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Adaptive Control of Variable Speed Wind Turbines

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Abstract – *This paper discusses the development of an adaptive feedback linearisation controller for a variable speed wind turbine. The controller provides an adaptive estimate of the turbine shaft torque. A feedback linearisation controller utilises the torque estimate to provide a torque reference for a field oriented squirrel cage induction machine. The induction machine is connected through a gearbox to the turbine shaft. The feedback linearisation controller ensures that a linear relationship is maintained between the turbine speed and an additional user defined input. The additional input is designed using linear control theory to provide stable error dynamics and speed tracking. The speed reference for the controller is a function of the wind speed and is chosen to ensure maximum energy capture from the wind for varying wind conditions. Simulation results demonstrate the effectiveness of such a controller in capturing maximum available energy from the wind.*

Résumé – *Cet article présente le développement d'un contrôleur adaptatif, feedback linéarisation, d'une turbine a vitesse variable d'une Eolienne. Le contrôleur permet une estimation adaptative de l'axe du moment d'inertie. Il utilise la valeur du moment de torsion estime pour définir un moment de torsion de référence pour le champ oriente cage écureuil d'une machine a induction. La machine a induction est connectée a l'axe de la turbine a travers la boite a vitesse. Le contrôleur assure une relation linéaire entre la vitesse de la turbine et un utilisateur additionnel défini a l'entrée. L'entrée additionnel est choisie en utilisant la théorie du contrôle linéaire pour donner une erreur dynamique stable et assure le suivi de la trajectoire de la vitesse. La vitesse de référence pour le contrôleur est une fonction de la vitesse du vent et elle est choisie pour assurer un maximum d'énergie fournie par le vent dans des conditions variables. Les résultats de la simulation démontrent l'efficacité d'un tel contrôleur pour l'enregistrement du maximum d'énergie disponible.*

Keywords: Controller – Adaptive – Feedback linearisation – Variable speed – Wind – Turbine – Shaft Torque – Squirrel cage – Induction machine.

1. INTRODUCTION

There are different wind turbine configurations for extracting energy from the wind including using synchronous or asynchronous machines, stall regulated or pitch regulated systems. The overall result however is the same, varying wind speeds result in power being transferred onto the grid at grid frequency [4]

It has been shown that, for grid connected wind turbines, the efficiency of constant speed systems is less than that of variable speed systems. So despite the extra cost of the power electronics, the life-cycle cost is lower. Many different configurations of variable speed wind turbines have been developed, a configuration presently being examined by many authors is the use of a doubly fed induction generator.

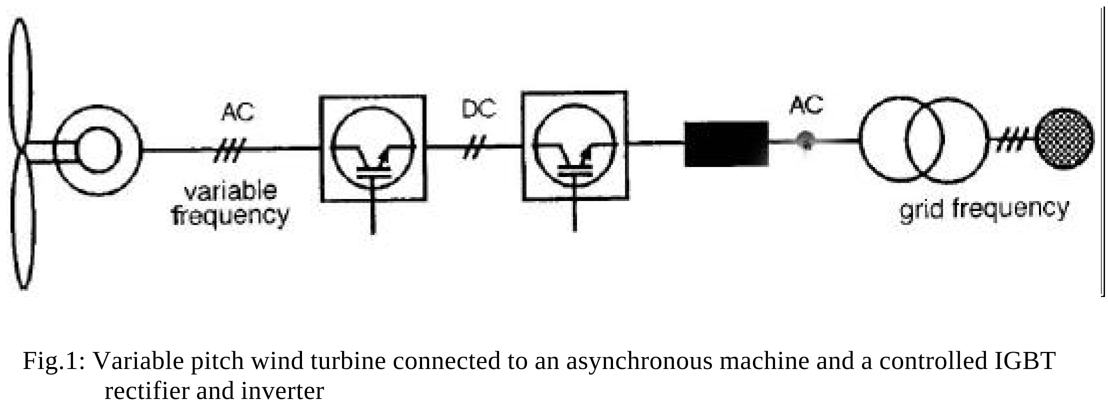

Fig.1: Variable pitch wind turbine connected to an asynchronous machine and a controlled IGBT rectifier and inverter

The scheme being examined here is the use of a variable speed turbine, connected to a squirrel cage induction generator. The generator is not connected directly onto the bus, but instead is coupled through a voltage source converter. The voltage source converter consists of two back to back inverters connected via a DC link. This decoupled set up allows electrical energy at an arbitrary frequency to be supplied to the grid at grid frequency. With this system, maximum energy can be extracted from the wind by varying the speed of the turbine for changing wind conditions. This energy can then be supplied to the grid at grid frequency through the voltage source converter [4].

The Power vs. speed curves of a typical wind turbine are given by the curves in figure 2. If for example the wind velocity is v_1 and the turbine operates at point A for a generator speed of w_1. Then the output power can be raised to the maximum value at point B by increasing the speed to w_2. If the wind speed now changes to v_2, the power output jumps to point C, at this wind velocity maximum power can be extracted by raising the speed to w_3. This shows that as the wind speed changes, the generator speed should track these changes, in order to extract maximum power.

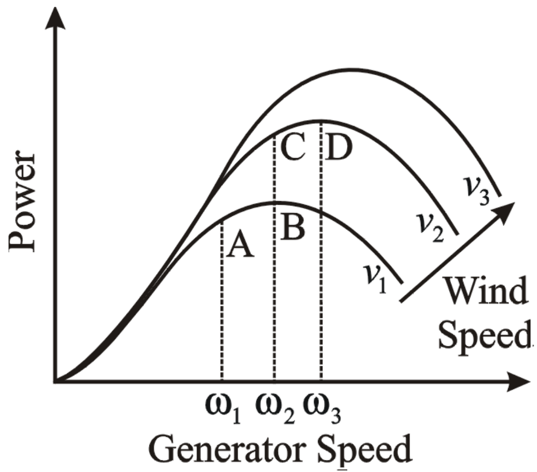

Fig. 2: Turbine power vs. speed

This control function has commonly been performed using PID controllers [8], however because the system is highly nonlinear, the PID controller parameters required for an optimal response change as the set-point changes. A Fuzzy logic controller can overcome this problem by varying its parameters according to the operating point - this approach has been used by many authors [5]. However fuzzy logic controllers do not guarantee an optimal response. An adaptive controller on the other hand estimates the uncertain plant parameters, allowing the controller parameters for an optimal response to be adjusted to account for changing plant dynamics. Thus far only a few applications of adaptive control applied to variable speed wind turbines have appeared in literature [1][7]. Adaptive control algorithms proposed in [1][7] use a doubly fed induction generator to adjust the turbine speed. In [7] a Static Kramer drive lies between the rotor circuit and the grid. Using this configuration the generator torque and hence the turbine speed is changed by adjusting the firing angle of the inverter. A similar scheme was used in [1], where the excitation voltage in the rotor circuit was also adjusted.

This paper develops an adaptive control scheme without the use of a doubly fed induction machine. A less costly squirrel cage induction machine is used in place of the doubly fed machine and the back to back IGBT converters replace the static Kramer drive. In this instance the back to back drives are connected to the stator circuit using the configuration outlined in figure 1.A Lyapunov model reference adaptive control algorithm is developed for this configuration. The adaptation scheme continuously estimates the plant parameters as the wind conditions change.A feedback linearisation method utilises these parameters to cancel the non-linearities in the plant - allowing a controller to be designed using linear control theory. The controller is tested in Simulink, using a detailed simulation of a nonlinear wind turbine. Using this environment the viability of the adaptive controller in controlling maximum energy capture is examined.

2. TURBINE EQUATIONS

The torque at the turbine shaft neglecting losses in the drive-train is given by:

$$T_a = \frac{1}{2} p r C_t(l) R^3 V^2 \tag{1}$$

$$l = \frac{wR}{V} \tag{2}$$

$$C_t = \frac{C_p}{l} \tag{3}$$

where

R is the wind turbine radius,

w is the rotational speed,

l is the ratio of blade tip speed to wind speed.

The maximum theoretical power that can be extracted from the wind wind by reducing its velocity was first discovered by Betz, in 1926 [6]. According to Betz, even if power extraction without losses was possible, only 59 % of the wind power could be extracted by the turbine $\left(C_{pBetz} = 0.59\right)$. For turbines with a low tip speed ratio, when swirl losses are taken into account, this figure can drop to approx 0.42.The value of C_p changes with rotational speed and wind speed, and is given by a nonlinear C_p vs. l curve, specific to each turbine design.

The curve used in this model, shown in figure 4, is an approximation of a C_p vs. curve of a 1.65MW turbine. The maximum C_p value taken from the curve is 0.457, the corresponding l value for maximum power capture is $l_{opt} = 8.08$.

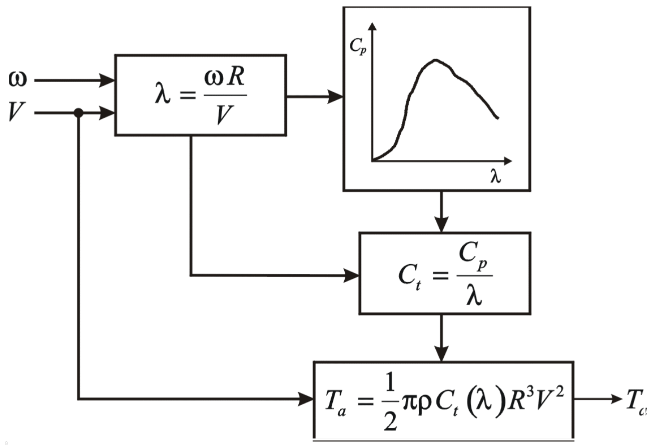

Fig. 3: Turbine equations modelled in Simulink

Using $V = 8m/s$ as an average wind speed at an Irish onshore site, as seen at the turbine face, the following calculation can be made.

With a turbine blade radius of 33m [3], a rotational speed of 18.7rpm results from the expression for tip speed ratio given in equation 2. This corresponds well with the expected rotational speed of a turbine of this rating using an $8m/s$ windspeed [3], and justifies the choice of C_p vs. l curve.

If the optimal relationship between turbine speed and wind speed can be maintained for varying wind speeds, then maximum power capture from the wind can be guaranteed.

$$w = \frac{l_{opt}}{R} V \tag{4}$$

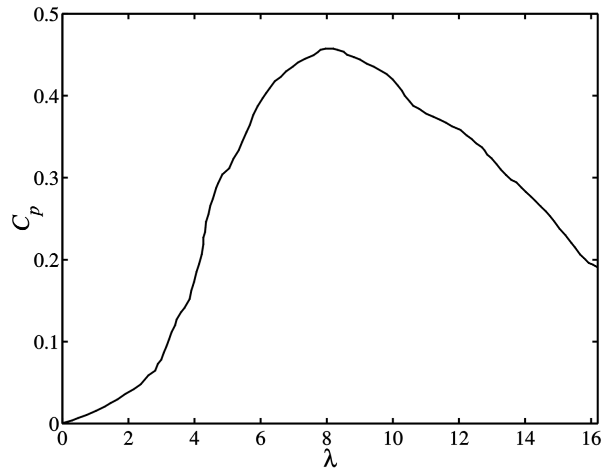

Fig. 4: C_p vs. l data used in lookup table for the turbine model

3. MOTOR EQUATIONS

A model of an induction machine in the dq frame, discarding the zero components, as developed as in [10]

$$\begin{aligned} v_{ds} &= r_s i_{ds} - w\, l_{qs} + \frac{d}{dt} l_{ds} \\ v_{qs} &= r_s i_{qs} + w\, l_{ds} + \frac{d}{dt} l_{qs} \\ v_{dr} &= r_r i_{dr} - (w - w_r) l_{qr} + \frac{d}{dt} l_{dr} \\ v_{qr} &= r_r i_{qr} + (w - w_r) l_{dr} + \frac{d}{dt} l_{qr} \end{aligned} \quad (5)$$

$$T_{em} = \frac{3P}{4}\left(l_{ds} i_{qs} - l_{qs} i_{ds} \right) \quad (6)$$

$$\begin{bmatrix} l_{ds} \\ l_{qs} \\ l_{dr} \\ l_{qr} \end{bmatrix} = \begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix} \quad (7)$$

$$\begin{aligned} L_s &= L_{ls} + L_m \\ L_r &= L_{lr} + L_m \\ L_{lr} &= L_m^2 - L_r L_s \\ w_{sl} &= w - w_r \end{aligned} \quad (8)$$

$$\begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix} = \begin{bmatrix} \frac{L_r R_s}{L_a} & w & -\frac{L_m R_s}{L_a} & 0 \\ -w & \frac{L_r R_s}{L_a} & 0 & -\frac{L_m R_s}{L_a} \\ -\frac{L_m R_r}{L_a} & 0 & \frac{L_s R_r}{L_a} & w - w_r \\ 0 & -\frac{L_m R_r}{L_a} & -w + w_r & \frac{L_s R_r}{L_a} \end{bmatrix} \begin{bmatrix} l_{ds} \\ l_{qs} \\ l_{dr} \\ l_{qr} \end{bmatrix} + \begin{bmatrix} v_{ds} \\ v_{qs} \\ v_{dr} \\ v_{qr} \end{bmatrix} \tag{9}$$

The nonlinear state space equation 9 can be derived from the above equations, this was modelled in Simulink with the output currents and torque derived using equations
7 and 6.

3.1. Field oriented control

$$\begin{bmatrix} v_{ds} \\ v_{qs} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} r_s + pL_b & -wL_b & p\frac{L_m}{L_r} & -w\frac{L_m}{L_r} \\ wL_b & r_s + pL_b & w\frac{L_m}{L_r} & p\frac{L_m}{L_r} \\ -\frac{r_r L_m}{L_r} & 0 & p + \frac{r_r}{L_r} & -w_{sl} \\ 0 & -\frac{r_r L_m}{L_r} & w_{sl} & p + \frac{r_r}{L_r} \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \\ l_{dr} \\ l_{qr} \end{bmatrix} \tag{10}$$

The motor equations can be rewritten as in equation 10, and the torque equation can also be re-written as

$$T_{em} = \frac{3PL_m}{4L_r}\left(i_{qs} l_{dr} - i_{ds} l_{qr}\right) \tag{11}$$

Ideal decoupling control between d and q axes can be achieved by imposing the following conditions.

$$\begin{aligned} l_{dr} &= \frac{d\, l_{dr}}{dt} = 0 \\ l_{qr} &= l_r = \text{constant} \end{aligned} \tag{12}$$

Using this condition on equation 10 above gives

$$w_{\text{sl}} = -\frac{L_m r_r}{L_r l_{qr}} i_{ds} \tag{13}$$

and

$$l_{qr} = \frac{L_m i_{qs}}{\left(1 + \frac{L_r}{r_r} s\right)} \tag{14}$$

and

$$i_{ds} = -\frac{4L_r T_{em}}{3PL_m l_{qr}} \tag{15}$$

Field oriented control has been implemented using Simulink in the manner shown in figure 5.As part of the FOC, current controllers for the i_{ds} and i_{qs} components were also implemented.

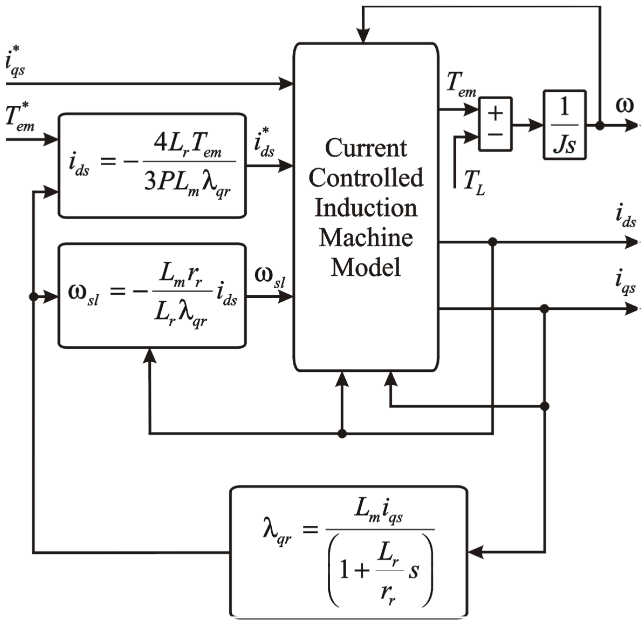

Fig. 5: Field oriented control block diagram

The goal of the input-output linearisation technique is to try to obtain, using state feedback and transformation, a linear relationship between a new input defined as v, and the output of the plant y [6]. This is outlined in figure 6 where the measured disturbance d is also cancelled.

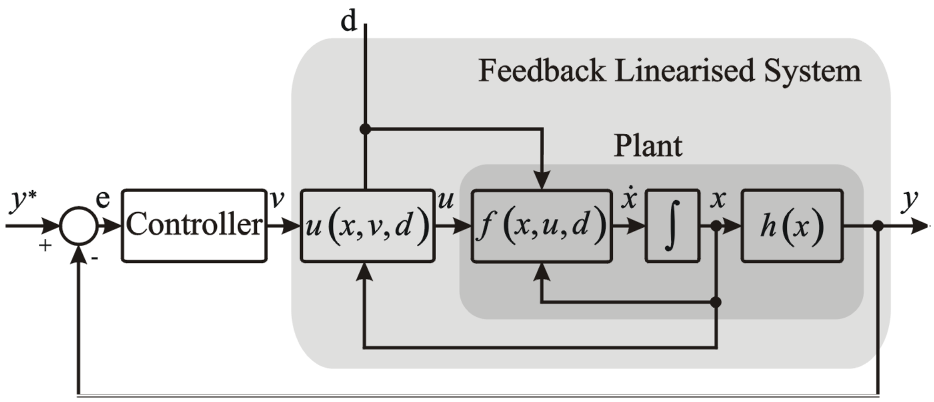

Fig. 6: Feedback linearised system configuration

4. FEEDBACK LINEARISATION

Examining the overall system of the wind turbine model connected through a gearbox to the Field oriented controlled induction machine, the total developed torque at the motor shaft and the motor angular speed are related by.

$$J_r \dot{w}_m = T_t - T_{em} \tag{16}$$

Where J_R is the combined motor and turbine inertia reflected to the motor shaft.

$$J_r = \left(\left(\frac{1}{n}\right)^2 J_T + J_M\right) \tag{17}$$

$$T_t = \frac{T_a}{n} \tag{18}$$

Now if the following relationship is maintained

$$T_{em} = J_R\left(\frac{\hat{T}_t}{J_R} - v\right) \tag{19}$$

Where v is an additional input, and $\hat{T}_t$ is an estimate of the reflected wind turbine torque then

$$\dot{w}_m = \left(\frac{\tilde{T}_t}{J_R} + v\right) \tag{20}$$

If $\tilde{T}_t$ can be made to approach zero using adaptive estimation of T_t then a linear relationship between the output speed and the additional input v results.

$$\dot{w}_m = v \tag{21}$$

The desired motor speed is given by equation 4 and the gearbox ratio n.

$$w_m^* = n\frac{l_{opt}}{R}V \tag{22}$$

$$e = w_m^* - w_m \tag{23}$$

We wish for the closed loop system to have exponentially stable error dynamics given by

$$\dot{e} + ke = 0 \tag{24}$$

This can be achieved by choosing v as

$$v = \dot{w}_m^* + ke \tag{25}$$

where k is a design parameter, in this instance $k = 1$ is chosen to provide error dynamics for the speed controller which decay to zero in approximately $5s$.

4.1. Adaptation law

From [2], if

$$e(t) = H(s)\left[kf^T(t)v(t)\right] \tag{26}$$

where $e(t)$ is a scalar, $H(s)$ is a strictly positive real transfer function, k is an unknown constant with known sign, f is a $m\times1$ vector function of time, and $v(t)$ is a measurable $m\times1$ vector. If f varies according to

$$\dot{f}(t) = -\operatorname{sgn}(k)gev(t) \tag{27}$$

with g being a positive constant, then $e(t)$ and $f(t)$ are globally bounded. If v is bounded then

$$e(t) \to 0 \text{ as } t \to \infty$$

Now from earlier the equation for the error dynamics can be written as

$$\dot{e} = -ke - \frac{1}{J_R}\tilde{T}_t \tag{28}$$

eqns. 26,27 suggest the following adaptation law for T_t.

$$\hat{T}_t = \frac{ge}{J_R} \tag{29}$$

The following block diagram representation of the feedback linearised system results, where g was chosen as 2×10^6.

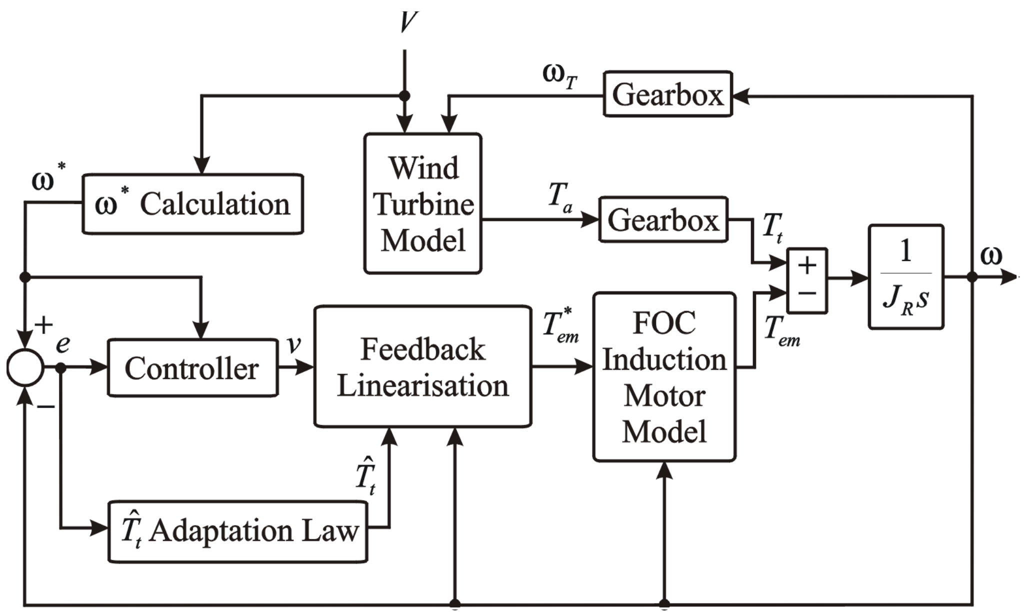

Fig. 7: Configuration of Adaptive Feedback Linearisation Controller

5. SIMULATION RESULTS

The signal shown in figure 8a represents a realistic wind signal [4] and is used as the input to the simulation. The adaptation law chosen in section 4.1 provides a reasonable estimate of the reflected turbine torque, this can be seen be seen in figure 8b. The effectiveness of both the adaptive feedback liberalization technique and the speed controller can be seen in figure 8c where maximum energy capture is ensured for varying wind conditions, the low value of C_p for the first ten seconds was due to the turbine accelerating form standstill to an a rotational speed of approximately 20 rpm for this wind signal.

6. CONCLUSION

This paper describes the development of an adaptive feedback linearisation controller for a variable speed wind turbine. The design incorporates a squirrel cage induction machine in place of the more commonly used and more costly doubly fed induction machine. A field oriented controller for the induction machine was developed, and an adaptation law was chosen to provide an estimate of the uncertain and time varying turbine torque. This signal was needed to linearise the system. A controller was then designed for the linearised system using linear control theory. Simulation results demonstrate the effectiveness of such a controller in ensuring maximum energy capture from the wind.

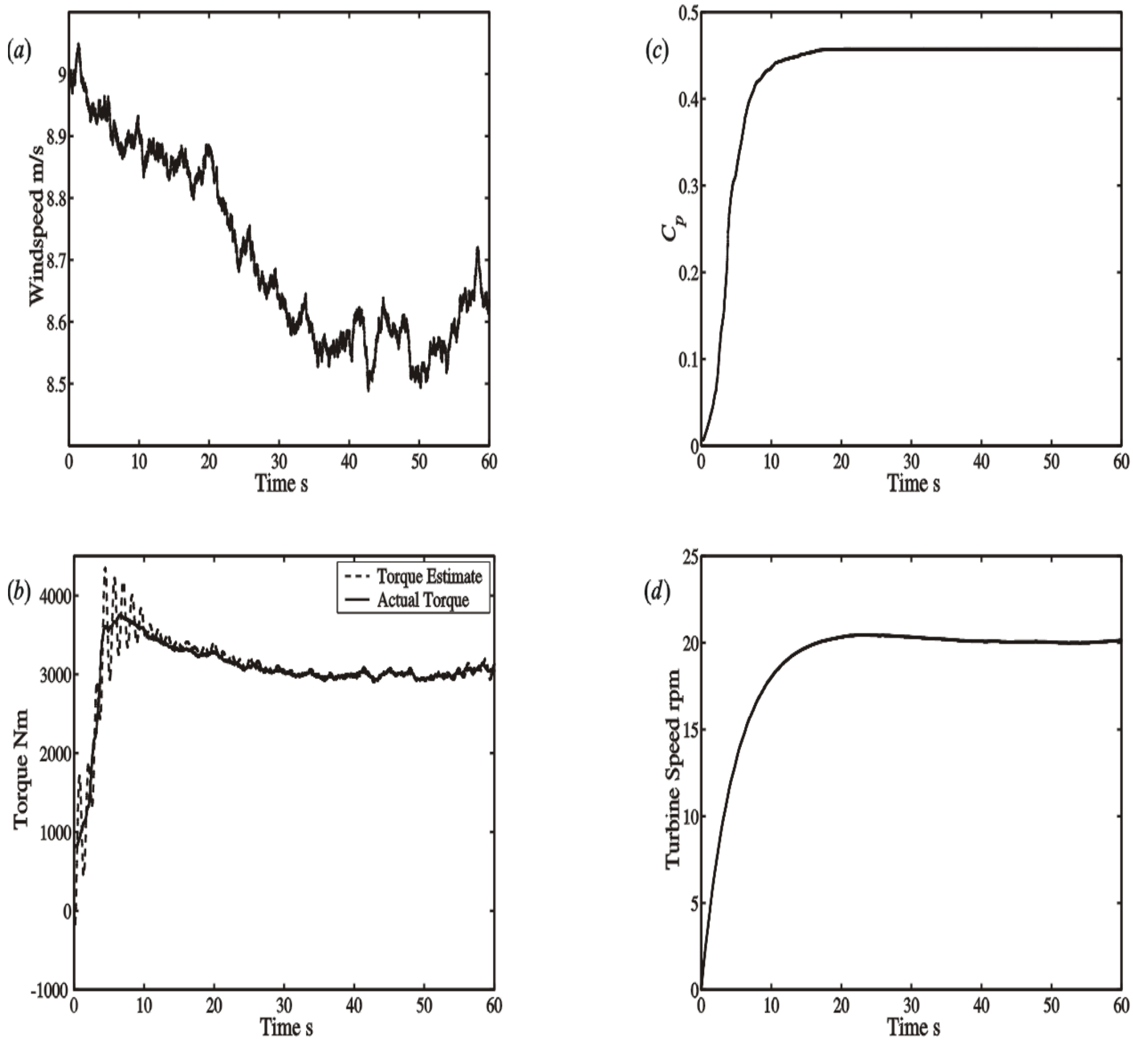

Fig. 8: (a) Wind signal, (b) Torque estimate, (c) Power coefficient, (d) Turbine speed.

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Appendix

$r = 1.25 kg / m^3$

$R = 33m$

$r_s = 0.029\Omega$

$r_r = 0.022\Omega$

$L_s = 0.0422 H$

$L_m = 0.0415H$

$L_r = 0.0422H$

$P = 4$

$J_T = 2.15 \times 10^6 Kgm^2$

$J_M = 63.87 Kgm^2$

$n = 98$