Study on Control for Small Wind Turbine System

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Abstract – **Nowadays, there are many methods used to control wind turbine system in order to get the maximum energy extracted and maintain rated output power. However, the methods are used must meet the requirement to ensure stability and optimal performance. This technical paper presents the study on control for small wind turbine system. In this paper, a control algorithm employs direct torque sensing, and it adjusts rotor speed by changing the dump load resistance using single fuzzy logic controller. Changes in the dump load vary the armature current, as well as the armature torque, which sets the rotor speed towards the desired level. The fuzzy relations between the variables and the fuzzy rules were stated in detail. A dynamics of 5kW small wind turbine using the permanent magnet DC generator is modelled and wind data generation with flexible wind field model is included. Simplified models representing rotor aerodynamics are used. The scheme is simulated in Matlab Simulink and results are presented.**

Keywords-component; Small wind turbine; Dynamic modelling; Fuzzy controller; Matlab Simulink

I. INTRODUCTION

Wind power is the conversion of wind energy into more useful forms, such as electricity, using wind turbines. Most modern wind power is generated in the form of electricity by converting the rotation of turbine blades into electrical current by means of an electrical generator [1].

Wind technologies have been developing rapidly over the last few decades, as it is renewable, cost-effective and also cause little harm to the nature with respect to other conventional energy. One of the most important tasks of a control strategy for wind turbines is to limit the power input to the turbine to a level that the mechanical and electrical components of the turbine are able to handle. This must be achieved by reducing the power extracted from the wind. Large wind turbines are complex in operation, deploy multitude of control methods and operate in grid-connected mode. On the other hand, small wind turbines can be used for stand-alone as well as grid-connected system [2].

There are many way configuration systems to control wind turbine that has been used in several wind turbines today such as an aerodynamic power control, fixed-speed system control and variable-speed system control [3]. Wind turbine generators used all over the world today are mostly operated with constant speed operation. This is mainly due to their simplicity in order of connection to the utility grid with no need of frequency conversion. However, constant speed operation implies that the mechanical structure of the turbine has to be strong as it is exposed to high loadings. Recently though, variable speed operation has gained interest, especially owing to their possibilities to lower stresses on the mechanical parts of the turbine [4].

Control of a wind turbine is very complex since the energy input that comes from the wind is highly fluctuating. These fluctuations will also introduce variations in the produced electric power which causes a negative power quality impact. By using rotor speed control these disturbance can be reduced and thereby also the loadings on the mechanical system [4]. In this paper will discuss and study about controlling the small wind turbine. Various dynamic aspects of a 5 kW prototype wind turbine using permanent magnet DC motor is modelled and simulated. For control this system, rotor speed control method is used and single fuzzy controller is employed in order to get maximum power extracted and maintain output power.

A. 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. 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 [6]. Figure 1 shows the block diagram for small wind turbine system that consist of permanent magnet DC generator, rotor and blade, controller and dump load.

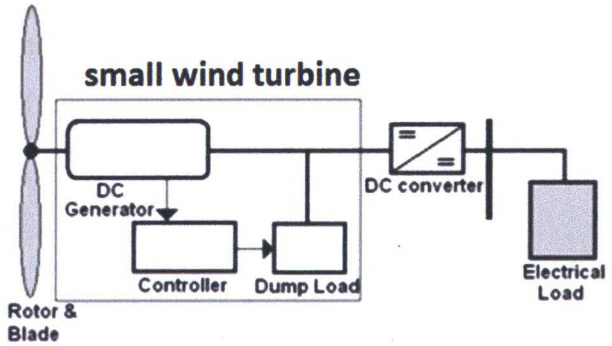

Figure 1: Small wind turbine block diagram

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 [6]. In this paper, a 5 kW prototype wind turbine having similar design parameters Eoltec's Scirocco E5.5-5 is considered for modelling and simulation. Typical parameters attributed to such a unit are listed in Table 1[7].

The turbine is considered to be two-bladed with 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 [6].

TABLE I. TABLE OF WIND TURBINE RATING

Symbol	Parameter	Value	Unit
P_r	Rated power	5000	(W)
P_{max}	Max. power	5200	(W)
R	Rotor radius	2.75	(m)
ω_{ro}	Rated rotor speed	25	(rad/s)
$V_{cut\ in}$	Cut-in wind speed	4	(m/s)
V_{rated}	Rated wind speed	12	(m/s)
$V_{cut\ out}$	Cut out wind speed	22	(m/s)
V_{sur}	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)

II. SCOPE OF STUDY

Several scope of works involved in this project as follows:

- Study the concept and control strategy of small wind energy conversion system.
- Learn fuzzy techniques for control the system.
- Learn to use Matlab Simulink software in order to develop the design of the project.
- Run the simulation and observed the results.
- Detected any problems and overcome it.
- Analysed the result and make discussion.

III. METHODOLOGY

A. Dynamic modelling of small wind turbine

(i) Wind Field

The models of wind speed variation are based on white noise, filtered by various wind models that act as band-pass filters within a range of $2x10^{-5}$ - 10 Hz to cause a notch in the power spectrum [5]. A stochastic wind pattern 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, $m_{wind}(t)$ is given below [6]:

$$\frac{dV_{turb}}{dt} = \frac{1}{T_v} V_{turb} + m_{wind}(t) \tag{1}$$

$$V_{wind} = V_{turb} + V_{avg} \tag{2}$$

$$T_v = \frac{10.5z}{V_o} \tag{3}$$

where T_v(s) is time constant, V_o(m/s) is median wind speed and z (m) is turbine hub height.

The addition of average wind, V_{avg}, to V_{turb} yields a more realistic wind pattern.

(ii) Rotor Aerodynamics

Measured wind at a point using an anemometer is different from what the whole rotor plane sees. A point wind data is essentially averaged over the swept area, which acts as a low-pass filter. This effect is commonly known as spatial filtering and can be formulated [5,6]:

$$\frac{V_{filt}}{V_{wind}} = \frac{\sqrt{2} + \beta sS}{(\sqrt{2} + \sqrt{\alpha}(\beta sS))(1 + \frac{\beta_s}{\sqrt{\alpha}}S)} \; ; \beta_s = \gamma \frac{R_{wt}}{V_{ws}} \tag{4}$$

In equation (4), the nominal parameters have empirical values of α= 0.55 and the decay factor over the disc, γ = 1.3. R_{wt}(m) is the turbine radius and V_{ws}(m/s) is the average wind speed at the hub height.

Another aerodynamic phenomenon, namely, the induction lag becomes dominant when the blades react to a sudden change in wind speed and hence to a changing angle of attack. As a result, the rotor experiences a wind speed, V_{eff}, which is different from the incident wind and is represented by a lag filter transfer function [5]:

$$\frac{V_{eff}}{V_{field}} = \frac{a_i s + \frac{1}{\tau_i}}{s + \frac{1}{\tau_i}} \tag{5}$$

where the time constant,$\tau_i = 9$ seconds and the empirical parameter identification for a_i = 1.37.

In smaller turbines effects of aerodynamic factors are less significant compared to the larger ones. The generated power is dependent on the effective wind speed, V_{eff}, and can be estimated by the turbine's power curve. This method simplifies the modeling without affecting the observations significantly.

(iii) Permanent Magnet DC Generator

A set of classical DC machine equations is considered here to represent the rectifier-coupled permanent magnet alternator, typical to direct drive small turbines. A 5 KW, 220V PM dc generator is considered for simplicity with regard to these equations [6]:

$$T_l = k\emptyset I_a \tag{6}$$

$$T_a = T_l + J\frac{d\omega_r}{dt} + B\omega_r \tag{7}$$

$$E_a = k\omega_r\emptyset \tag{8}$$

$$V_t = E_a - L_a\frac{dI_a}{dt} - R_a I_a \tag{9}$$

The drive train is directly coupled and lumped values of inertia and friction are considered.

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 as shown as Figure 2 could be used [6].

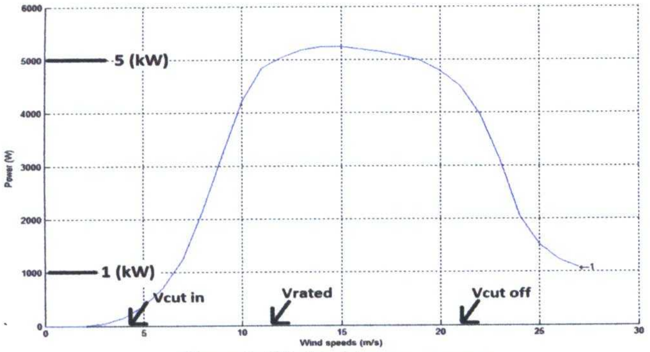

Figure 2: Wind turbine power curve

B. Control Strategy of the Wind System

According to the wind condition, the running of variable speed wind turbine generator system can be divided into three stages:

(i) Below rated wind speed, (V_{rated}) the control goal is to extract maximum available power by controlling the rotation speed of the rotor.

(ii) When the wind exceeds cut-off limit ($V_{cut\,off}$), decrease of rotor's speed is necessary in order to prevent excessive stress on the machine parts.

(iii) At intermediated wind speeds, ($V_{rated} \leq V_{wind} \leq V_{cut\,off}$), the controller should maintain constant rated power, P_{rated} at the output.

A single 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. Figure 3 show the block diagram to control the system [6].

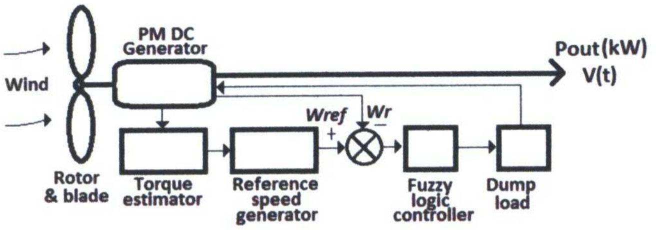

Figure 3: Block diagram of system controller

C. Desired Speed Estimation

The algorithm for determining reference rotor speed from an estimated/measured rotor torque could be established from the wind turbine aerodynamic behaviour, the turbine catches only a part of the kinetic energy contained in the wind. The maximum extractable power from wind is limited by the Betz coefficient, C_{pb} (eq. 10). In fact, C_p is much lower than the theoretical value (eq. 11) [6].

$$P_{wind} = C_{pb}\frac{1}{2}\rho(\pi R^2){V_{eff}}^3 \tag{10}$$

$$P_a = C_p\frac{1}{2}\rho(\pi R^2){V_{eff}}^3 \tag{11}$$

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 as shown as equation below [6].

$$T_a = \frac{P_a}{\omega_r}\ ;\ \lambda = \frac{\omega_r R}{V_{eff}}\ ;\ C_p = C_t\lambda \tag{12}$$

From (11) and (12), rotor torque could be express as the following equation:

$$T_a = C_p\frac{1}{2}\rho(\pi R^5)\frac{1}{\lambda^3}{\omega_r}^2 \tag{13}$$

Assuming the estimated torque, T_a' to be same as actual rotor torque, T_a, three regions of operation could be identified:

(i) Below rated wind speed ($T_a' < T_r$)

At below rated wind speed, the desired aim is to extract maximum available power. This is possible when the C_p and λ have optimum value. Therefore, from (13) yields:

$$T_a' = C_{po}\frac{1}{2}\rho(\pi R^5)\frac{1}{{\lambda_o}^3}\ {\omega_r}^2 = K_t{\omega_{ref}}^2 \tag{14}$$

where $$K_t = \frac{\rho}{2}\pi R^5 C_{po}\frac{1}{{\lambda_o}^3}\ ;\ K_w = \frac{1}{\sqrt{K_t}} \tag{15}$$

then below wind speed rated, reference rotor speed:

$$\omega_{ref} = \sqrt{\frac{T_a'}{K_t}} = K_w\sqrt{T_a'} \tag{16}$$

(ii) At intermediated wind speeds ($T_r \leq T_a' < T_{max}$)

The desired rotor speed is considered to be the rated speed as shown as Figure 4. Hence, reference rotor speed at intermediated wind speeds is:

$$\omega_{ref} = \omega_{ro} \tag{17}$$

(iii) When the wind exceeds cut-off limit ($T_a' \geq T_{max}$)

When the wind speed increases beyond the cut-off ratings and the rotor torque reaches the maximum allowable torque, the reference rotor speed is dependent on rated maximum power and rotor torque. Thus, reference rotor speed:

$$\omega_{ref} = \frac{P_{max}}{T_a'} \tag{18}$$

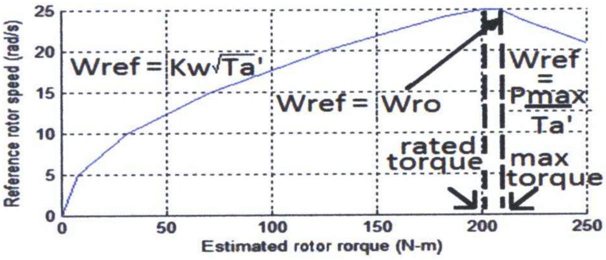

Figure 4: Reference rotor speed

D. Fuzzy Controller for Small Wind Turbine

1) Introduction of Fuzzy Logic Control

Fuzzy controller is mainly used in nonlinear system which cannot be accurately modelled and has more inputs, uncertain factors and inaccurate properties. However, an understanding of the system and the control requirements is necessary. The fuzzy controller designer must define what information or data flows into the system (input variable), how the information is processed (control strategy and decision), and what information flows out of the system (solution or output variable) [9].

The fuzzy controller includes four parts: fuzzification, fuzzy rule base, reasoning and defuzzification [8]. Figure 5 shows the block diagram of fuzzy controller.

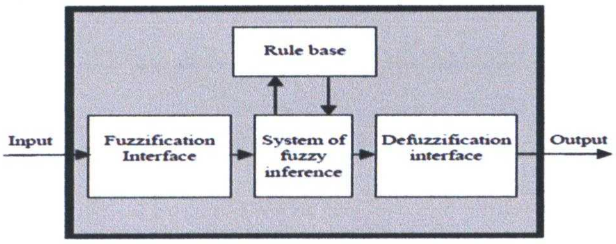

Figure 5: Block diagram of fuzzy controller

2) The Choice of Linguistic Variable and Determination of Membership Function

Fuzzy controller has two inputs and one output. The input variable is speed error, *e*(*t*) (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. Speed error, *e*(*t*) includes {Negative Big, Negative Small, Zero, Positive Small, Positive Big} five fuzzy gaussian subsets, using language variables, which can be expressed as {NB, NS, Z, PS, PB}, the domain is -10 to 10 as shown as Figure 6. Rate of change in error, *de*/*dt* includes {Negative Big, Negative Middle, Negative Small, Zero, Positive Small, Positive Middle, Positive Big} seven fuzzy gaussian subsets, using language variables, which can be expressed as {NB, NM, NS, Z, PS, PM, PB}, the domain is -200 to 200 as shown as Figure 7. Dump load, R_{dump}, includes {Very Low, Low Mid, Low, Middle, High, High Middle, Very High} seven fuzzy gaussian subsets, using language variables, which can be expressed as {VL, LM, L, M, H, HM, VH}, the domain is 4 to 15 as shown as Figure 8.

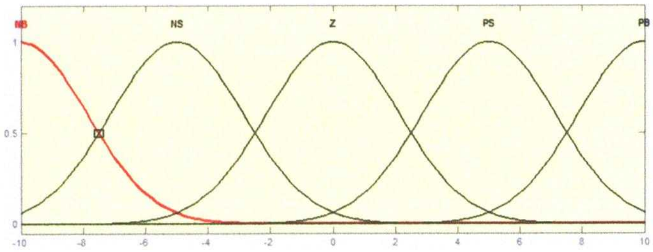

Figure 6: Membership function input (speed error)

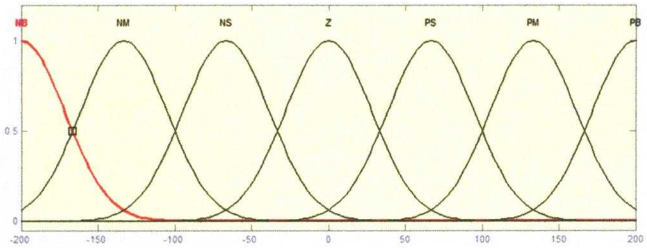

Figure 7: Membership function input (rate of change in speed error)

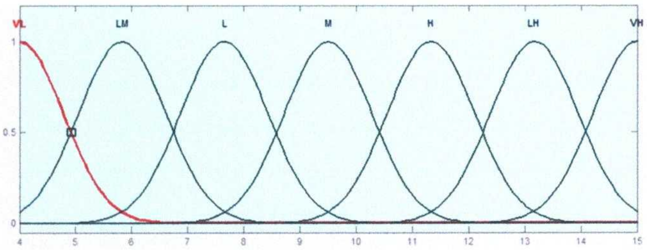

Figure 8: Membership function of output (dump load)

3) The Determination of Fuzzy Rules, Reasoning and Defuzzification

Fuzzy control rules come from the comparing with the actual rotor speed and the error signal [6].

$$e(t) = \omega_{ref} - \omega_r \tag{19}$$

$$\frac{de(t)}{dt} = \mathrm{Lt}_{\Delta t \to 0} \frac{e(t)-e(t-1)}{\Delta t} \tag{20}$$

When the error is big, the controlling variable (dump load), should be chosen to remove the error. When the error is small, the controlling variable (dump load), should be chosen to prevent the overshoot and maintain the stability of the system. The rules uses in this paper are expressed as a collection of 'IF – THEN' statements [9]. There are 35 sentences. The table of control rules is shown in Table 2.

TABLE II. TABLE OF FUZZY CONTROLLER RULE BASE

de(t)/dt e(t)	**NB**	**NM**	**NS**	**Z**	**PS**	**PM**	**PB**
NB	VL	VL	VL	LM	L	M	M
NS	VL	LM	LM	L	M	M	H
Z	L	L	M	M	M	H	H
PS	L	M	M	H	LH	LH	VH
PB	M	M	H	LH	VH	VH	VH

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

The defuzzification process converts the results of fuzzy inference into numerical values. The centroid method (Mamdani method) of defuzzification is employed [6]. Figure 9 shows fuzzy rule surface view in three dimensional.

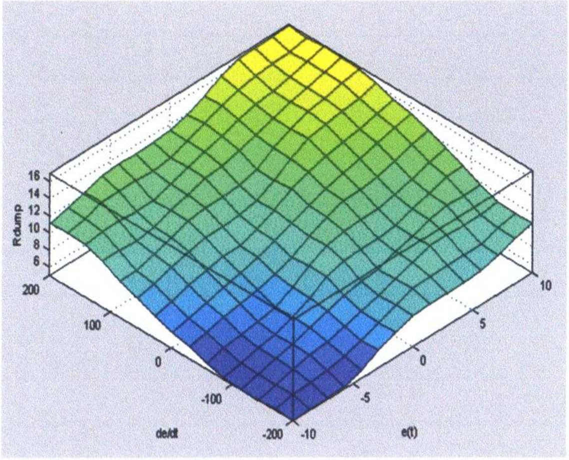

Figure 9: Fuzzy rule surface view

E. Flow Chart for the Simulation.

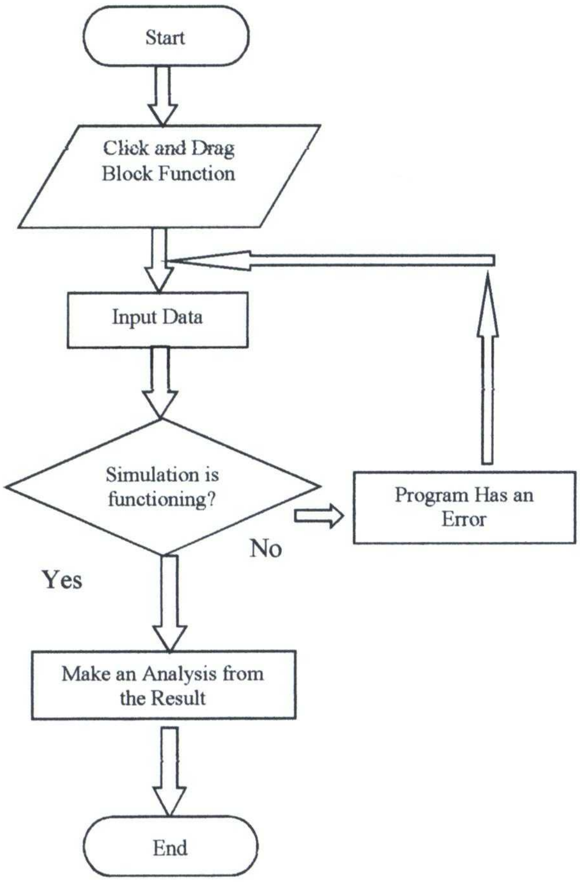

Figure 10: Flow Chart for the Simulation

IV. RESULT AND DISCUSSION

Figure 11 show the simulator of small wind turbine system. Several block diagrams involved when making this simulator such as Band-Limited White Noise, Integrator, Gain, Scope, Sum, Constant, Lookup Table, Saturation, Fuzzy Logic and etc.

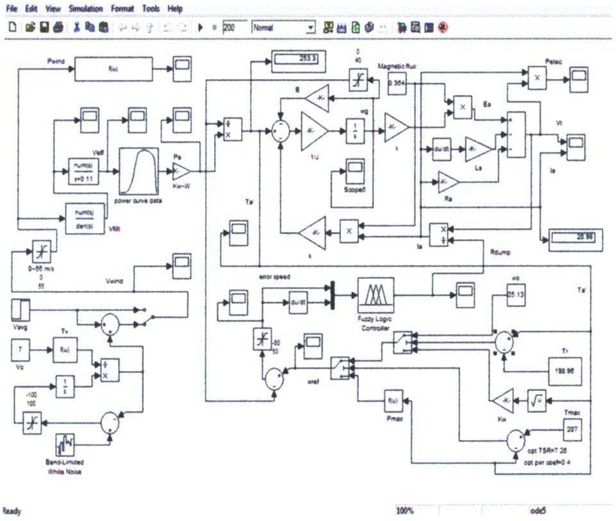

Figure 11: Simulator of Small Wind Turbine

Before running this simulator, the initial setting for the several parameters is set. Table 3 shows the parameter that used in this simulation [6].

TABLE III. TABLE OF INITIAL VALUE FOR WIND TURBINE

Symbol	Parameter	Value	Unit
z	Turbine hub height	15	(m)
V_o	Median wind speed	7	(m/s)
k	Generator constant	25.82	-
∅	Magnetic flux	0.364	(V/rad/s)
B	Damping constant	0.005	(Nm/rad/s)
J	Moment of inertia	1.75	(Kg-m2)
L_a	Armature inductance	15	(mH)
R_a	**Armature resistance**	1.525	**(Ohms)**
T_r	Rated rotor torque	200	(N-m)
T_{max}	Max. rotor torque	208	(N-m)
C_{pb}	Betz coefficient	0.5926	-
ρ	Air density	1.22	(Kg/m3)
K_t	Controller parameter	0.315	-
K_w	Controller parameter	1.782	-

A. Simulation Result

Matlab Simulink is used for simulating the models. After complete running simulation for small wind turbine system, all data are captured. Below is the graph show the results after simulation.

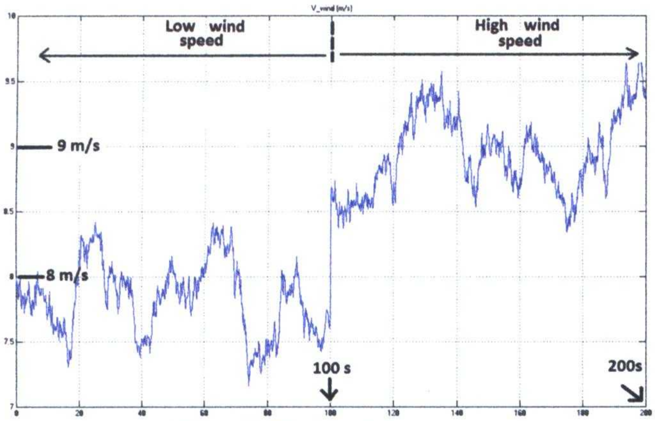

Figure 12: Wind speed, V_{wind} (m/s)

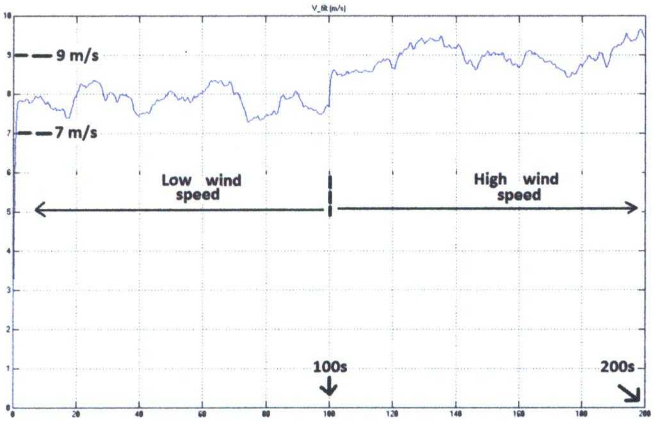

Figure 13: Wind speed filter, V_{filt} (m/s)

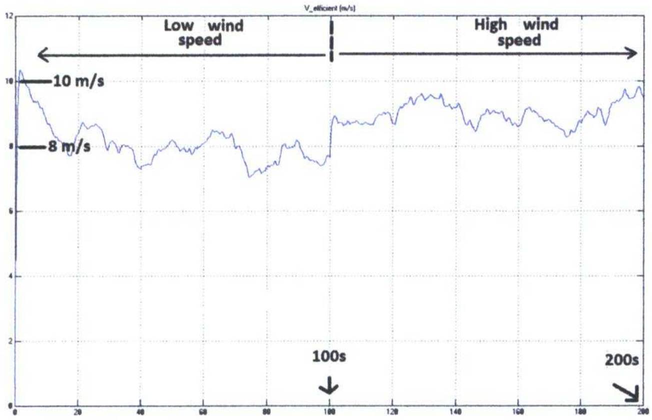

Figure 14: Wind speed efficient, V_{eff} (m/s)

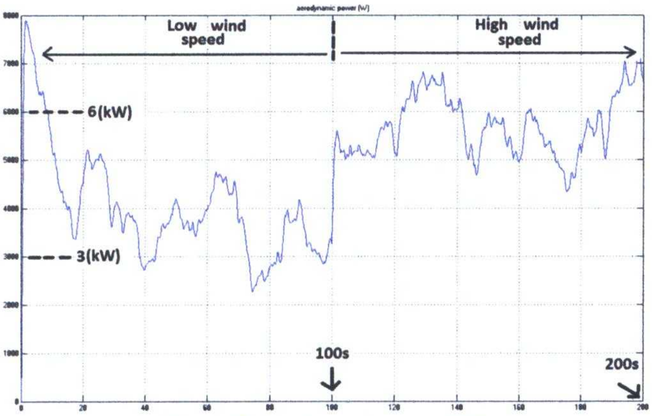

Figure 15: Aerodynamic power (kW)

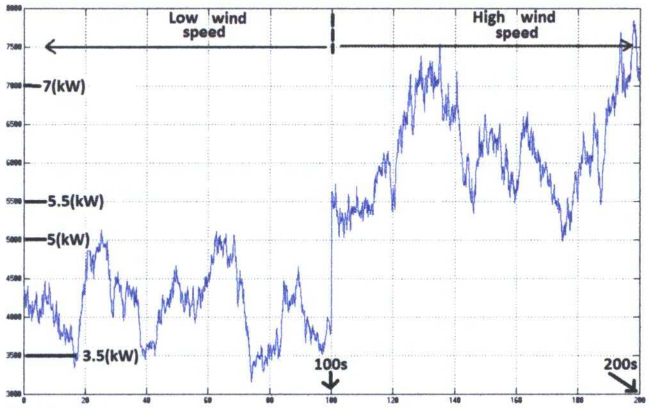

Figure 16: Power wind , P_{wind} (kW)

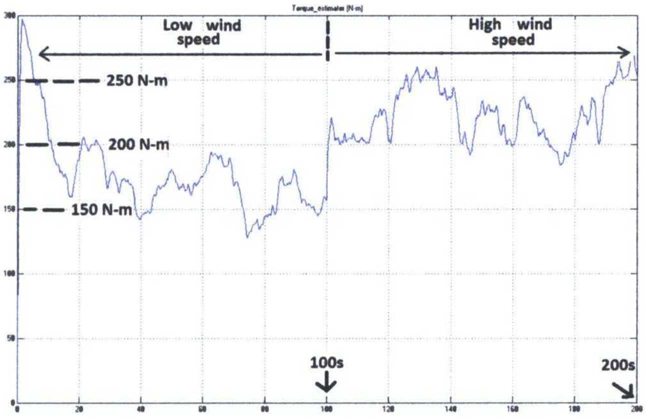

Figure 17: Torque estimator (N-m)

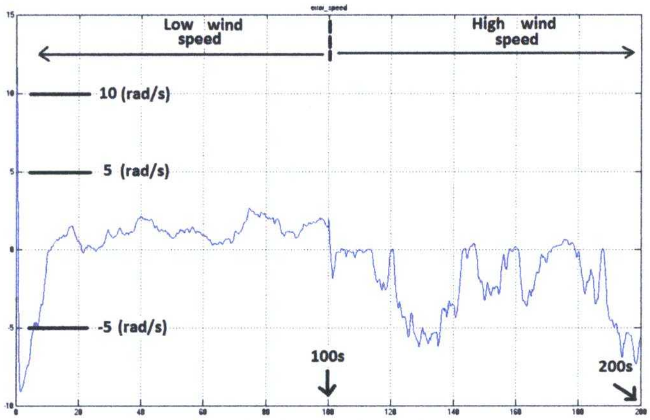

Figure 18: Rotor speed error (rad/s)

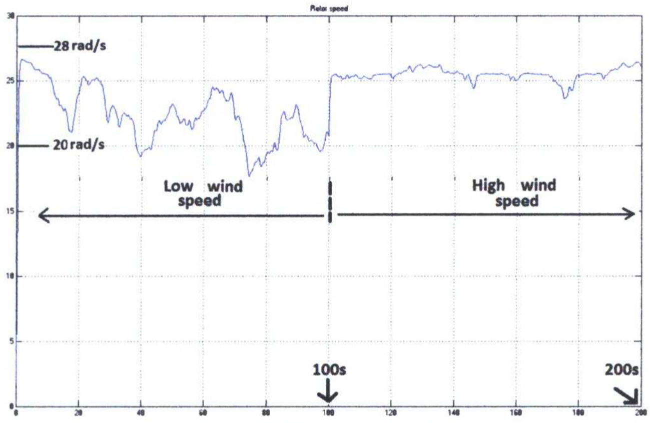

Figure 19: Rotor speed (rad/s)

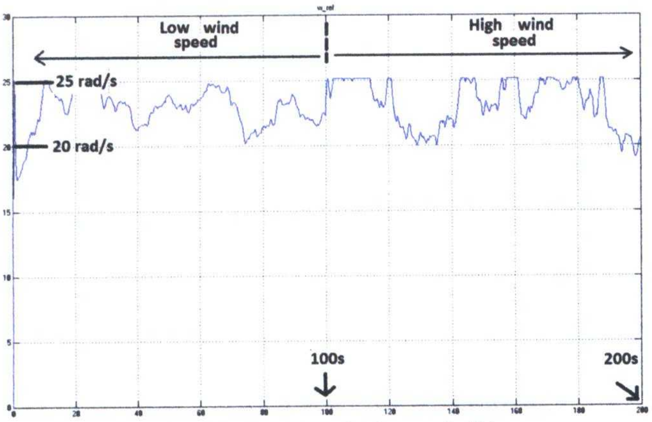

Figure 20: Rotor speed reference (rad/s)

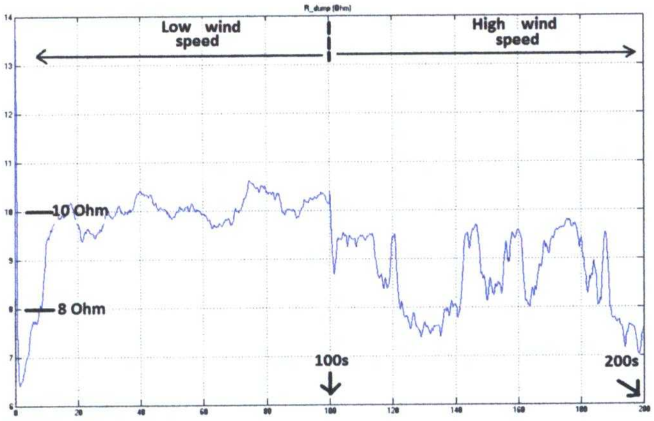

Figure 21: Dump load, R_{dump} (Ohm)

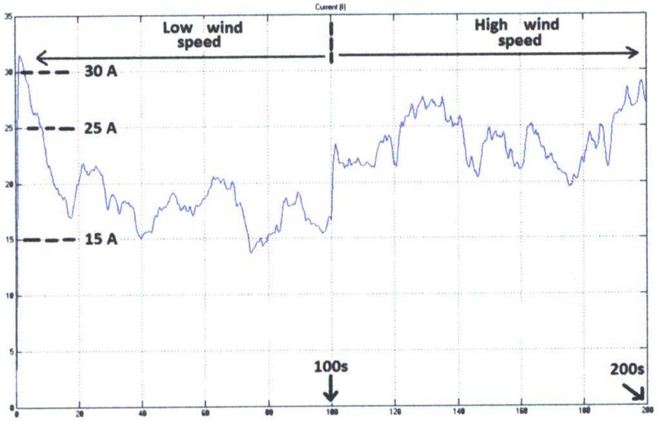

Figure 22: Current (A)

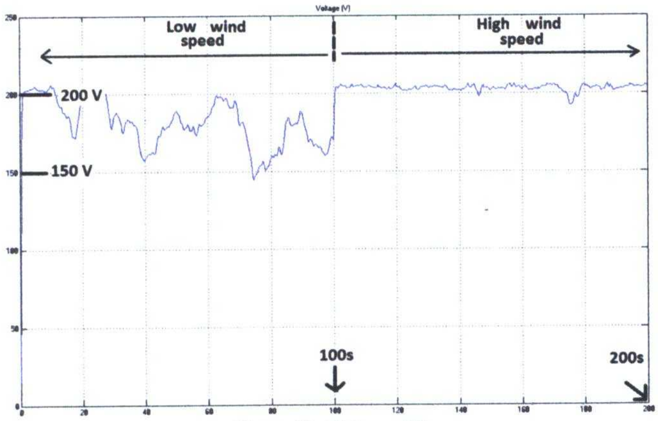

Figure 23: Voltage (V)

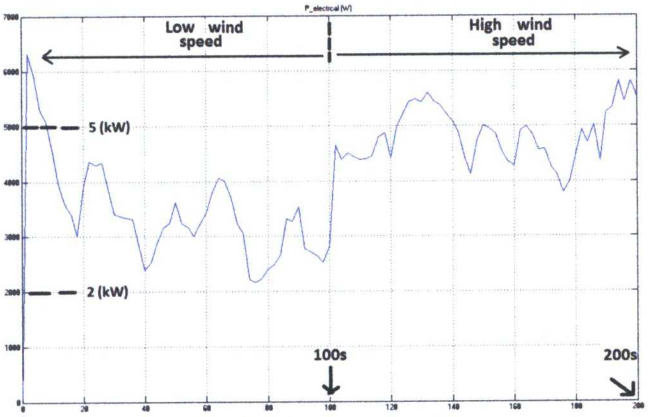

Figure 24: Power electrical (kW)

For this project, the time for running the simulation is set to 200 second. Input to the model is an average wind speed, having a step change at t=100s (8 to 9m/s). From 0s to 100s shows that the wind in low speed while above 100 second show the wind in high speed. Referring to the input wind field (Appendix 1), a wind speed pattern as shown as Figure 12 is generated by the wind field model (1) adds turbulent components to the average value of wind speed. Then, the wind variations experienced by the rotor surface are converted from point to surface data by the spatial filter (4) in rotor aerodynamics (Appendix 1). It acts as a low pass filter and removes some of the higher harmonics in the winds as shown as Figure 13. But, there is not much difference between the filtered and the effective wind that shows in Figure 14. This implies that induction lag model (3) is not of much significance owing to the fact that, small turbines are fairly fast in responding to sudden wind speed change [6]. Figure 15 shows the aerodynamic power that produced using typical set of power curve data (2) after through spatial filter and the induction lag in rotor aerodynamics. Figure 16 shows the maximum extractable power in wind, P_{wind}, that is limited by the Betz coefficient, C_{pb}.

Figure 17 shows estimated rotor torque,T_a' that assume same as actual rotor torque, T_a, referring in model permanent magnet dc generator (Appendix 1). Figure 18 shows the rotor speed error between rotor speed,ω_r, and rotor speed reference, ω_{ref}. The graph shows that the error with when wind speeds ranging from 7 to 8.5 m/s (t=0 to 100s), the speed error is below 5 rad/s and magnitude of the dump load is between 9 to 11 ohms. The result for rotor speed,ω_r, and rotor speed reference, ω_{ref}, are show in Figures 19 and 20.

Figure 21 shows the dump load, R_{dump}, in all condition of wind speed. At low wind speed condition, the fuzzy logic controller is tried to increase the magnitude of dump load resistance in order to decrease the armature current which also vary the decreasing armature torque to produce optimum energy. It can be seen that in the high wind also the fuzzy logic controller decrease the magnitude of dump load resistance in order to increase the armature current which also vary the increasing armature torque to maintain output power and prevent it from rotor over speed which cause the damage for components. Figure 22 shows the armature current, I_a, which at beginning (low wind speed), the turbine produce in range of 15A to 23A and at higher wind speed, it produce in range of 20A to 28A.

Figure 23 shows the small wind turbine generates rated voltage 220 V (±15) at rated wind speed. From the graph also show the voltage produce at below rated wind speed in range 150V to 200V. In Figure 24 shows the output power that produced in range from 2kW to 4kW at below wind rated. At higher and rated wind speed, the turbine generates 4kW to 6kW output power. It shows that the output power produced depends on wind speed level.

During simulation with Matlab Simulink, problems with algebraic loops and extreme numerical values were experienced with almost all variable step solvers [6]. By changing the value in parameter block could give the different output desired (shape of graph).

In this simulation also, the 'fixed-step: ODE5 (Dormand Prince)' method are used in avoiding those problems without deviating significantly from the expected results. From this simulation also, there is still disturbance occur in the output power, ($P_{electrical}$). However, it could give the good performance in order to control the system by a single fuzzy controller.

V. CONCLUSION

After doing simulation using Matlab Simulink, it can conclude that the results from the graph show that the single fuzzy logic controller can be used to control full range wind speed. Besides that, gain the knowledge of control strategy and operation of the small wind turbine. Understand the process of simulation by using Matlab Simulink from the creating process until running the simulation and get the result from the simulation. By the used of the mathematical model, it will assist in the understanding of dynamic modelling of the small wind turbine system.

VI. FUTURE DEVELOPMENT

For the future development, the small wind turbine system modelled in this paper could be used for the investigation of hybrid applications such as wind-solar or wind-fuel cell systems. It also can be investigated the combination used of power electronic to control the system in order to increase the efficiency and optimal performance.

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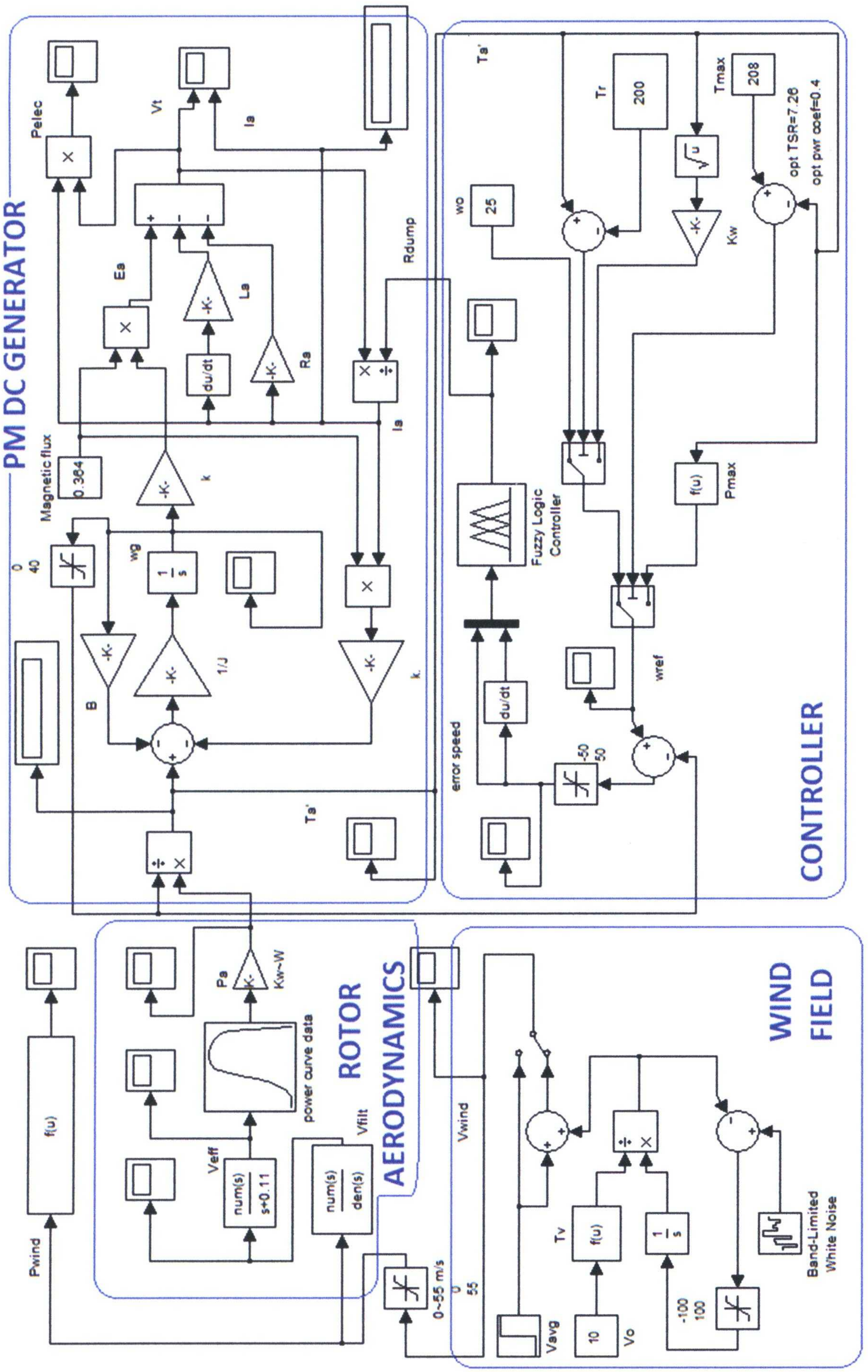
APPENDIX 1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Ea
La
Ra
du/dt
-K-
Pelec
Vt
Ia
Rdump
Is
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wg
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1/J
B
0
40
Ta'
CONTROLLER
Ta'
wo
25
Tr
200
Tmax
208
Kw
opt TSR=7.26
opt pwr coef=0.4
Fuzzy Logic Controller
Pmax
f(u)
error speed
du/dt
-50
50
wref
ROTOR AERODYNAMICS
Pa
Kw~W
power curve data
Veff
num(s)
s+0.11
Vfilt
num(s)
den(s)
Pwind
f(u)
0~55 m/s
0
55
WIND FIELD
Vwind
Tv
f(u)
1/s
Vavg
10
Vo
-100
100
Band-Limited White Noise