}$$

Then we can calculate appropriate output power of turbine in each wind speed:

Power=ratio*power (9)

2.2. Hydrogen electrolyzer characteristic

Technical specifications of the electrolyzer system used in the study are chosen from a technical report as a high-purity hydrogen and oxygen (HHIG) production [12]. An electrolyzer cell is an equivalent of an electromotive force V_0 and internal resistance *R0* Fig.4 During nominal operation, the electrolyzer consumes 44.075 kw nominal power. Nominal flow rate of hydrogen is 7.5 Nm 3 / h when the amount of current and voltage is 410 amps and 107.5 volts, respectively. The hydrogen electrolyzer system used in this study is a combination of modules that are 23 series and two parallel rows.

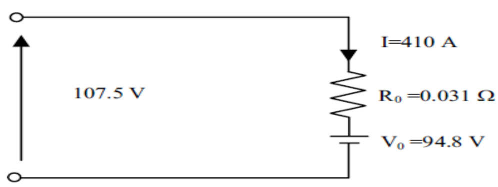

Fig. 1. Equivalent circuit of an electrolyzer cell

According to the Faraday's laws the mass of hydrogen produced at the cathode is related to the amount of current pass through the electrolyte [13]:

$$m_{H2} = \frac{M_{H2} I_c t}{ZF} . \eta_f \quad \text{And } n = \frac{m_{H2}}{M} = \frac{I_c t}{ZF} . \eta_f \qquad (10)$$

Where:

- m_{H2} mass of the hydrogen produced at an electrode in Kg
- F = 96485 C mol^{-1} is the Faraday constant
- M_{H2} molecular mass of hydrogen (kg mol^{-1})
- z is the electrons transferred per ion.
- η_f Faraday efficiency
- I_c current through electrolysis
- t time of electrolysis
- n amount of substance (number of moles)

We can calculate mass flow of hydrogen as below:

$$\dot{m}_{H2} = \frac{m_{H2}}{t} = \frac{M_{H2} I_c}{ZF} . \eta_f \qquad (11)$$

In electrolyse process we have:

$$H_2O \rightarrow 2H_2 + O_2 \qquad (12)$$

$$36gr \rightarrow 2(2)gr + 32gr$$

According to eq.11 the quantity of water flow can be expressed as below:

$$\dot{m}_{H2} = \frac{m_{H2O}}{9} = \frac{M_{H2} I_c}{ZF} . \eta_f$$ and

$$K = \frac{ZF}{M_{H2}} = 95529702.9699$$

$$\dot{m}_{H2} = \frac{m_{H2O}}{9} = \frac{I_c}{K} . \eta_f \qquad (13)$$

2.4. Hydrogen storage tank design

Hydrogen as an energy carrier can be stored in all three states of matter. Fig.5 shows main methods of hydrogen storage. The general way to store hydrogen in the gas form is pressurized vessels. Because hydrogen behaves like an ideal gas at ambient temperatures, and follows the ideal gas law. In a given volume and temperature, the energy density of storage is measured by increasing the pressure of the storage vessel. The only problem with this is the safety features and regulations that limit the allowable pressure. However, the gravimetric energy density of hydrogen storage largely depends on the material of the container, because light materials usually do not tolerate high pressures [14].

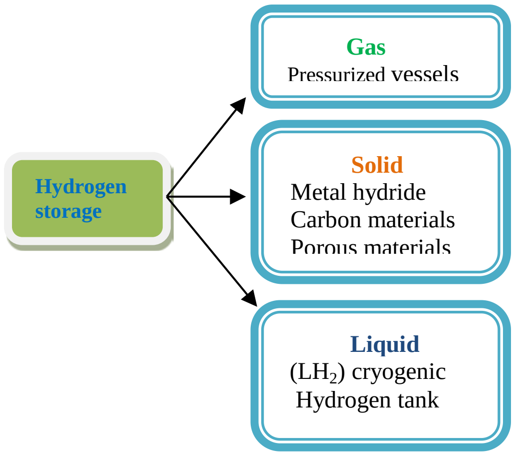

Fig.5 .Hydrogen storage methods

As we know:

$$P.V = nZRT \qquad (14)$$

Replace n with molecular weight M_W:

$$n = \frac{M}{M_W} \quad \text{and } PV = \frac{M}{M_W} ZRT$$

Then in Constant volume we have

$$P.V = \frac{M}{M_W} ZRT$$

$$M = \int \dot{m}_{H2} dt$$

$$P = \frac{M}{V.M_W} ZRT = \frac{\int \dot{m}_{H2} dt}{V.M_W} ZRT \qquad (15)$$

The hydrogen storage system can be calculated using Eq.(15), which directly calculates the tank pressure for the hydrogen flow rate to the tank. The tank is filled with the hydrogen produced by the electrolyzer,

And $P_t = P_{ti} + \frac{\int \dot{m}_{H2} dt}{V.M_W} ZRT$ then

$$P_t - P_{ti} = \int \frac{ZRT \dot{m}_{H2}}{V.M_W} dt \qquad (16)$$

Where:

- P_t is pressure, expressed in Pascal
- P_{ti} is initial pressure, expressed in Pascal
- V is tank volume, expressed in m^3
- n is number of kilo moles
- Z is the compressibility factor
- R is the constant of gases, equal to 8314 J / (K kmol)
- T is temperature, expressed in Kelvin
- M_w is the molecular weight, kg/kmole
- $\dot{M}$ produced hydrogen molecular rate flow in to the tank

The system dynamics can be expressed as follow:

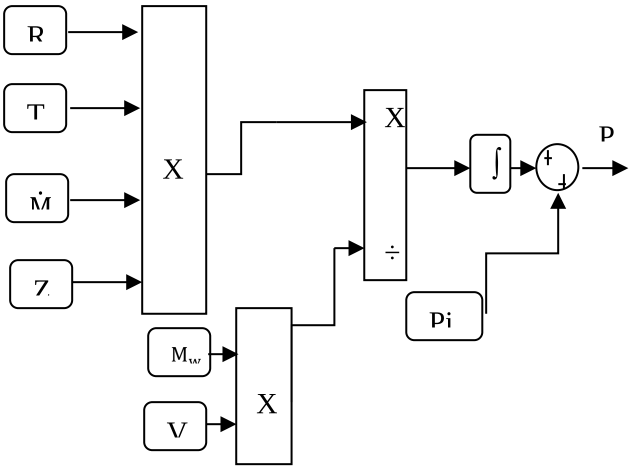

Fig.6.Hydrogen storage tank model

In each internal pressures equation below estimates minimum thickness of the cylindrical storage tank of hydrogen.

$$t = \frac{P.R}{S.E-0.6P} \quad (17)$$

$$P = \frac{S.E.t}{R+0.6t} \quad (18)$$

Where:

t : tank thickness(inch)

P: tank internal pressure (psi)

S: allowable stress (psi)

E: joint efficiency

R: internal radius (inch)

The compression force, compressor energy requirements, and auxiliary power requirements such as pumps, valves, and fans in this model are neglected.

3. THE PROPOSED CONTROL SYSTEM

In this study, we use PSF algorithms along with the fuzzy controller .In Fig.7 , the general principles of this method are shown for a set of wind turbines. In this control system, P_ref, which is the same as P_MPPT is calculated based on the equation (3), whose only variable is the ω (i.e. permanent magnet synchronous generator speed),for each of turbo-compressors and is compared with the power generated via turbo-compressors and the error signal is applied to the fuzzy controller set.

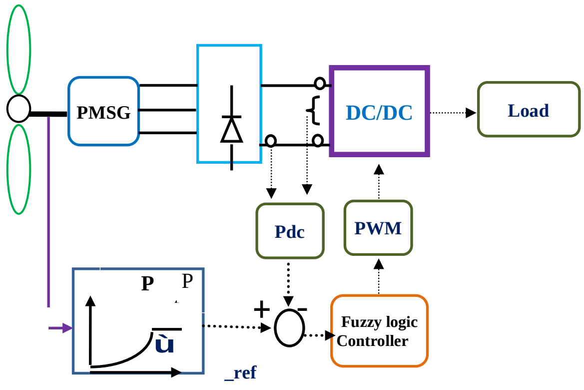

Fig.7 .Proposed system with Fuzzy Logic Controller and PSF algorithm for a wind turbine

The output of the fuzzy controller is modulated using a saw-tooth wave and the duty ratio of each boost converter is produced .The proposed MPPT algorithm based on a fuzzy logic controller that directly adjusts the DC/DC converter duty cycle to control generator speed

Designing Mamdani-type fuzzy controllers is based on the sufficient knowledge of the system behaviors instead of on an exact mathematical model. There are two inputs for the fuzzy controllers of the boost converters. The first input is the output error of the system and is shown in equation 19.

$$e(k)=P_{ref\_i}-P_i(k) \quad (19)$$

The second input is the difference between consecutive errors and is shown in equation 20.

$$de(k)=e(k) - e(k-1) \quad (20)$$

Both inputs are fed with the fuzzy controller and the fuzzy controller output is *duty ratio* changes Dd(k). Therefore, the control scheme is shown in Fig 8:

In this control system, the fuzzy controller output Dd(k) is added to the previous value of *duty ratio* and the desired output is finally obtained for the duty ratio.

$$d(k)=d(k-1)+Dd(k) \quad (21)$$

The fuzzy controller uses triangular membership functions in the controller input.

For an actual data, the fuzzification system finds its fuzzy membership degree in each language variable. In this study, we used a five-level fuzzification system. The graphical representation of the membership function and the rule-base used in this study are in accordance with Fig.9 and the Table 1.

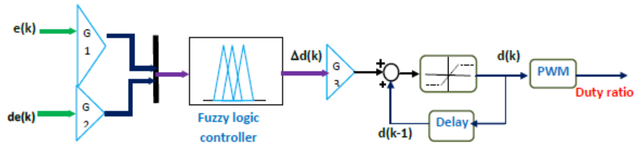

Fig. 8. Block diagram of the FLC

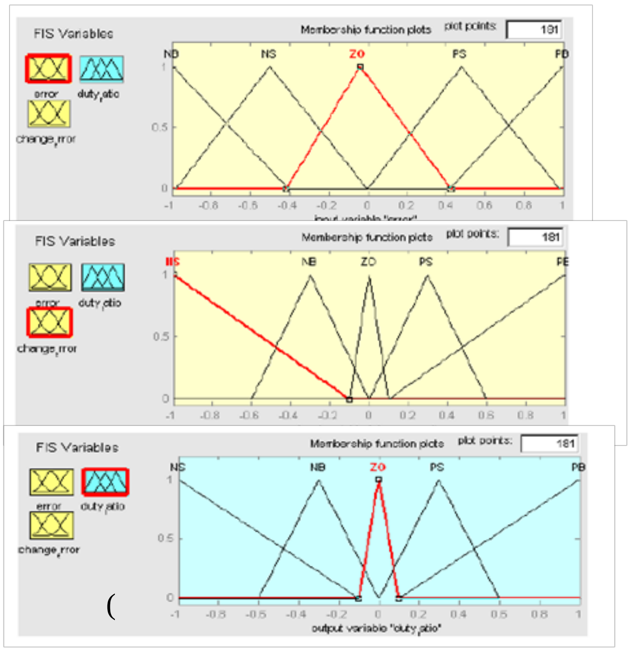

Fig. 9. Member ship function of e,de and duty ratio

Table I: Rule table for fuzzy controller

Duty ratio		error				
		NB	NS	ZO	PS	PB
de	NB	NB	NB	NB	NS	ZO
	NS	NB	NB	NS	ZO	PS
	ZO	NB	NS	ZO	PS	PB
	PS	NS	ZO	PS	PB	PB
	PB	ZO	PS	PB	PB	PB
	NB	NB	NS	ZO	PS	PB

4. SIMULATION AND RESULTS

The entire control system of the proposed FLC based MPPT algorithm was simulated by Matlab/Simulink. The control system consist of 2 wind turbines model, 2 fuzzy logic controller, 2 PMSG, 2 DC/DC converter and a Hydrogen production and storage tank system. Wind turbines and PMSG's model parameters are shown in Table 2. In the next step, variable and different wind velocities are applied to each turbine and the results of the proposed control system is illustrated in Fig.11 and Fig.12.

As it is obvious from the Figures, the output power of each wind turbine is subject to wind changes. Fig.13 shows the output power of total turbines, which is applied to the electrolyzer system. As it can be observed, this amount is approximately equal to the sum of two turbines, which is indicative of the validity of the proposed control system. For example, between 0.5 and 1 second, the power of each turbine alone is not high, but the total sum of their powers together is significant.

Fig.14 is hydrogen production rate and is proportional to total power of wind system.

Fig 15 shows the A.C. [line-line] voltage of each of the generators. As it was mentioned in the introduction section, variable wind velocities in these turbines produce a voltage with variable range and frequency. These figures clearly prove this point. The proposed system delivers these variable voltages as D.C. voltage with a specified range to consumer.

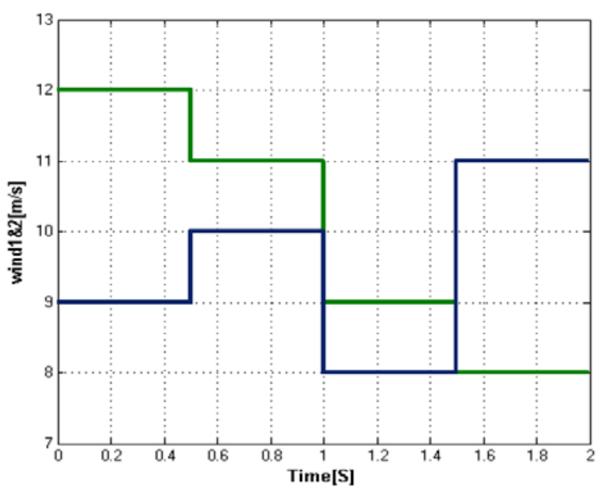

Fig.10 .two different wind speed

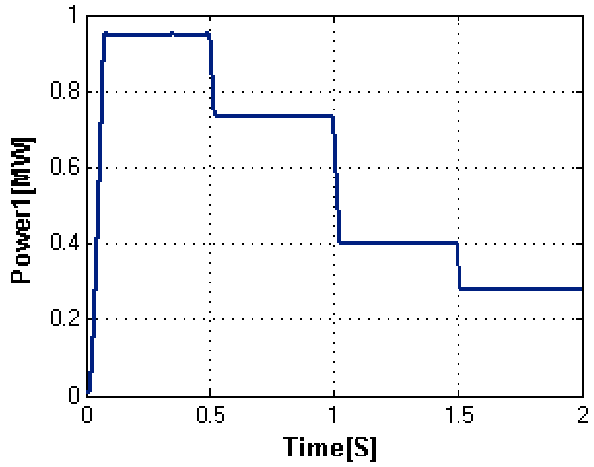

Fig.11 .output power of PMSG1

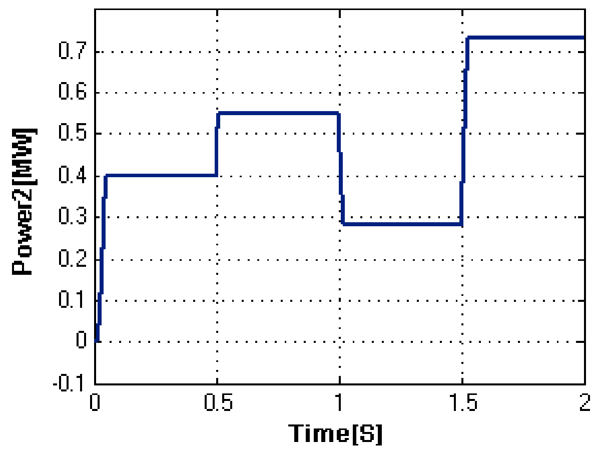

Fig.12 .output power of PMSG2

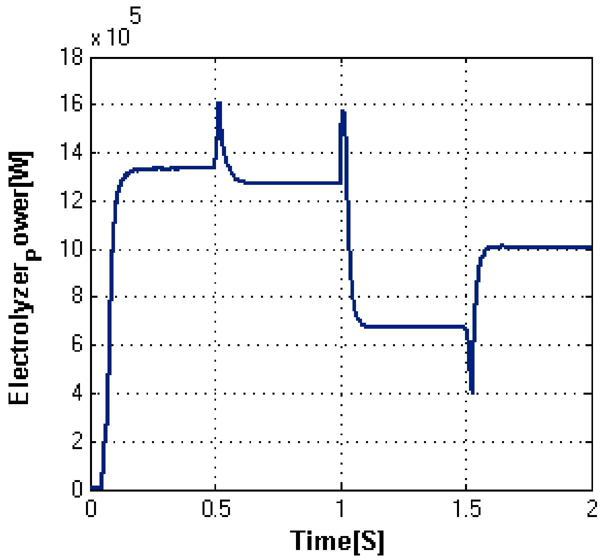

Fig.13 .Total output delivered to Electrolyzer

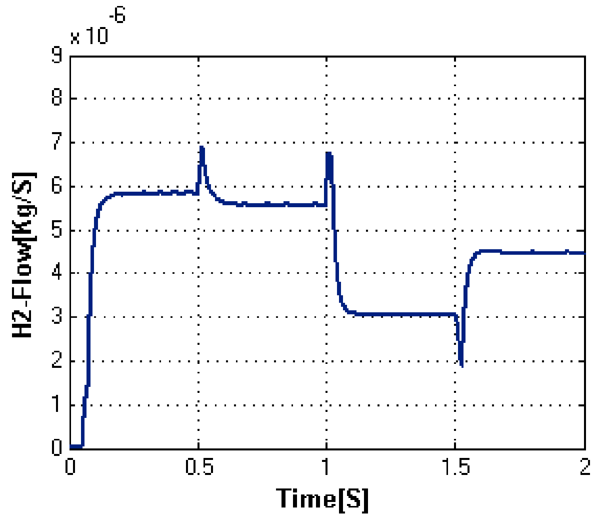

Fig.14 .Produced Hydrogen gas flow rate

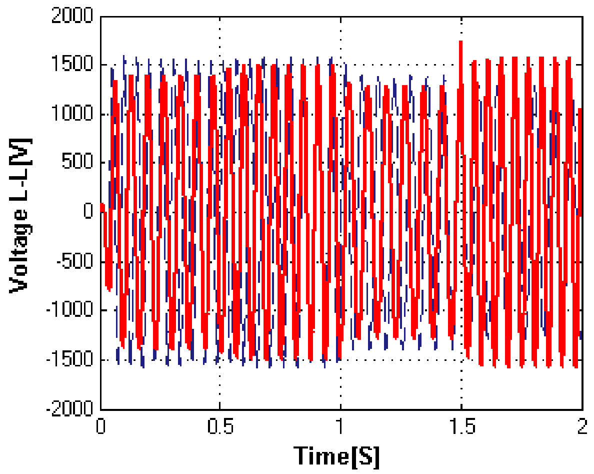

Fig.15 .Output voltage of three PMSG[L-L]

5. CONCLUSION

In this study we present the modelling of wind system that consist wind turbine, water electrolysis and storage tank in a natural gas pipe line station that. We have given special attention to hydrogen production and storage during electrolysis process in simulation environment. The power of the total production can be applied to a set of hydrogen electrolysis and the hydrogen is produced for storing in a pressurized tank.

This work has the merit below:

-proposed control system was independent from wind speed. A novel fuzzy control based MPPT for PMSG –wind power system was discussed and the result was shown in simulation. Using fuzzy control algorithm show that As a rapid changes of the wind speed, are carefully followed and responded in an appropriate manner and the maximum power is injected to load. The proposed system has a better performance in terms of range of fluctuations. On the other hand, since the fuzzy system is independent of the system internal specifications, this can be regarded as one of the advantages of the proposed system.

- We use multiple turbines that produce power with different wind speed and individual dc-dc boost converter for each wind turbine system. The advantage of this system is the parallel use of multiple turbines and increasing the reliability of the system in case of failure of a turbine or lack of wind flow at one point.

-a new estimation method was introduced to pitch angle control system in wind turbine instead of conventional pitch control

Table 2. Parameter of the Turbine-Generator system

PMSG(salient-pole)	
Rated Output	1[MVA]
Rated Voltage	1025[V]
d axis reactance	7[mH]
q axis reactance	5.5[mH]
Winding resistance	0.01[Ω]
Back EMF waveform	Sinusoidal
Pole pairs	51
Frequency	20[Hz]
Flux linkage established by magnets	9.76[Wb]
Wind turbine	
Rated power Pwn	2[MW]
Rated Rotational Speed	23.33[rpm]
Rated Wind Speed	12.205[m/s]
Radius of Wind Turbine	36[m]
Maximum Power Coefficient c_p	0.441

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