WIND ENERGY CONVERSION SYSTEM WITH COGENERATION OF HYDROGEN FOR REMOTE AREA APPLICATION

[1]SMRITHI AJIT, [2]MINI V.P

1,2Electrical and Electronics Engineering Department,
College of Engineering Trivandrum(CET),Kerala, India
E-mail: [1]smrithijit@gmail.com, [2]minivp@cet.ac.in

Abstract— The exponentially growing world population has exponentially growing energy needs. To satiate this energy demand without bringing adversities to the environment we need renewable, green sources of energy. In remote areas where people do not have access to the grid, the use of hybrid Distributed Generation Systems employing a combination of energy sources like wind, solar, hydrogen etc is a suitable green solution to the energy problem. PMSGs find use in small scale wind generation units owing to their distinct advantages of smaller size and better efficiency when compared to their counterparts. However, a typical problem with green energy sources is it's storage when the load connected to it is not operational. The option of using batteries as an energy storage medium is expensive and also poses certain environmental problems depending on the environmental factors to which it is subjected and the type of technology involved. In this context, a hybrid wind energy generation system using a Permanent Magnet Synchronous Generator with cogeneration of hydrogen has been introduced in this paper. The authors propose to store the excess wind energy (during the absence of connected load) as hydrogen; hydrogen being a fuel source with high calorific value and having a wide spectrum of applications from fuelling cars to being used as cooking gas. Here, the authors suggest the use of hydrogen to generate dc voltage using PEM fuel cells to drive dc loads like street lighting. The work involves the design and simulation of the entire Wind Energy Conversion System with the cogeneration of hydrogen in MATLAB®SIMULINK and the analysis of the performance of the system under constant and variable wind speed conditions.

Index Terms— Cogeneration, Hydrogen, Permanent Magnet Synchronous Generator, Wind Energy Conversion System.

I. INTRODUCTION

Growing populations have growing energy needs and growing energy needs ultimately call for green, alternative sources of energy which will help satiate the energy requirements without imposing adversities on the environment. Among green energy sources, wind is a widely preferred candidate. Though there are different machines capable of harvesting energy from wind the relatively lower cost, lower maintenance, higher efficiency and steady performance make PMSG well suited to the application **[1-11]**. Harvesting wind energy and using it for sourcing power to remote areas requires extensive survey of wind patterns and geological survey of the area where the windmill is to be set up. Many at times to accommodate variations in wind pattern, wind energy may be used in combination with solar PV panels and or hydrogen production units to ensure a steady power supply **[1, 7, 8, 9]**. In remote areas where people do not have accessibility to the power grid this is a practically feasible DG solution.

However, in order to maximize efficiency of energy production, wind energy must be stored in some form so that the huge expenses and inconvenience incurred due to the shutdown of the plant when loads connected to it are not operational can be avoided. In a typical remote area application where the industrial load operates for almost 12 hours in a day, in the remaining 12 hours the Wind Energy Conversion System needs to be shut down or alternatively the wind energy need to be stored in some form for later use. This is usually possible through the use of energy storage devices such as batteries. However, major drawbacks of batteries include that they occupy a large area, their efficiency is very less, they are expensive to maintain, and they affect the environment adversely by releasing toxins as in the case of portable batteries or corrode easily (when used in coastal areas); the degree of adversity varying with the application of the battery system, the technology in use and the conditions of operation **[11]**.

However, a more efficient energy storage solution is to store the solar or wind energy in the form of hydrogen so that hydrogen can be further utilized to produce more energy. Hydrogen fuel has a very high energy content of about 243KJ/mol and finds numerous applications. In the case where industrial load is available for only half a day the wind energy available during the rest of the day can be reliably converted to hydrogen using Electrolyzers **[6,7]** and can be reconverted to dc voltage using PEM fuel cells for driving dc loads like street lighting. It may be stored in metal hydrides as suggested in **[7]** since in this method more volume of hydrogen is stored compared to liquid and gaseous form thus eliminating the need for compressors. The advantage of storing excess wind energy as hydrogen lies in that it can be used when required by the industrial load by converting the dc voltage from PEMFC to ac thus acting as a power backup solution. The production of hydrogen can be further boosted with the help of biological resources like algae **[12]**

The authors of this paper have modeled a WECS (Wind Energy Conversion System) with cogeneration of hydrogen using Matlab®Simulink and have analyzed the performance graphs of the system obtained from the simulation of the Matlab®Simulink model of the system **[1,8,9]**. In remote areas where people do not have accessibility to the power grid this is a practically feasible DG solution.

II. WIND ENERGY CONVERSION SYSTEM

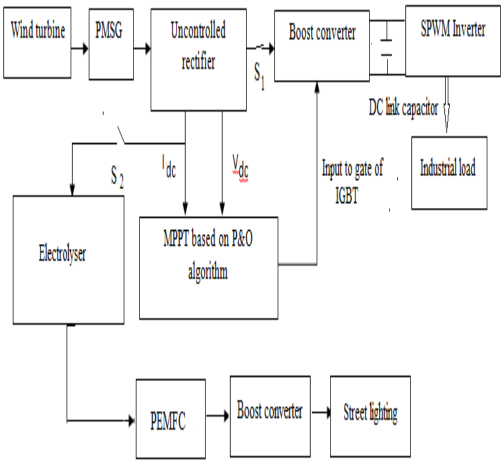

Fig1: Block Diagram of the Wind Energy Conversion System with cogeneration of hydrogen

The Wind Energy Conversion System shown in the figure above consists of a Horizontal Axis Wind Turbine coupled to an 8.5KW PMSG that produces ac output, an uncontrolled rectifier along with a boost converter that converts variable ac to fixed dc and a SPWM (Sinusoidal Pulse Width Modulated Inverter) that produces ac at a constant frequency of 50Hz. A two mass drive train is used to model the transient stability associated with the connection between the shaft of the wind turbine and the PMSG. An MPPT based on P&O (Perturbation and Observation) **[4,5]** algorithm is employed just after the rectifier to ensure that maximum power is extracted from wind at any wind speed. Switches S_1 and S_2 have been used to represent the operation of the system under two different conditions. When S_1 is on, S_2 is off during the first 12 hours of the day showing that the boosted dc output from the boost converter is given to an inverter across a dc link capacitance and is used to drive the industrial load for. Approximately in the next 12 hours S_2 is on and S_1 is off showing that when the industrial load is off the wind energy is used to produce hydrogen (using an electrolyzer). This hydrogen is utilized by a 6.5KW Proton Exchange Membrane Fuel Cell Stack to produce dc output.

A. WIND TURBINE

Owing to the higher efficiency and flexibility offered by Horizontal Axis Wind Turbines compared to Vertical Axis Wind Turbines, they are increasingly preferred these days in combination with PMSGs.
The power produced by the wind turbine is given by the equation

$P_m = 0.5 C_p \rho A v^3$ ……………… (1)

where, ρ is the air density, A the cross sectional area of the turbine, v is the wind velocity, and C_p is the power coefficient of the turbine. The density of air is taken to be around 1.225kg/m^3 while the value of C_p depends on pitch angle β and tip speed ratio λ given by:

$\lambda = R\omega_m / v$ …………………(2)

where, ω_m is the angular velocity of the turbine . R is the blade radius and v is the velocity of wind
With the power coefficient is given by:

$c_p(\lambda,\beta) = c_1\left(\frac{c_2}{\lambda_i} - c_3\beta - c_4\right) e^{\frac{-c_5}{\lambda_i}} + c_6\lambda$ …….. (3)

$\frac{1}{\lambda_i} = \frac{1}{\lambda+0.08\beta} - \frac{0.035}{\beta^3+1}$ ………….….. (4)

The maximum value of C_p is limited by the Betz limit of 0.593. However for practical purposes this value is taken to be between 0.4 and 0.5.
c_1= 0.5176, c_2=116, c_3=0.4, c_4=5, c_5=21, c_6=0.0068
The specifications of the wind turbine include:
Blade radius= 2.3m , C_p=0.48,Tip speed ratio $\lambda = 8.1$, Pitch angle $\beta = 0$, base wind speed=12m/sec

B. TWO MASS DRIVE TRAIN

In this paper, the WECS is presented with a two-mass drive train model **[3]** which helps model the connection of the shaft of the turbine with the PMSG.

$2H_{tur}\,(d\omega_{tur}/dt) = T_{tur} - K_s\theta_s - D_s(\omega_{tur} - \omega_{gen})$…. (4)

$2H_{gen}\,(d\omega_{gen}/dt) = K_s\theta_s - T_{gen} + D_s(\omega_{tur} - \omega_{gen})$….. (5)

$\frac{d\theta_s}{dt} = \omega_{tur} - \omega_{gen}$ ……….. (6)

T_{tur} =Wind turbine torque
T_{gen} = Generator torque
H_{tur} = Wind turbine moment of inertia constant
H_{gen} = Generator rotor moment of inertia constant
ω_{tur} = Wind turbine speed
ω_{gen} = Generator speed
K_s = shaft stiffness
D_s = Damping coefficient
The specifications of the drive train include: Inertia at turbine (p.u) = 4, damping coefficient =1, shaft stiffness = 0.3.

C. PERMANENT MAGNET SYNCHRONOUS GENERATOR

PMSG is a good option for stand-alone systems due to its' inherent advantages of higher efficiency and compactness when compared to their counterparts like induction generators. The specifications of the PMSG used in this system are summarized at the end of the section. The dynamic model of PMSG can be represented in rotating reference frame with the help of following equations [3].

$$V_q = -R_s i_q - L_q \frac{di_q}{dt} - \omega_r L_d i_d - \omega_r \lambda_m \quad \text{.........} (7)$$

$$V_d = -R_s i_d - L_d \frac{di_d}{dt} - \omega_r L_q i_q \quad \text{.........} (8)$$

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)[(L_d - L_q) i_d i_q - \lambda_m i_q] \quad \text{.........} (9)$$

where, V_d and V_q are d axis and q axis stator voltages , R_s is the stator resistance, λ_m is the magnetic flux linkage,

i_d and i_q are d axis and q axis stator currents and ω_r is the angular speed of PMSG.

In the case of cylindrical rotor,

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)\lambda_m i_q \quad \text{.........} (10)$$

since, $L_d \approx L_q$

When the PMSG is running at rated torque with a q axis stator current i_q of 20A, the corresponding magnetic flux linkage associated with the permanent magnets of the machine may be taken to be 0.5Wb. Other specifications of the PMSG include: Rated Voltage and frequency = 400Vrms, 50Hz, No. of pole pairs = 5, rated synchronous speed=153rad/sec, armature resistance=0.425 Ω , Stator inductance L_d=L_q=8.4mH

D. POWER ELECTRONICS

The power electronics consists of an uncontrolled rectifier, boost converter and an MPPT. The uncontrolled diode bridge rectifier has the advantage of being cheaper and being easier to implement compared to fully controlled bridge rectifier. Maximum power point tracking in WECS can be achieved using TSR control algorithm, Optimal torque control algorithm or Perturbation and Observation algorithm **[4]**; of which Perturbation and Observation algorithm is commonly preferred over the others due to its advantages of being more simple, efficient, not needing prior knowledge of wind turbine characteristics and not requiring devices like anemometer. In the system described in the paper however, the use of Perturbation and Observation algorithm has been suggested since it is a WECS of small capacity; the application being distributed generation. Here, the voltage and current parameters obtained from the uncontrolled rectifier are given as inputs to the MPPT which calculates the instantaneous power and, depending on whether the operating point is to the left or right of the operating point, the MPPT adjusts the duty cycle suitably to achieve the criterion of maximum energy extraction **[9]**. The output duty cycle of the MPPT serves as the gate signal of the IGBT of the boost converter. The output voltage made available across a dc link capacitor of suitable value is given to a Sinusoidal Pulse Width Modulated Inverter which produces ac at a constant frequency of 50Hz.SPWM is a popular modulation technique widely preferred due to its advantages of producing output with lower harmonics and having lower switching losses and ease of implementation **[2]**.

E. ELECTROLYZER AND PEMFC

Hydrogen production rate of an electrolyzer cell is directly proportional to the electrical current in the equivalent electrolyzer circuit as per Faraday's law **[8]**. The dc output current measured from the uncontrolled rectifier is fed to the electrolyzer to produce hydrogen in Kmols/sec. The electrolyzer is mathematically modeled using the equation given below:

$$\dot{n}_{H2} = \eta_F \frac{n_c I}{zF} \quad \text{....................}(11)$$

$\dot{n}_{H2}$ = hydrogen production rate[mols^{-1}]

η_F = faraday efficiency

n_c = number of cells in series

n= number of moles of electrons per moles of water,

F=Faraday constant 96485[A s mol^{-1}]

The electrolyzer is interfaced by help of a step-down DC/DC converter. The Proton Exchange Membrane Fuel Cell (PEMFC) uses hydrogen fuel and oxygen from the air to produce electricity. In this paper a 6.5KW PEMFC with 65 cells along with a boost converter are used to produce a constant output voltage of 100 volts. DC output from PEMFC can also serve special applications like providing voltage for powering special lights and carbondioxide pumps required to enhance hydrogen production of genetically modified algal cultures that not only pose an immense potential as an energy source in terms of the hydrogen production but also as a rich source of biofuel.

III. RESULTS

The Wind energy conversion system consisting of PMSG as the generator is developed and simulated using Matlab® Simulink tool box. The mathematical model of the entire WECS is developed as discussed in the previous sections and the simulation results are discussed in this section. The results are taken assuming stepped wind profile with the intention of understanding the behavior of the system. It is found that even at a variable wind speed the output of the inverter is constant and same as that obtained during constant wind speed operation.

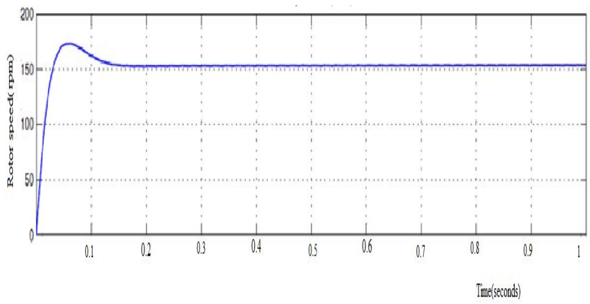

Fig1: PMSG rotor speed variation with time in rpm

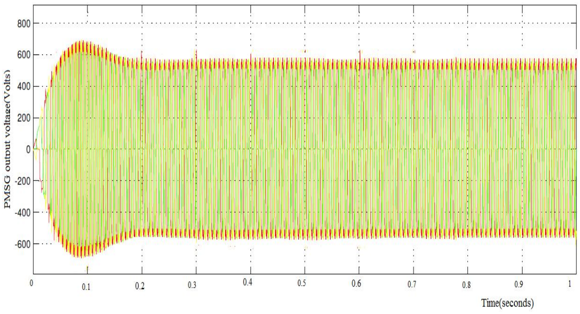

Fig 2: PMSG output voltage variation with time

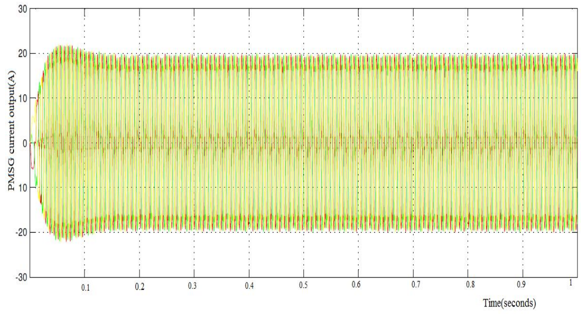

Fig 3: PMSG output current variation with time

Simulation results show that the PMSG runs at its rated synchronous speed of 153rad/sec after 0.15sec and produces instantaneous output ac voltage of 565.7 Vp-p (line to line and corresponding to 400V rms) and instantaneous stator current of 20A as shown in Fig 2 and Fig 3 respectively. At a constant wind speed of 12m/sec the frequency of operation of PMSG is found to be 125 Hz while in variable speed condition it is found to vary with wind speed. The line to line voltage (square waveform) of the inverter and the sinusoidal output of the inverter filter are obtained to be approximately 565.7 Volts peak to peak at a constant frequency of 50Hz (Fig 4 and Fig 5). Fig 6 shows hydrogen generation during the time when the three phase load is not operational. The amount of hydrogen output produced by the electrolyzer is represented in kmols/sec. The electrolyzer is found to produce an average output of 2.3×10^{-6} kmols/sec at a base wind speed of 12m/sec. Fig 7 indicates a stack efficiency of 55% for the PEMFC. The output of the PEMFC is boosted to about 100 volt dc as shown in Fig 8.

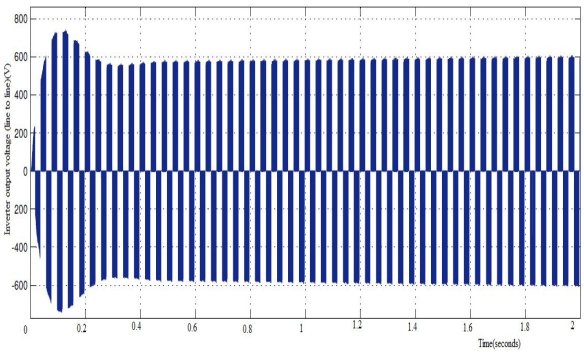

Fig 4: Variation of Line to Line voltage output of the inverter with time

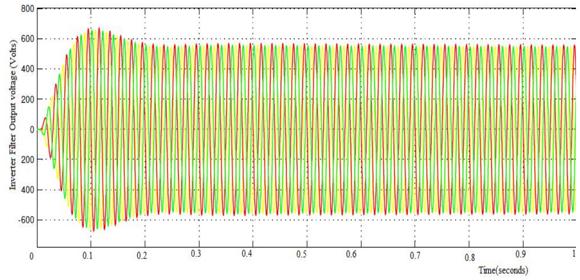

Fig5: Inverter filter output voltage

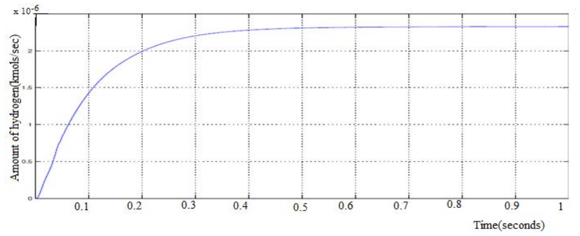

Fig 6: Amount of hydrogen produced at electrolyzer output in kmols/sec

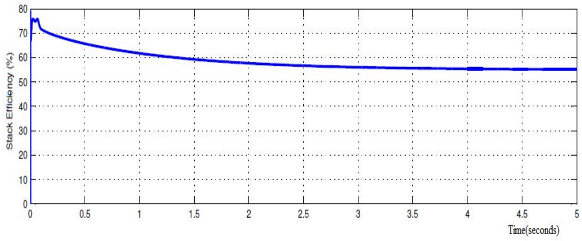

Fig 7: Stack efficiency of PEM fuel cell

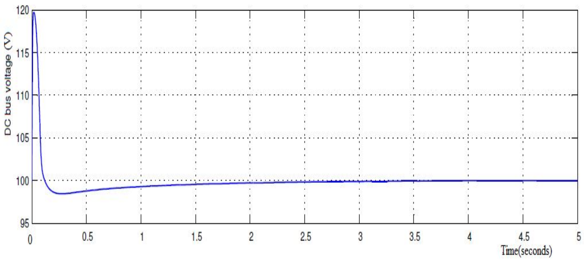

Fig8: DC voltage at the output of the PEMFC and boost converter

CONCLUSIONS

The results of the simulation of the WECS proposed in the paper are in agreement with the generally expected results and the system has been found to generate constant output voltage even under varying wind speed conditions. The Wind Energy Conversion System with hydrogen cogeneration if implemented on large scale, with suitable interconnection between various green technologies, will function as a self sufficient standalone system satisfying the entire energy needs of the remote area. If average wind speeds are maintained, the wind turbine can be coupled with hydrogen production units to generate hydrogen and used for various other applications. The water from Waste Water and Sewage Plants (after removal of solid particles) can be diverted to electrolyzers thus producing more hydrogen. The future scope of the work lies in finding other technologies that can assist in green energy production and that can integrate into the proposed system and also working out the economic aspects involved in the same.

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