ISSN (Online) 2321 – 2004
ISSN (Print) 2321 – 5526

INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH IN ELECTRICAL, ELECTRONICS, INSTRUMENTATION AND CONTROL ENGINEERING
Vol. 2, Issue 1, January 2014

Modelling of Stand –Alone Wind Energy Conversion System using Fuzzy Logic Controller

Nivedita Chakraborty[1] and Minakshi Deb Barma[2]

Department of Electrical Engineering, NIT Agartala, Tripura, India[1,2]

Abstract: The concern for environment due to the ever increasing use of fossil fuels and rapid depletion of the conventional sources of energy has led to the development of alternative sources of energy. Wind energy, the kinetic energy associated with movement of large masses of air, is an inexhaustible source of energy which generates electricity without harming our environment. But it is unreliable energy source as wind conditions are uncertain and unpredictable. This paper focuses on developing a fuzzy logic controller based Stand-Alone Wind Energy Conversion System, where this controller manages power production and power storage according to wind conditions & load demand. This proposed system will help us to get a smooth AC output voltage to supply to fixed Load under any wind speed. The effectiveness of the proposed system for its application in autonomous wind energy system is verified with simulation results, which is carried out using MATLAB.

Keywords: Variable Speed Wind Turbine, Synchronous Generator, Fuzzy Logic Controller, Stand-Alone Wind Energy Conversion System, 3-PH Diode Bridge Rectifier, Boost Converter.

I. INTRODUCTION

Before the industrial revolution life was simple and unsophisticated. Gradually, with the beginning of the age of machines, industrial revolution spread to the whole world. This led to an increase of energy requirement by leaps and bounds. Among various energy sources, Conventional source of energy generates pollutants and the fossil age is expected to cover only a span of 1000 years of human history. The increasing demand for non-fossil fuel based source is a driving force behind the advancement of renewable energy today. Wind Energy emerged as most economical of all renewable energy sources. It is thought that wind was first used to propel sailing boats, but the static exploitation of wind energy by means of wind mills is believed to have been taking place for about 4000 years [2]. Primary force for wind energy is developed due to differential heating of earth at equator and Polar Regions. The power available in the winds over the earth surface is estimated to be $1.6x10^7$MW. There has been remarkable growth of wind power installation in the world. In worldwide there are now many thousands of wind turbines operating with a total nameplate capacity of 196,630 MW [7]. Wind energy has been used for thousands of years for milling grain, pumping water and other mechanical power applications. Today it finds its application both as Grid Connected & Off Grid Electrical Power Source [2].

For uniform development of any country Electrification of rural areas is very important .For villages of remote areas which are unlikely to be electrified by conventional grid extension , Stand-Alone Wind Energy Conversion Systems(WECS) can be considered as an effective way to provide continuous power to electrical loads. The main parts of a Stand-Alone WECS are wind turbine, electrical generator, power electronic converter, battery, filter and inverter. Conventional DC generators are no more favoured due to their high cost, weight and maintenance problems. Primary advantages of Induction generator are rugged, brush less construction, low capital cost and better transient performance. But it requires AC excitation current, which is mainly reactive. Both electrically excited & permanent magnet rotor Synchronous Generators produce high quality output and are universally used for power generation. Here the wind turbine shaft speed is stepped up with the help of gears to suit the electrical generator speed. Recent advancement in power electronics has paved the way for variable speed drive system in which rotor speed is allowed to vary optimally with the wind speed to capture maximum power .In case of Variable speed direct Drive, the generator is directly coupled to the turbine shaft without gear box. Main benefits are lower nacelle weight, reduced noise & vibration, lower power loss and less frequent servicing requirement at the nacelle which is particularly very attractive for offshore installations [2]. A control unit monitors and controls the interaction among various blocks for optimal energy balance.

Fuzzy logic Control is based on a logical system that is much closer in spirit to human thinking and natural language than traditional logical systems. The Fuzzy Logic tool which was introduced by Lotfi Zadeh (1965) emerged as one of the most active and fruitful areas for research in the application of fuzzy set theory [3]. FLC is an attractive choice when precise mathematical formulations are not possible due to lack of quantitative data regarding the input-output relations. It has excelled in dealing with systems that are complex, ill-

ISSN (Online) 2321 – 2004
ISSN (Print) 2321 – 5526

defined, non-linear or time Varying .It has better stability, small overshoot and faster response than conventional systems and control complexity is less .It is more robust than other non-linear controllers [3].

In this paper, we propose a Stand-Alone WECS using a variable speed synchronous Generator, a battery bank and one fuzzy controller to manage the operation of battery according to wind power production and load demand. The Controller assured the load demand in any wind condition with a good power quality and regulated battery charging process to prevent the battery from gassing and sulphating.

II. SYSTEM DESCRIPTION

The proposed system consists of a total fixed load of 21.5 kW powered by a 42.5kVA synchronous generator, a variable speed wind turbine and a lead acid battery for back up storage .In this WECS a diode bridge rectifier will rectify AC power and one boost converter will increase the DC voltage. Fuzzy controller is used for electrical power management. A pulse width modulation (PWM) Inverter is used to provide a 400V, 50 Hz voltage to load. If wind conditions are favourable, the wind turbine will be the main provider for load. If available wind does not produce the required quantities of power and battery's capacity is enough, the battery will be switched on to give power to load. If wind power exceeds load demand, the surplus can be stored in the battery and if the battery is full, the surplus will be discharged into a dumb resistance [1]. Thus, the battery is not the main provider to load, so the charge-discharge cycle is reduced, battery life is extended. For this power management our controller needs two information: the battery state-of-charge (SOC) and the error between wind power and load demand (DeltaP). Here controller will decide the duty cycle of the switch of boost converter (D), the moment to switch on and off the battery (operation of S_1) and the moment to discharge the surplus into dumb resistance (operation of S_2).

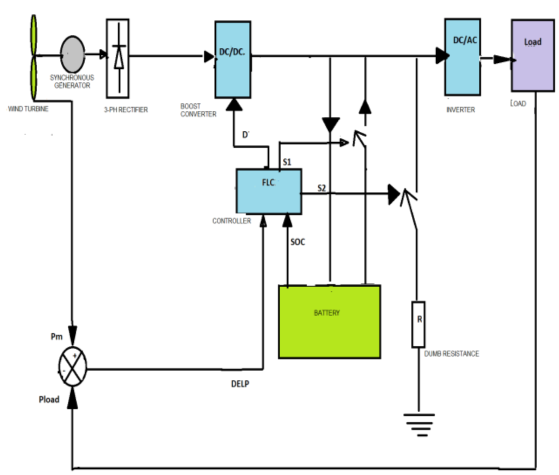


Fig. 1 Proposed system with Fuzzy Logic Controller.

A. *Factors Affecting The Wind Power*

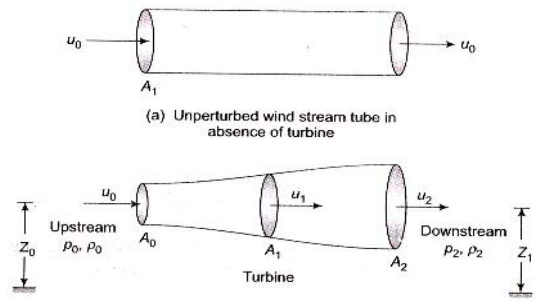


Fig. 2 Betz model of expanding air stream tube.

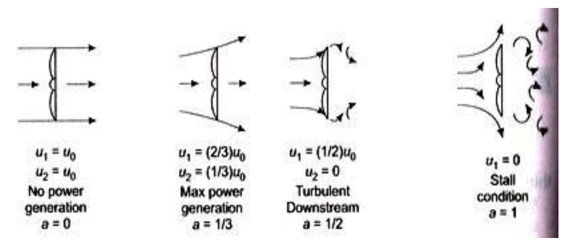


Fig. 3 Value of 'a' at Different wind Condition.

Wind Turbines can be broadly classified into two categories, Horizontal Axis Wind Turbine and Vertical Axis Wind Turbine. The aerodynamics is related to basics of Fluid Mechanics. Some important terms related to wind turbine blades are Chord, Angular Speed in rad/s, Angle of Incidence, Pitch Angle, Drag Force, Lift Force, Axial Force, Tangential Force and Solidity [2]. The kinetic energy of wind in joules per second is [1, 2]

$$P_0 = 0.5mV^2 = (0.5\rho AV^3). \quad (1)$$

Where m is mass in kg, V is air velocity in m/s, ρ is air density (1.225 kg/m^3), A is cross section area. So, wind power is dependent on the density of air and velocity of wind where the density of air is a function of pressure, temperature and relative humidity. The rotor of the turbine collects energy from the whole area swept by the rotor. For the purpose of simple analysis a smooth laminar flow with no perturbations is assumed (Fig.2). Now the power extracted from wind is equal to loss in kinetic energy per unit time [2]

$$P_T = [0.5m(u_0{}^2 - u_2{}^2)]. \quad (2)$$

Where u_0 & u_2 are windspeeds upstream & downstream respectively.

$$u_1 = [\tfrac{1}{2}(u_0 - u_2)]. \quad (3)$$

Here a is a interference factor, where

$$a = \left(\frac{u_0 - u_1}{u_0}\right). \quad (4)$$

Again, $P_T = [4a(1-a)^2 P_o]$. (5)

Here the term $4a(1-a)^2$ is equal to a factor C_p (power coefficient) which is the fraction of available power in the wind that can be extracted .The maximum value of C_p i.e. 0.593 occurs at 'a'= 1/3 (Fig.3). So, as per Betz criterion, a turbine can theoretically extract a maximum of 59% of available power in wind. However, for Constant wind speed the power extraction by a turbine will decrease if the blades

ISSN (Online) 2321 – 2004
ISSN (Print) 2321 – 5526

INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH IN ELECTRICAL, ELECTRONICS, INSTRUMENTATION AND CONTROL ENGINEERING
Vol. 2, Issue 1, January 2014

are so close together, or rotating so rapidly that a blade moves onto the turbulence created by a preceding blade; or the blades are so far apart or rotating so slowly that much of the air passes through the cross-section of the device without interacting with the blades [2]. One important factor here is the tip speed ratio(TSR) which is defined as ratio of Speed of tip of the rotor blade to Speed of on coming air. Practically for a particular wind speed there exists a particular TSR to produce maximum output. Variation of output power of a turbine with TSR & Blade pitch angle is shown in fig. 4. These are the main factors affecting Wind Power. Besides, solidity is also a factor. High Solidity rotor use drag force and turn slower. Low solidity rotors, on the other hand, use lift force [2] .

B. Model of Synchronous Generator

Fig.5 illustrates an elementary salient pole synchronous machine. Where $\theta = \omega_g t$, ω_g is constant rotor angular velocity in radians per second. Each of the 3-ph windings and field winding has the general form of voltage equation

$$v_g = [ri + \frac{d\varphi}{dt}] . \quad (6)$$

Where, v_g is applied voltage, r winding resistance , i input current and φ is flux linkages .The flux linkages of phase A can be written as

$$\varphi_a = [L_a i_a + M_{ab} i_b + M_{ac} i_c + M_{af} i_f] . \quad (7)$$

Here L denotes self inductance & M is mutual inductance between any phase and winding .

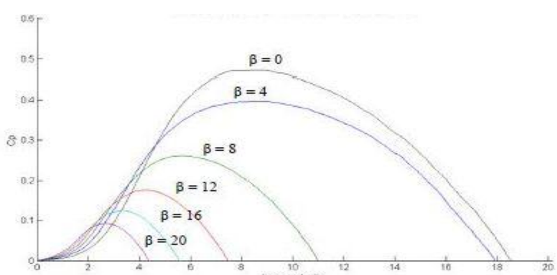


Fig .4 Family of C_p curves as function of tip-speed-ratio and pitch angle.

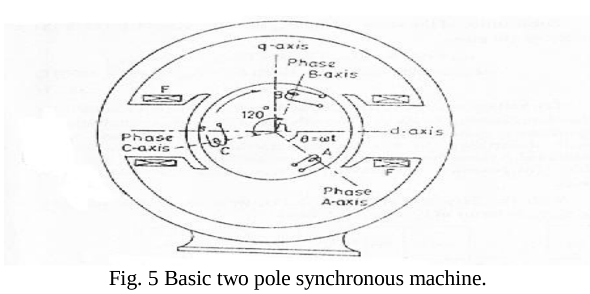


Fig. 5 Basic two pole synchronous machine.

The solution of voltage equations can be simplified if these equations are expressed in terms of dqo variables through Park's equations as follows

$$v_d = \frac{\sqrt{2}}{\sqrt{3}}\left[v_a \cos\theta + v_b \cos\left(\theta - \frac{2\pi}{3}\right) + v_c \cos\left(\theta - \frac{4\pi}{3}\right)\right]. \quad (8)$$

$$v_q = \frac{\sqrt{2}}{\sqrt{3}}\left[-v_a \sin\theta - v_b \sin\left(\theta - \frac{2\pi}{3}\right) - v_c \sin\left(\theta - \frac{4\pi}{3}\right)\right]. \quad (9)$$

$$v_0 = \frac{1}{\sqrt{3}}[v_a + v_b + v_c]. \quad (10)$$

Similarly current of each phase can be expressed. Here 'd' and 'q' denotes direct and quadrature axis component respectively. Here we have used a Synchronous Generator model of (42.5 Kva, 400 V line-line Voltage, 1500 rpm) in our simulation.

C. Model of Rectifier

The output voltage of the 3-ph Synchronous generator then rectified through a 3-ph diode bridge rectifier (Fig.6). With L_s (source inductance) is zero, the current I_d flows through one diode from the top group and one from the bottom group. In the top group, the diode with its anode at the highest potential will conduct; in the bottom group, the diode with its cathode at the lowest potential will conduct while the other two in the particular group become reverse biased. In this six pulse rectifier each diode conducts for 120^0. When Diode 1 is conducting I_a is equal to I_d; when diode 4 is conducting I_a is $-I_d$; and is equal to 0 when neither diode 1 nor 4 is conducting. Here the output voltage of the rectifier [4]

$$v_{rec} = v_{rms}\sqrt{2}\,\frac{\sin(\frac{\pi}{6})}{\frac{\pi}{6}} = (1.35 v_{rms}). \quad (11)$$

Where, v_{rms} is the root-mean square value of input line voltage.

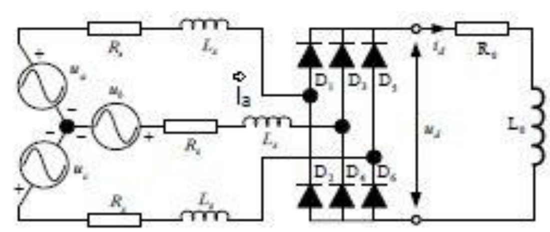


Fig. 6 Three Phase Bridge Rectifier.

D. Model of Boost Converter

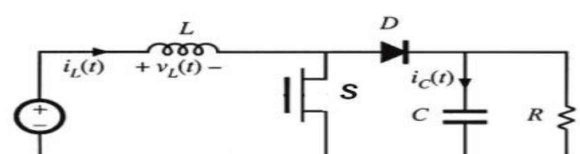


Fig. 7 Boost Converter.

As the name implies, in a boost converter the output voltage is always greater than the input voltage [4]

$$v_{dc} = \left(\frac{v_{rec}}{1-D}\right). \quad (12)$$

Here D is the duty ratio of the switch, v_{dc} is the output voltage of the boost converter. In this switch-mode dc-dc converter, when the Switch is on, the diode is reversed

ISSN (Online) 2321 – 2004
ISSN (Print) 2321 – 5526

INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH IN ELECTRICAL, ELECTRONICS, INSTRUMENTATION AND CONTROL ENGINEERING
Vol. 2, Issue 1, January 2014

biased, thus isolating the output stage. When the switch is off, the output stage receives energy from the inductor as well as from the input .Here the switching frequency f_s of switch S, generally lies in the range of 1 kHz to 1 MHz. In Continuous conduction mode the inductor current flows continuously and if the average load current drops below average output current , the current conduction will become discontinuous. Herevalue of inductor L is chosen as 4 mH to minimize the ripple in current and the C is 5000 μF to minimise the ripple voltage. In our project in order to keep the output voltage constant Fuzzy Controller will decide the duty cycle D for the boost converter.

E. Model of Battery

In this proposed model, we have used a Lead Acid Battery as a storage device .The terminal voltage of the battery V_b will be selected in a manner as

$$v_b > \left(\sqrt{\left(\frac{2}{3}\right)}\ v_{rms}\right). \qquad (13)$$

Here v_{rms} the line-line rms voltage of the generator. Here we have used a battery model of 144 Ahr with 780 nominal voltage in our simulation.

F. Model of Inverter

Here we have used Voltage Source PWM inverter where IGBT and Diodes are used as devices. Here for generating discrete pulses the same triangular voltage waveform is compared with three sinusoidal control voltages that are $120^0 out$ of phase. Modulation index

$$m_a = \left(\frac{v_{control}}{v_{tri}}\right). \qquad (14)$$

and frequency modulation ratio

$$m_f = \left(\frac{f_s}{f_i}\right). \qquad (15)$$

Where f_s is carrier frequency of the triangular wave which determines the frequency with which the inverter switches are to be switched. The control signal is used to modulate the switch duty ratio and has a frequency of f_1.

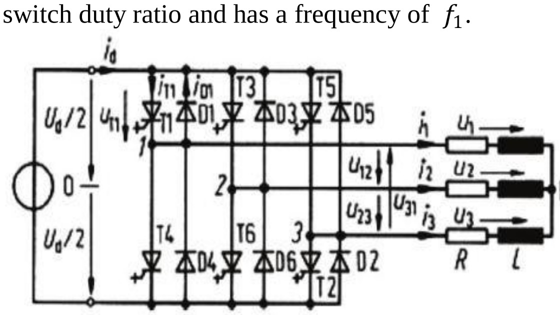


Fig. 8 Voltage Source PWM inverter.

Here the fundamental output line-to-line voltage is [4]

$$v_{ab} = \left(\frac{\sqrt{3}}{2\sqrt{2}} m_a u_{dc}\right). \qquad (16)$$

Where u_{dc} is the input DC voltage.

G. Model of Low pass Filter

To ensure a constant output voltage a low pass filter is used at the output. The voltage ripple can be minimized by selecting a corner frequency f_c [4]

$$f_c = \left(\frac{1}{2\pi\sqrt{LC}}\right). \qquad (17)$$

H. Fuzzy Logic Controller

The fuzzy logic tool is a mathematical tool for dealing with uncertainty which offers the important concept of computing with words. A simple fuzzy system consists of four blocks (Fig.9). The fuzzy set is defined by a membership function "μ"that maps objects in a domain of concern to their membership value in the set. It can be various types such as trapezoidal, triangular & Gaussian according to the process parameter. The Fuzzy logical operation is Fuzzification. There are basically two methods for this namely, Mandani & Sugeno. Defuzzification is the process of converting the fuzzy conclusion into the crisp one. Generally used methods for this are Adaptive integration, Center of Area, Center of Gravity, First of Maximum, Last of Maximum, Mean of Maximum etc. [3].

In this project, The FLC Controller input variables are the battery state-of charge (SOC) and the power error DeltaP. The output is the duty cycle D applied to the boost converter and control signals for operation of switch S_1 & S_2 . The linguistic term sets used in the controller are given below [1].

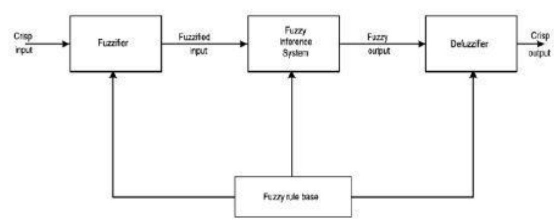


Fig. 9 Basic blocks of FLC.

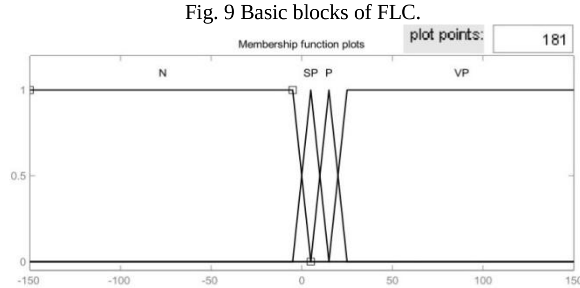
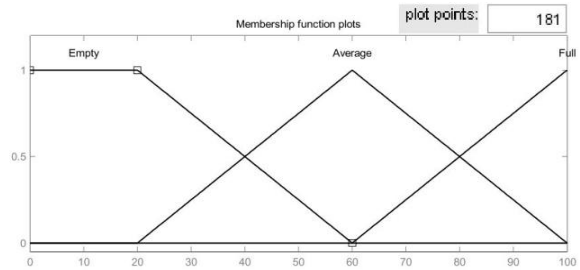


Fig. 10 Four terms of error power DeltaP [N(Negative); SP(Small Positive); P(Positive); VP(Very Positive)].



ISSN (Online) 2321 – 2004
ISSN (Print) 2321 – 5526

INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH IN ELECTRICAL, ELECTRONICS, INSTRUMENTATION AND CONTROL ENGINEERING
Vol. 2, Issue 1, January 2014

Fig. 11 Three terms of Battery SOC [Empty; Average; Full] (varying from 0% to 100%).

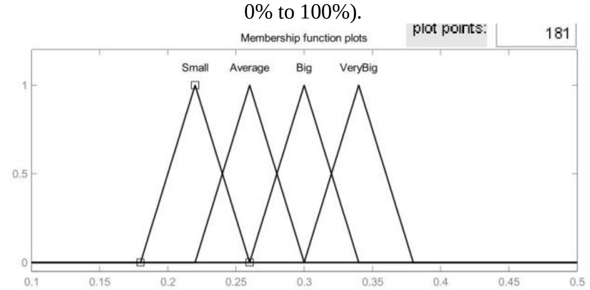


Fig. 12 Four terms of Duty Cycle D [Small ; Average ; Big ; Very Big]varying from 22% to 34% .

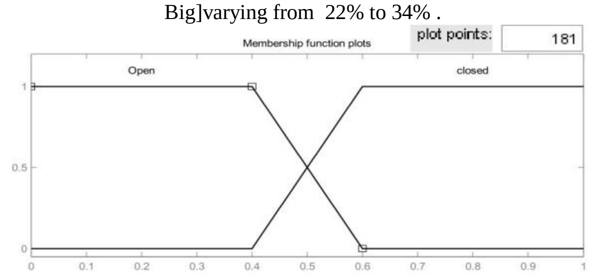


Fig. 13 Two terms of state of switch S_1 and S_2 [Open ; Close].

As inference method for the rules describing FLC dynamic is used the method of inference min-max.

$$\mu_{A\cap B}(x) = min(\mu_A(x), \mu_B(x)). \quad (18)$$

$$\mu_{A\cup B}(x) = max(\mu_A(x), \mu_B(x)). \quad (19)$$

D		SOC		
		Full	Average	Empty
DeltaP	N	Big	Big	Small
	SP	VeryBig	Big	Small
	P	VeryBig	VeryBig	Average
	VP	VeryBig	VeryBig	Average

Fig. 14 Rules Of D.

S_1		SOC		
		Full	Average	Empty
DeltaP	N	Close	Close	Open
	SP	Open	Open	Open
	P	Open	Open	Open
	VP	Open	Open	Open

Fig. 15 Rules Of S_1.

S_2		SOC		
		Full	Average	Empty
DeltaP	N	Open	Open	Open
	SP	Open	Open	Open
	P	Open	Open	Open
	VP	Close	Open	Open

Fig. 16 Rules Of S_2.

The design of the rules was based on Mamdani fuzzy rules. Example , "If the error between wind power and load demand is Very Positive and the battery state of charge is Full , then the Duty cycle should be Very Big, switch 1 should be opened and switch 2 should be closed". The inference mechanism and the twelve IF-Then rules defined in relation with the considerations, generates the approximation of the FLC output represented in Fig.14,15 & 16.The overall fuzzy subset representing output control variable is defuzzified using center of gravity method [1].

III. SIMULATION AND RESULTS

The described system is implemented in MATLAB SIMULINK and the designed fuzzy logic controller is defined using the Fuzzy Logic Toolbox. Here we have considered a fixed load of 21.5 Kw and Battery state-of-charge is supposed to be 90% (Full).

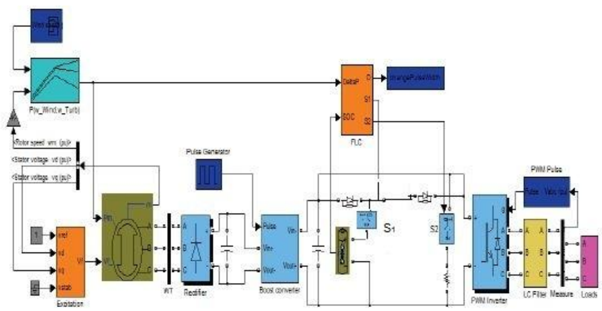


Fig. 17 Implementation in Simulink.

In this paper, a wind turbine model is simulated by using a look-up table. (Fig.18).

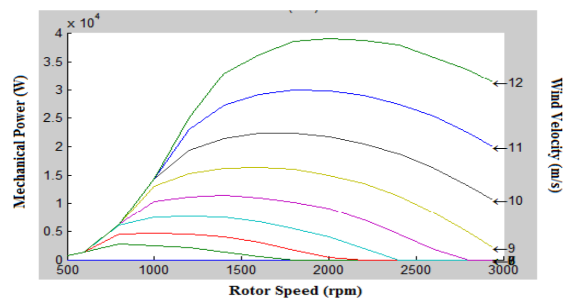


Fig. 18 Wind Turbine Characteristics.

Now to see the power management by the controller we are considering two different conditions.

- Wind Speed 12m/s, Battery SOC 90% and total working Load 21.5 kW;
- Wind Speed 12m/s, Battery SOC 90% and total working Load 11.5 kW.

Here in both the conditions for first few seconds the wind turbine generated power is 35 kW. In first condition as all the loads are working total load demand 21.5 kW. The Positive surplus (about 13.5 kW) is too small to charge the battery or to discharge through the dumb resistance, so S_1 and S_2 are both open. The Fuzzy Controller decides the duty ratio of Boost converter 0.33 (Very Big). But in second condition, the load demand is only11.5 Kw & Battery SOC is still 90%. This Very Positive DeltaP (23.5 kW) is so high for battery charging process , which may cause gassing the battery , so S_2 is closed to waste the rest power into a dumb resistance . The Fuzzy Controller decides the duty ratio of Boost converter 0.34 (Very Big) but Battery is not charged because the voltage applied to battery's end is smaller than 780 V. To isolate the Battery from the rest of the circuit S_1 remain open.

ISSN (Online) 2321 – 2004
ISSN (Print) 2321 – 5526

INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH IN ELECTRICAL, ELECTRONICS, INSTRUMENTATION AND CONTROL ENGINEERING
Vol. 2, Issue 1, January 2014

But after some time, in both the cases, the generated power of the wind turbine being dependent of rotational speed of the turbine, decreases. Negative DeltaP with battery Full SOC opens Switch S_2 & closes Switch S_1 to provide power to load .This leads to decrease battery SOC. The controller decides the Duty ration of Boost Converter as Big (0.3). Here The duty ratio decreased to keep the charging voltage below the battery voltage .In the whole process we get a constant voltage of 780 V DC at Inverter input terminals .Here the Battery is not charged because the voltage applied to battery's end is smaller than 780 V.

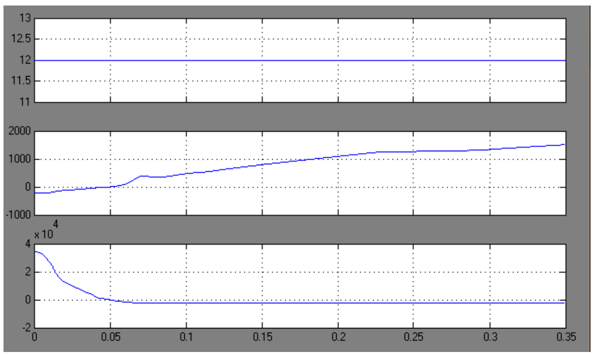


Fig. 19 Wind turbine characteristics (Wind Speed, generated Torque, generated Power) in both conditions.

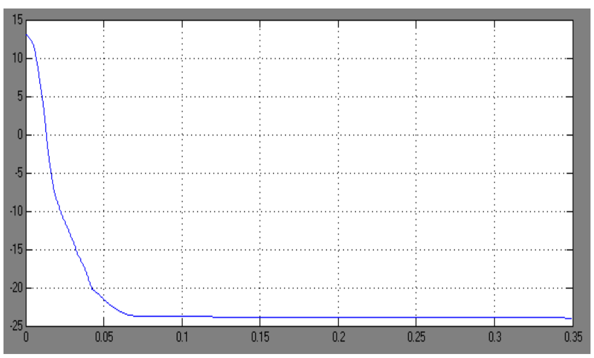


Fig. 20 DeltaP in first condition.

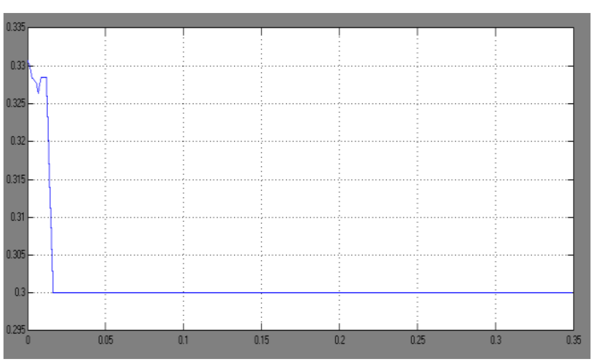


Fig. 21 Duty ratio of boost converter in first condition.

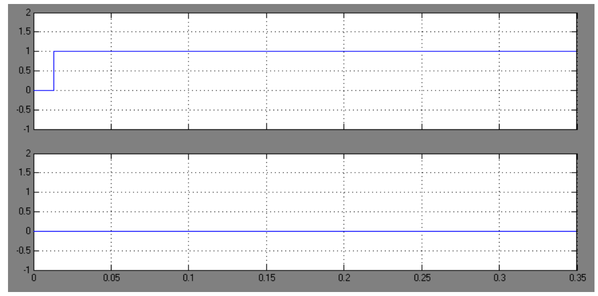


Fig.22 State of S_1 and S_2 in first condition.

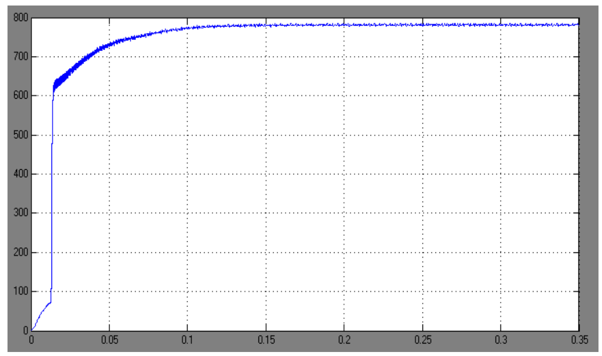


Fig. 23 Input Voltage at Inverter terminal at first condition.

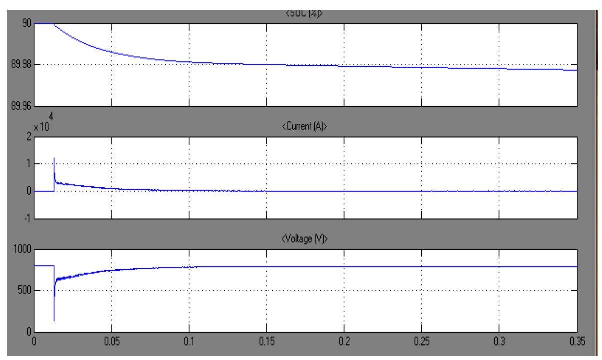


Fig. 24 Battery output (SOC, Current , Voltage) at first condition.

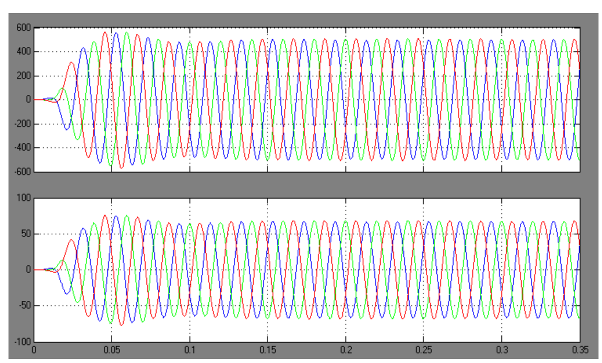


Fig. 25 Inverter output at first condition.

ISSN (Online) 2321 – 2004
ISSN (Print) 2321 – 5526

INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH IN ELECTRICAL, ELECTRONICS, INSTRUMENTATION AND CONTROL ENGINEERING
Vol. 2, Issue 1, January 2014

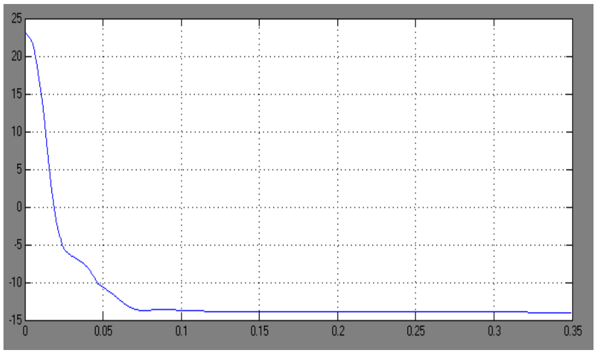


Fig. 26 DeltaP in second condition.

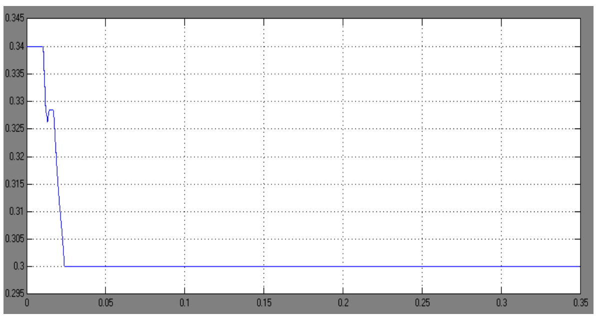


Fig. 27 Duty ratio of boost converter in second condition.

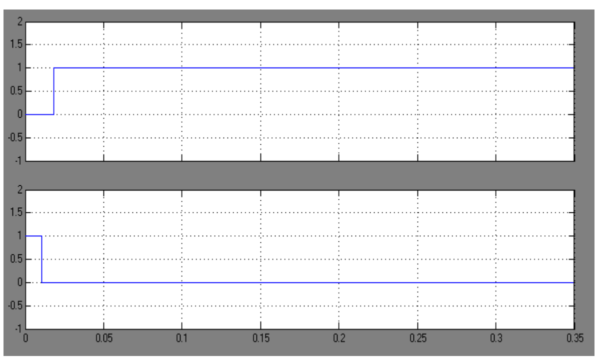


Fig. 28 State of S_1 and S_2 in second condition.

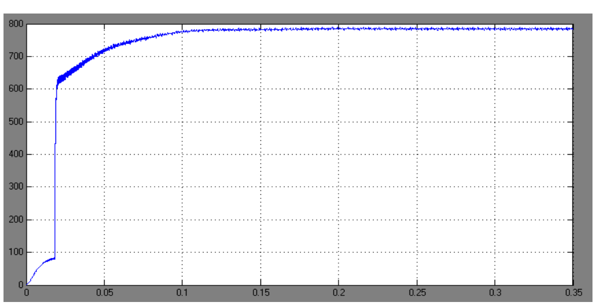


Fig. 29 Input Voltage at Inverter terminal in second condition.

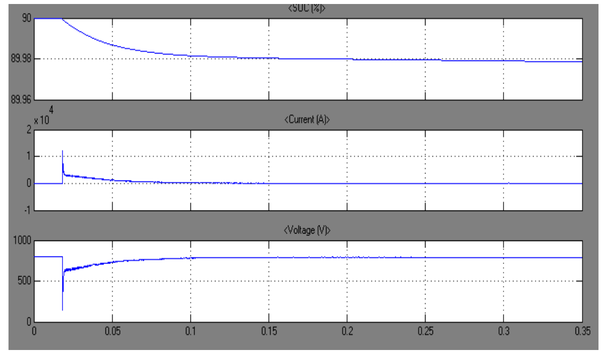
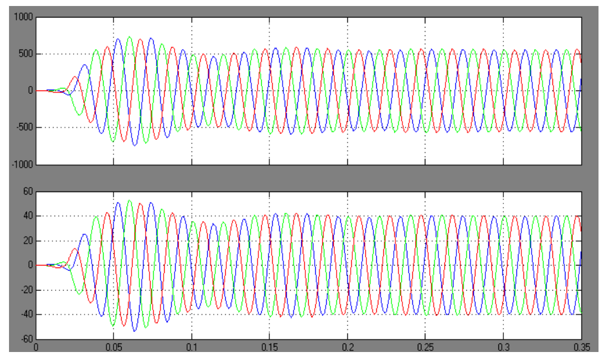


Fig. 30 Battery output (SOC, Current , Voltage) in second condition.



Fi.31 Inverter output.

These results show that our controller worked well. A 400V, 50 Hz voltage is always provided to load despite wind conditions in order to respect load demand.

IV. FUTURE WORK & CONCLUSIONS

This paper presents a fuzzy power management for electricity distribution for stand-alone system. With information about load and battery state-of-charge, control signals were generated to manage well the power production for any wind conditions in respecting load demand. The simulation results show a good behaviour of our controller.
It is evident from the previous results, that the generated power from the turbine depends on rotor speed. In next stage one controller will be designed to track the optimum rotor speed to achieve the maximum power point of the turbine. Through this controller, control signals will be generated so that maximum power can be recovered from the wind in respect of Load demand. Reducing the charging & discharging cycle this will extend battery life.

REFERENCES

[1] Huynh Quang Minh, Nollet Frédéric, Essounbouli Najib and Hamzaoui Abdelaziz, "Control of permanent magnet synchronous generator wind turbine for stand-alone system using fuzzy logic," Atlantis press, France, pp. 720-727, 2011.
[2] B H Khan, *Non-Conventional Energy Resources*, 2nd Reprint, Tata McGraw-Hill, New Delhi, India, 2007.

[3] Gaurav, and Amit Kaur, "Comparison between Conventional PID and Fuzzy Logic Controller for Liquid Flow Control: Performance Evaluation of Fuzzy Logic and PID Controller by using MATLAB/Simulink," ISSN:2278-3075,Volume-1,Issue-1, International Journal of Innovative Technology and Exploring Engineering (IJITEE), pp. 84-88, 2012.

[4] Ned Mohan, Tore M. Undeland, William P. Robbins, *POWER ELECTONICS Converters, Applications, and Design*, Third Edition, Reprint, Wiley India (P.) Ltd., New Delhi , India, 2010.

[5] Udhayakumar P, Saravanan C, and Lydia M., "Stand-Alone Wind Energy Supply System using Permanent Magnet Synchronous Generator," ISSN: 2278-3075,Volume-2,Issue-3, International Journal of Innovative Technology and Exploring Engineering (IJITEE), pp.130-135, 2013.

[6] Abdul Motin Howlader, Naomitsu Urasaki, Shantanu Chakraborty, Atsashi Yona, Tomonobu Senjyu and Dr. Ahmed Y. Saber, " Fuzzy Controller Based Output Power leveling Enhancement for a permanent Magnet Synchronous Generator," IEEE International Conference on Fuzzy Systems, Taipei, Taiwan, pp. 656-661, 2011.

[7] Ahmed M. Hemeida, Wael A.Farang, and Osama A. Mahgoub, "Modelling and Control of Direct Driven PMSG for Ultra Large Wind Turbines," World Academy of Science, Engineering and Technology 59 2011, pp. 918-924, 2011.

[8] C.N. Bhende, S. Mishra, and Siva Ganesh Malla, "Permanent Magnet Synchronous Generator Based Stand-Alone Wind Energy Supply System," Vol.2, No.4, IEEE TRANSACTIONS ON SUSTAINABLE ENERGY, pp. 361-373, 2011.