THE UNIVERSITY OF ADELAIDE

School of Electrical and Electronic Engineering

Analysis and Modelling of the Effects of Inertia and Parameter Errors on Wind Turbine Output Power

Chun Tang

A thesis presented for the degree of Master of Engineering Science

2009

Dedicated to my late grandmother, Honghui Xu

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Abstract

Wind energy is an important renewable energy source. The average output power of a wind turbine is one of the main concerns in wind generation systems. The factors which affect the average output power include the location, the wind characteristics, the design of the blades and the control system etc. In this thesis, the effects of the inertia of a wind turbine under dynamic wind speed conditions, and the effects of the parameter errors under steady-state operation on the average output power are examined.

Maximum power point tracking is used to control the generator of a wind turbine in order to maximise the electrical output power of the wind turbine. However, under rapidly changing wind conditions, the output power of the wind turbines is reduced due to their inertia preventing them operating at the optimal turbine speed. Limited research into analysing this power reduction has been performed. Even under steady-state operating conditions, the maximum power coefficient and the optimal tip-speed ratio of the wind turbine generally need to be known for maximum power point tracking. Errors in the estimated parameters will result in an output power reduction for the wind turbine.

Therefore, an understanding of the sensitivity of wind turbine blade parameter errors to the output power reduction under steady-state conditions of wind turbines is also a significant issue.

The first part of the work in this thesis investigates the wind turbine output power reduction due to inertia under dynamic wind speed conditions. It is assumed that the wind turbine blade characteristics is known accurately and that a maximum power point strategy based on controlling the generator input torque as a function of generator speed is used (optimal torque control). The concept of the small-signal turbine time constant is introduced to denote the time constant of the response of a wind turbine for a small change in wind speed under the maximum power point operating conditions. It is shown that the turbine time constant is inversely proportional to the average wind speed, and the natural time constant is defined as the turbine time constant at the rated wind speed. An analytical equation for the small-signal output power reduction of a wind turbine with infinite inertia is then derived as the function of the ratio of the variance to the square of the average wind speed. For the small-signal finite inertia case, a scaling factor is added which is a function of the turbine time constant at the average wind speed and the "equivalent frequency" of the wind speed variations. Real wind speed data is utilised to test the analytical equation against simulation results for the power reduction with both infinite and finite inertia. As the wind speed profiles are not small-signal variations, the analytical results do not accurately predict the actual power reductions. The analytical results however provide useful physical insights into the differences in the power reductions with the different wind speed profiles and turbine inertia. Finally, some limited experimental measurements of the time-constant of a turbine are performed.

The second part of the work in this thesis investigates the effect of wind turbine blade parameter errors on the steady-state output power of a wind turbine. Two types of maximum power point tracking control strategies are investigated: constant tip-speed ratio control and optimal torque control. The analysis is carried out for a particular wind turbine blade characteristic. The steady-state output power reduction with errors in the maximum power coefficient and the optimal tip-speed ratio is shown graphically and compared for the two control strategies.

Statement of Originality

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List of Publications

[P1] C. Tang, M. Pathmanathan, W.L. Soong and N. Ertugrul, “Effects of Inertia on Dynamic Performance of Wind Turbines,” Australasian Universities Power Engineering Conference, AUPEC, Sydney 2008.

[P2] M. Pathmanathan, C. Tang, W.L. Soong, N. Ertugrul, “Comparison of power converters for small-scale wind turbine operation”, Australasian Universities Power Engineering Conference, AUPEC, Sydney 2008.

[P3] M. Pathmanathan, C. Tang, W.L. Soong, N. Ertugrul,, “Detailed investigation of semi-bridge switched-mode rectifier for small-scale wind turbine applications”, IEEE International Conference on Sustainable Energy Technologies, 2008, Singapore, pp. 950-955.

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Symbols

ω	turbine speed in rad/s
η	combined efficiency of the generator and the power electronics
ρ	air density or plastic density
λ	tip-speed ratio
γ	blade pitch angle
τ	turbine time constant
σ	standard deviation of a wind speed variation
β	factor of the finite inertia effect on the power reduction
σ^2	variance of a wind speed variation
$\lambda_{(res)}$	resultant tip-speed ratio
$\lambda_{0(act)}$	actual optimal tip-speed ratio
$\lambda_{0(est)}$	estimated optimal tip-speed ratio

ω_{eq}	equivalent frequency of a real wind speed variation
λ_o	optimal tip-speed ratio
τ_o	natural time constant
ΔP	power reduction
ω_{rated}	rated turbine speed in rad/s
ΔT	acceleration torque
Δv	peak variation of wind speed
A	swept area of blades
C_p	power coefficient of wind turbines
$C_{p(res)}$	resultant power coefficient
C_{p0}	maximum power coefficient
$C_{p0(act)}$	actual maximum power coefficient
$C_{p0(est)}$	estimated maximum power coefficient
C_{pmax}	maximum power coefficient
C_t	torque coefficient
J_g	rotor inertia of the generator
J_t	turbine inertia
k	ratio of the optimal turbine speed to the current wind speed
k_0	ratio of the optimal torque to the square of turbine speed
m_R	mass of the rectangular shape blade
m_{rotor}	mass of the rotor blades
m_T	mass of the triangular shape blade
n	turbine speed in rpm
n_{opt}	optimal turbine speed in rpm
$P_{(res)}$	resultant output power

$P_{0(act)}$	actual maximum output power
$P_{0(est)}$	estimated maximum output power
P_J	output power with finite inertia
$P_{J=\infty}$	output power with infinite inertia
$P_{J=0}$	output power with zero inertia
P_m	mechanical output power
P_{out}	output power of the wind turbine system
P_{rated}	power rating
$P_{reduction}$	power reduction
R	radius of the rotor of a wind turbine
T_g	generator torque
T_{opt}	optimal generator torque
T_{opt}^*	reference of the optimal generator torque
T_{rated}	rated torque of a wind turbine
T_t	turbine torque
v	wind speed
v_{CMC}	cube-root-mean-cube of wind speed
v_m	average wind speed
v_{rated}	rated wind speed

Abbreviations

CTC	constant tip-speed ratio control
MPPT	maximum power point tracking
OSP	over-speed protection
OTC	optimal torque control
PR	power reduction
TI	turbulence intensity
TSR	tip-speed ratio