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DYNAMIC MODELING, SIMULATION AND CONTROL OF A SMALL WIND ENERGY CONVERSION SYSTEM

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ABSTRACT

In this paper dynamics of a small wind energy conversion system is modeled and simulated. Wind data generation with a flexible wind field model and the design of a fuzzy logic controller for optimum power extraction is included. Simplified models representing rotor aerodynamics are used. Control algorithm employs direct torque sensing and it adjusts rotor speed by changing the dump load. The scheme is simulated in Matlab-Simulink^{TM} and results are presented. The proposed model could be investigated further for analysis, design and performance evaluation of remote and off-grid wind energy conversion systems in standalone or hybrid applications.

Keywords: Small wind turbine, Fuzzy controller, Dynamic modeling and simulation

1. INTRODUCTION

The search for clean and low cost energy alternatives has yielded wind energy as an excellent candidate against conventional fossil fuel based power generation. Large wind turbine based grid connected wind farms have proven to be a commercial success in Europe and North America. Small wind energy conversion systems (WECS) are potential candidates for remote and off-grid power generation in standalone or hybrid applications. Although a great volume of publications regarding large machines is available in the literature, a systemic approach for modeling, analysis and design of small wind turbines is not abundant. Design of small WECS requires a delicate balance of simplicity of operation, good aerodynamic and electrical performance, survivability at extreme winds, and affordability by the end user. There exists a great need for sound research, development, testing, and incentive programs in support of this technology [1].

With a renewed interest in wind energy in Bangladesh, wind turbines could be considered for standalone or wind-solar systems for coastal and northeastern regions [2]. Unlike many other alternative energy sources (solar PV arrays, fuel cells etc.) wind turbines generally involve less sophistication. Therefore, prospects of designing, testing and installing smaller turbines could not be overruled.

In this paper various dynamic aspects of a 5 kW wind turbine and its controller is modeled and simulated. For emulating realistic wind variations, a wind field model is considered. Several issues regarding the rotor aerodynamics are taken into account in simplified forms. Matlab-Simulink^{TM} is used for simulation of the system. Simulation results indicating the performance of the turbine, generator and the controller, under varying wind conditions are presented and analyzed.

2. SMALL WIND TURBINE TECHNOLOGY

Small turbines are broadly rated anywhere from 50 W to 10 KW, with diameters ranging from 1m to 10m. Most of the promising commercially available units are horizontal-upwind type having two or three blades [1,3]. Unlike older pitch or stall-regulated machines, newer turbines are generally yaw regulated and operate in variable speed variable frequency (VSVF) mode. With changes in wind direction, a tail fin aligns the rotor against the wind. A passive furling mechanism allows the rotor body to furl away in case of high winds. These mechanisms are essential in regulating the power extracted by the system and reducing structural stress on the machine parts and the tower [3].

In this paper, a 5 kW prototype wind turbine having similar design parameters as Vergnet's GEV5/5 [4] or Eoltec's Scirocco E5.5-5 [5] is considered for modeling and simulation. Typical parameters attributed to such a unit are listed in table 1.

Table 1: Wind turbine rating

Symbol	Parameter	Value	Unit
P_r	Rated power	5000	(W)
P_{max}	Maximum power	5200	(W)
R	Rotor radius	2.75	(m)
ω_{ro}	Rated rotor speed	25	(rad/s)
V_{cutin}	Cut-in wind speed	4	(m/s)
V_{rated}	Rated wind speed	12	(m/s)
V_{cutout}	Cut-out wind speed	22	(m/s)
V_{surv}	Survival wind speed	55	(m/s)
λ_o	Optimum TSR	7.26	-
C_{po}	Opt. Power coefficient	0.4	-
V_{to}	Rated terminal voltage	220	(V)

The turbine is considered to be two-bladed with a rotor speed from 80 to 240 rpm. Unlike high-speed turbines (500 to 1200 rpm) with a tip speed ratio of 8~10, this machine essentially runs at low speeds and its optimum tip speed ratio, λ_o (TSR) is therefore lower [5].

3. DYNAMIC MODELING

3.1 Wind Field

Investigation of wind turbine performance and design of controllers require a realistic set of wind data with durations ranging form minutes to hours [6,8]. The wind data generally contains a rapidly varying turbulence component superimposed on a slowly varying mean wind speed. A first order wind model that generates the turbulent component, V_{turb} by filtering random white noise, $m(t)$ is given below [7]:

$$\begin{aligned} \frac{dV_{turb}}{dt} &= \frac{1}{T_v} V_{turb} + m(t) \\ V_{wind} &= V_{turb} + V_{avg} \qquad (1) \\ T_v &= \frac{10.5z}{V_o} \end{aligned}$$

Addition of average wind, V_{avg} with V_{turb} yields the wind speed having a more realistic time varying pattern. The time constant is site dependant and a typical set of data is given in appendix 1.

3.2 Effects of Rotor Aerodynamics

The rotor surface experiences a wind variation slightly different from wind speed inspected at a point on that surface. A point wind data is essentially averaged over the swept area of the blades, which acts as a low-pass filter. A second order model could be used to consider this spatial filtering effect as given in [7]:

$$\frac{V_{filt}}{V_{wind}} = \frac{0.3575s + 1.414}{0.1778s^2 + 0.95s + 1.414} \qquad (2)$$

With rapid changes in wind speed, the turbines yaw mechanism exhibits over/undershoots. As a result the rotor experiences a wind speed, V_{eff}, which is further deviating from the incident wind during the transients and could be represented by a transfer function [7]:

$$\frac{V_{eff}}{V_{filt}} = \frac{1.37s + 0.11}{s + 0.11} \qquad (3)$$

Estimating the power captured by the rotor is computationally demanding and requires an understanding of the interaction between the rotor's aerodynamics, drive train design, wind conditions etc. To simplify this job, a typical set of power curve data (fig. 1) could be used.

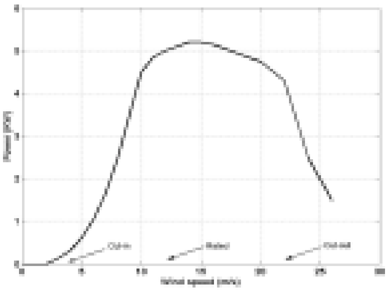


Figure 1.Wind turbine power curve

3.3 Generator

Recent wind turbines are equipped with a Permanent Magnet ac generator [3]. However, a 5 KW, 220V PM dc generator is considered in this paper to maintain simplicity and reduce simulation time. Since, the system is directly coupled, lumped values of inertia and friction are considered for the whole drive train. Equations representing a dc generator are given below (parameters in appendix 1):

$$\begin{aligned} T_l &= k\phi I_a \\ T_a &= T_l + J\frac{d\omega_r}{dt} + B\omega_r \\ E_a &= k\omega_r\phi \qquad (4) \\ V_t &= E_a - L_a\frac{dI_a}{dt} - R_a I_a \end{aligned}$$

4. CONTROLLER DESIGN

The control problem of the wind energy converter could be defined as follows: at below rated wind speed, (V_{rated}) the control goal is to extract maximum available power. When the wind exceeds cut-out limit (V_{cutout}), decrease of rotor's speed is necessary in order to prevent excessive stress on the machine parts. At intermediated wind speeds ($V_{rated} \le V_{wind} \le V_{cutout}$), the controller should maintain constant rated power, P_{rated} at the output.

A PD-type fuzzy logic controller (FLC) is employed in this scheme to extract optimum power at various wind speed levels. The key assumption for the controller's operation is that, the rotor torque at any instant could be determined by means of a torque sensor or torque estimator. Rotor torque is used to generate a desired reference rotor speed level that would enable optimum power extraction. Reference rotor speed is compared with the actual rotor speed and the error signal is used by the controller to adjust the dump load. Changes in the dump load vary the armature current, I_a as well as the armature torque T_l, which sets the rotor speed towards the desired level.

4.1 Determination of Reference Rotor Speed

The algorithm for determining reference rotor speed from an estimated/measured rotor torque could be established from the basic principles of wind energy engineering. The maximum extractable power from wind is limited by the Betz coefficient, C_{pb} (eq. 5). Actual, C_p is much lower than the theoretical value (eq. 6).

$$P_{wind} = C_{pb}\frac{1}{2}\rho(\pi R^2)v_{eff}{}^3 \qquad (5)$$

$$P_a = C_p\frac{1}{2}\rho(\pi R^2)v_{eff}{}^3 \qquad (6)$$

The tip speed ratio (TSR) λ is a measure of the rotor's rotational speed at any given wind speed, whereas the power coefficient C_p is the product of torque coefficient C_t and TSR (eq 7).

$$T_a = \frac{P_a}{\omega_r};\lambda = \frac{\omega_r R}{v_{eff}};C_p = C_t\lambda \qquad (7)$$

From eq. 7 and 6, following expressions of rotor torque could be found:

$$T_a = C_t\frac{1}{2}\rho(\pi R^3)v_{eff}{}^2 \qquad (8)$$

$$T_a = C_p\frac{1}{2}\rho(\pi R^5)\frac{1}{\lambda^3}\omega_r{}^2 \qquad (9)$$

Rated rotor torque, T_r and maximum rotor torque T_{max} could be found by dividing rated power, P_r and maximum power P_{max} (table 1) with rated rotor speed, ω_{ro}, respectively. Assuming the estimated torque $T_a{}'$ to be same as actual rotor torque T_a, three regions of operation could be identified: $T_a{}' < T_r$; $T_r \le T_a{}' < T_{max}$; and $T_a{}' \ge T_{max}$.

Various techniques for direct torque control, including use of neural network and Kalman filters in conjunction with observers and estimators are available in the literature [7]. Design of such estimator is expected in later works.

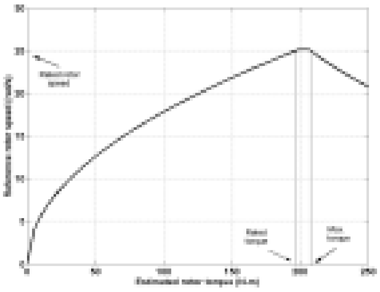


Figure 2. Reference rotor speed

At below rated winds ($T_a{}' < T_r$), the desired aim is to extract maximum available power. This is possible when the C_p and λ have optimum value. Therefore, eq. 9 yields:

$$T_a{}' = C_{po}\frac{1}{2}\rho(\pi R^5)\frac{1}{\lambda_o{}^3}\omega_r{}^2 = k_T\omega_{ref}{}^2 \qquad (10)$$

The below rated reference rotor speed is:

$$\omega_{ref} = \sqrt{\frac{T_a{}'}{k_T}} = k_w\sqrt{T_a{}'} \qquad (11)$$

At intermediate conditions ($T_r \le T_a{}' < T_{max}$), the desired rotor speed is the rated speed. Since the turbine operates in near-rated region and the interval is quite small (fig. 2), such specification would induce little error.

$$\omega_{ref} = \omega_{ro} \qquad (12)$$

When the wind peaks up and rotor torque exceeds the peak design value ($T_a{}' \ge T_{max}$), the rotor speed should be limited by the maximum extractable power value (eq. 14), as the condition in eq. 10 prevails.

$$P_{max} = k_T\omega_{ref}{}^3 \qquad (13)$$

With equations 13 and 10, above rated reference rotor speed could be found as:

$$\omega_{ref} = \frac{P_{max}}{T_a{}'} \qquad (14)$$

Equations 11, 12 and 14 are therefore sufficient to determine reference rotor speed to be used for control purposes.

4.2 Design of the FLC Controller

A fuzzy logic controller (FLC) provides a systematic and efficient mean for associating qualitative fuzzy linguistic information for controlling a process by using rules of thumb. Fuzzy controllers are model free and could be employed successfully where system information is insufficient and operating conditions are uncertain.

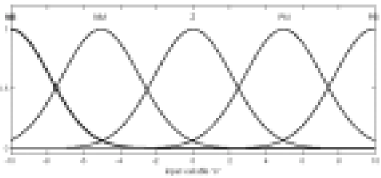
Since the aerodynamics involved with a wind turbine's operation is fairly uncertain and its performance is highly site dependant, a fuzzy controller appears suitable in such application. Furthermore, variable speed operation as attributed to the turbine under consideration, requires separate sets of control objective. Use of PID type controller would require more than one controller and gain scheduling scheme. However, a PD type FLC used here could operate individually for all ranges and without precise scheduling [9,10].

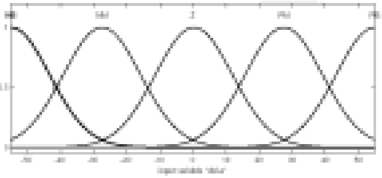
Design of a fuzzy controller involves several steps such as, input-output variable identification, fuzzification, definition of control rules, inference and defuzzification.

The error, *e* (difference between reference and actual rotor speed) and rate of change in error *de/dt* are taken as the input to the controller. The value of dump load, R_{dump}, which needs to be switched on/off, is the controller output.

$$e(t) = \omega_{ref} - \omega_r$$
$$\frac{de(t)}{dt} = \underset{\Delta t \to 0}{Lt} \frac{e(t) - e(t-1)}{\Delta t} \qquad (15)$$

Fuzzification is done using five gaussian membership functions for each of the parameters.


(a) Input (error)


(b) Input (rate of change in error)

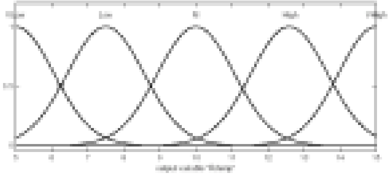

(c) Output (Dump load)

Figure 3. Fuzzy variables and membership functions

Fuzzy rules that map the inputs to the output, often called fuzzy associative memory (FAM), are given in table 2 and corresponding control surface is shown in fig. 4.

Table 2: Fuzzy associative memory (FAM)

(de/dt) e	NB	NM	Z	PM	PB
NB	VLow	VLow	Low	Low	M
NM	VLow	Low	Low	M	High
Z	Low	Low	M	High	High
PM	Low	M	High	High	VHigh
PB	M	High	High	VHigh	VHigh

The computation unit compares the fuzzified inputs and determines the degree of fulfillment (DOF) of each rule given in the FAM and infers the minimum (AND operation) of the compared values.

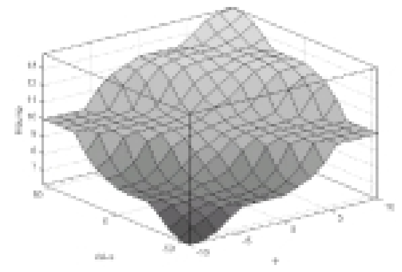


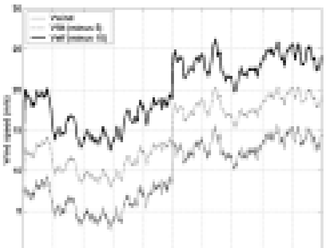
Figure 4. Fuzzy rule surface view

The defuzzification process converts the results of fuzzy inference into numerical values. The centroid method (Mamdani method) of defuzzification is employed.

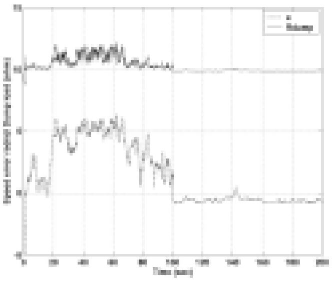
5. SIMULATION AND RESULTS

Matlab-Simulink^{TM} is used for simulating the models. The Simulink block diagrams are given in the Appendix 2 (fig. 6).

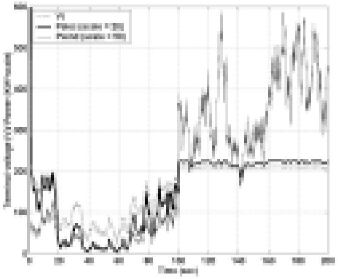
Input to the model is an average wind speed, having a step change at t=100s (8 to 12m/s). Simulation is done for 200s. A wind speed pattern, generated by the wind field model (eq. 1) adds turbulent components to the average value. The sampling time for wind turbulent component is taken to be 0.5s. Wind variations experienced by the rotor surface is converted from point to surface data by the spatial filter (eq. 2). It acts as a low pass filter and removes some of the higher harmonics in the winds (fig. 5(a)). But, there is not much difference between the filtered and the effective wind. This implies that induction lag model (eq. 3) is not of much significance owing to the fact that, small turbines are fairly fast in responding to sudden wind speed change.


(a) Wind speed variations


(b) Rotor speed



(c) Controller input/output



(d) Power and voltage output

Figure 5. Simulation results

The rotor speed deviates significantly from the reference speed at lower winds (fig. 5(b)). At higher winds (~12m/s), the speed error is minimized and the controller achieves near-rated rotor speed. With wind speeds ranging from 3 to 9 m/s (t=0 to 100s), the speed error is below 7 rad/s and magnitude of the dump load is 10 to 13 ohms (fig. 5(c)). At t>100s, the turbine slightly overspeeds (~1 rad/s). The output voltage of the generator is highly dependant on the wind speed. At rated and above rated winds, the turbine generates rated voltage of 220V (±5%). The electrical power output is also dependant of the wind speeds, as expected. The turbine regulates its power output to the rated level (t=100 to 200s) by means of the rotor aerodynamics and the controller as seen in fig. 5(d).

During simulation with Simulink^{TM}, problems with algebraic loops, extreme numerical values and slowness were experienced with almost all variable step solvers. However, the ‘fixed-step: ODE5 (Dormand Prince)’ method proved to be successful in avoiding those problems without deviating significantly from the expected results. It could be seen from the simulations, a small turbine with proper yaw, furling and aerodynamic settings, could be controlled successfully by a single PD type controller. However, the performance of the turbine at near-rated conditions is better than that of low or excessive winds.

6. CONCLUSION

Dynamic modeling and simulation of a small wind turbine and design of a fuzzy controller are presented. Use of the proposed control algorithm removes the need for wind speed sensing with anemometers, provided a suitable torque estimation technique is available. Simulation indicates that the effect of sudden wind speed variation is minimal on the performance of a well-designed fast responding small turbine. A single fuzzy logic controller can be used to control such a wind turbine over a full range of wind speed. Such fuzzy logic controller is able to maintain rotor speed and output power within design limits at various operating conditions. Further work might include, modeling of PM ac generator and application of power electronics at the output of the wind turbine. The wind energy converter model outlined in this paper could also be used for the investigation of standalone power generation and hybrid applications such as wind-solar or wind-fuel cell systems.

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NOMENCLATURE

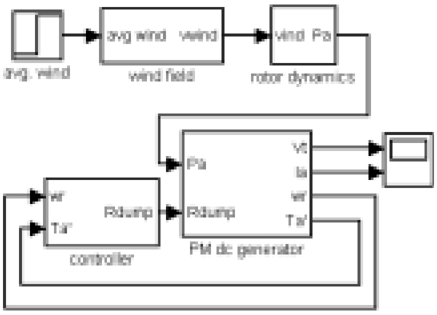
Symbol	Parameter	Unit
$m(t)$	Random white noise	(m/s^2)
V_{turb}	Wind turbulence	(m/s)
V_{avg}	Mean wind speed	(m/s)
V_{wind}	Wind speed	(m/s)
T_v	Time constant	(s)
V_{filt}	Filtered wind speed	(m/s)
V_{eff}	Effective wind speed	(m/s)
I_a	Armature current	(A)
T_l	Load torque	(N-m)

T_a	Armature torque	(N-m)
E_a	Induced voltage	(V)
V_t	Terminal voltage	(V)
P_a	Aerodynamic power	(W)
ω_r	Rotor speed	(rad/s)
P_{wind}	Maximum extractable power in wind	(W)
C_p	Power coefficient	-
λ	Tip speed ratio (TSR)	-
C_t	Torque coefficient	-
T_a'	Estimated rotor torque	(N-m)
ω_{ref}	Reference rotor speed	(rad/s)

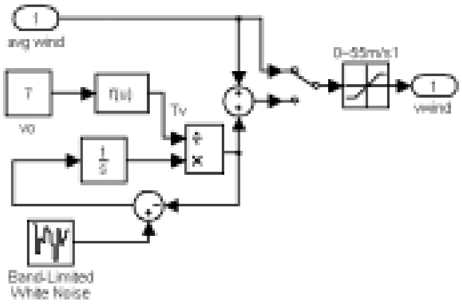
APPENDIX 1

Symbol	Parameter	Value	Unit
z	Turbine hub height	15	(m)
V_o	Median wind speed	7	(m/s)
k	Generator constant	25.82	-
ϕ	Magnetic flux	0.364	(V/rad/s)
B	Damping constant	0.005	(Nm/rad/s)
J	Moment of inertia	1.75	(Kg-m^2)
L_a	Arm. inductance	15	(mH)
R_a	Arm. resistance	1.525	(Ohms)
C_{pb}	Betz coefficient	0.5926	-
ρ	Air density	1.22	(Kg/m^3)
T_r	Rated rotor torque	198.96	(N-m)
T_{max}	Max. rotor torque	207	(N-m)
k_T	Controller param.	0.315	-
k_w	Controller param.	1.783	-

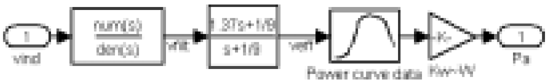
APPENDIX 2



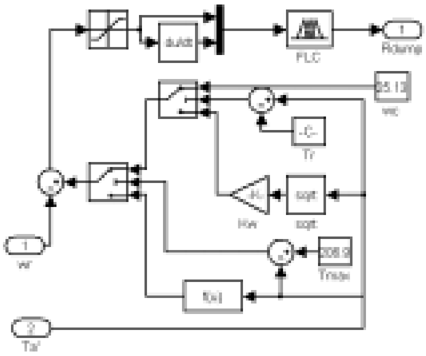
(a) Overall scheme and the subsystems



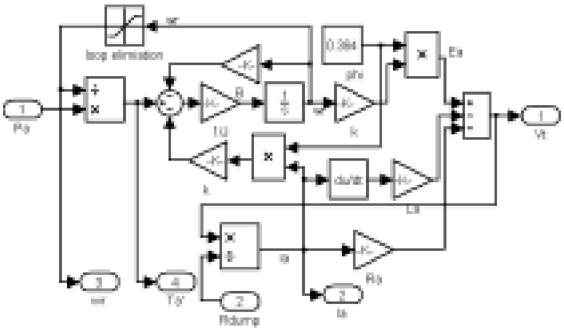
(b) Wind field subsystem



(c) Rotor dynamics subsystem



(d) Controller subsystem



(e) PM dc subsystem .

Figure 6. Simulink blocks