POWER OPTIMIZATION CONTROL OF SMALL-SIZED WIND TURBINE FOR MALAYSIA WIND CONDITION

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Specially dedicated to

My beloved father and mother,

To my family members and friends

Thanks for all the encouragement and support

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ABSTRACT

This thesis presents 'Power optimization control of a small-sized wind turbine for Malaysia wind condition.' The study involves the small-sized (6kW) Stall-Regulated Variable-Speed Wind-Turbine (SRVSWT) with Squirrel Cage Induction Generator (SCIG) to compete the performance of existing Variable-Pitch Variable-Speed Wind-Turbine (VPVSWT). Nowadays, the VPVSWTs are widely used for modern wind turbines since they can produce better power regulation than the Fixed-Speed Stall-Regulated Wind-Turbine (FSSRWT). However, VPVSWT has some drawbacks such as more complexes and costly, heavier due to the requirements of extra electronic devices and also requires higher maintenance costs. Therefore, in this study, the Linear Quadratic Regulator (LQR) controller is proposed to improve power regulation of the SRVSWT system by maximizing its power generation along the low wind speed conditions (from the 'cut-in' to the 'rated' wind speeds). Using LQR controller, power can be regulated better by controlling the generator torque by controlling the stator and rotor current of the SCIG. Results show that the LQR controller is capable to regulate the maximum power generation in response to the instantaneous wind speed variations. Comparative study has been performed with the classical Proportional and Integral (PI) controller that uses speed loop control method. The comparative results indicate that the proposed LQR controller performs better power tracking performance than PI controller. However, in terms of speed loop tracking performance, the PI controller demonstrates faster speed tracking than the LQR. Too faster response however, would stress the wind turbine generator. Overall, LQR controller performs better power regulation with reasonable speed response through the generator torque control which is feasible to optimise the wind turbine operation suitable for Malaysia wind conditions. Thus, lighter, simpler and cheaper wind turbine can be used not only in Malaysia, but also in locations with low wind velocities.

ABSTRAK

Tesis ini membentangkan ‘Kawalan pengoptimuman kuasa turbin-angin bersaiz-kecil untuk keadaan angin di Malaysia’. Kajian melibatkan Turbin-Angin Bilah-Pegun Kelajuan-Boleh-ubah (SRVSWT) bersaiz kecil (6kW) dengan Penjana Induksi Sangkar Tupai (SCIG) untuk menyaingi prestasi Turbin-Angin Bilah-Boleh- ubah Berkelajuan-Boleh-ubah (VPVSWT) sedia ada. Kini, VPVSWT digunakan secara meluas untuk turbin angin moden kerana mereka boleh menghasilkan pengaturan kuasa lebih baik berbanding Turbin-Angin Kelajuan-Tetap Berbilah- Pegun (FSSRWT). Walau bagaimanapun, VPVSWT mempunyai beberapa kelemahan seperti lebih kompleks dan mahal, lebih berat disebabkan keperluan peranti-peranti elektronik tambahan dan juga memerlukan kos penyelenggaraan yang lebih tinggi. Oleh itu, dalam kajian ini, Pengawal Linear Kuadratik (LQR) dicadangkan untuk memperbaiki pengaturan kuasa sistem SRVSWT dengan memaksimumkan penjanaan kuasa disepanjang keadaan-keadaan kelajuan angin rendah (dari kelajuan angin ‘dipotong’ hingga kelajuan angin ‘dikadar’). Menggunakan pengawal LQR, kuasa boleh diatur dengan lebih baik dengan mengawal tork penjana dengan mengawal arus pemegun dan pemutar SCIG. Keputusan menunjukkan bahawa pengawal LQR mampu mengatur penjanaan kuasa maksimum sebagai tindak balas terhadap kelajuan angin semasa yang berubah-ubah. Kajian perbandingan telah dijalankan dengan pengawal klasik Berkadar dan Kamiran (PI) dengan menggunakan kaedah kawalan gelung kelajuan. Hasil perbandingan menunjukkan pengawal LQR yang dicadangkan melaksanakan prestasi pengesanan kuasa yang lebih baik berbanding pengawal PI. Tetapi, dari segi prestasi pengesanan gelung kelajuan, pengawal PI menunjukkan pengesanan kelajuan yang lebih cepat daripada LQR. Tindak balas terlalu cepat walau bagaimanapun, boleh menegang penjana turbin angin. Secara keseluruhannya, pengawal LQR melaksanakan pengawalan kuasa yang lebih baik dengan tindak balas kelajuan yang munasabah melalui kawalan tork penjana yang boleh dilaksanakan untuk mengoptimumkan operasi turbin angin yang sesuai untuk keadaan-keadaan angin di Malaysia. Maka, turbin angin yang lebih ringan, yang lebih mudah dan lebih murah boleh digunakan bukan sahaja di Malaysia, tetapi juga di lokasi-lokasi dengan halaju angin yang rendah.

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LIST OF SYMBOLS

A	-	Rotor swept area
C_P	-	Power coefficient
$C_{P\max}$	-	Maximum power coefficient
C_Γ	-	Torque coefficient
G_F	-	Shaping filter
d, q -axes	-	Direct and quadrature axes
i	-	Gearbox ratio
i_{ds}, i_{dr}	-	Stator and rotor current for d-axis
i_{qs}, i_{qr}	-	Stator and rotor current for q-axis
I_s, I_r	-	Stator and rotor current
I_m	-	Magnetizing current
J	-	Rotational inertia; Performance index
J_l	-	Rotational inertia rendered at LSS
J_h	-	Rotational inertia rendered at HSS
$k_{\sigma,v}$	-	Slope of regression curve between v_m and σ_v
K_p, K_i	-	Proportional and integral gain
K_{pt}	-	Gain
K	-	State-feedback/optimal gain
L_t	-	Turbulence length
L_s, L_r	-	Stator and rotor inductance
L_m	-	Magnetizing inductance
ω_m	-	Mechanical rotor speed
V_{cut-in}	-	Cut in wind speed

V_{int}	-	Intermediate wind speed
V_{rated}	-	Rated wind speed; Rated terminal voltage
p	-	Number of pole pairs
P_{wind}	-	Power in the available wind speed
P_{aero}	-	Aerodynamic power/power capture
P_a	-	Air gap power
P_{lr}	-	Rotor copper loss
P_g	-	Generated power
Q, R	-	Weighting matrices
R	-	Rotor radius
R_s, R_r	-	Stator and rotor resistance
T	-	Sampling period
T_F	-	Shaping filter's time constant
T_i, T_{pt}	-	Time constant
Γ_g	-	Generator torque
Γ_{mech}	-	Mechanical torque
Γ_{aero}	-	Aerodynamic torque
Γ	-	Beta function
V_{ds}, V_{dr}	-	Stator and rotor voltage for d-axis
V_{qs}, V_{qr}	-	Stator and rotor voltage for q-axis
V_s, V_r	-	Stator and rotor terminal voltage
V_m	-	Magnetizing voltage
X_{ls}, X_{lr}	-	Stator and rotor leakage reactance
X_{Lm}	-	Reactance of magnetizing inductance
λ	-	Tip speed ratio
λ_{opt}	-	Optimum tip speed ratio
β	-	Pitch angle
u, v	-	Wind speed
ρ	-	Air density

ω_r	-	Rotor speed
ω_s	-	Synchronous speed
s	-	Slip
ω_{sl}	-	Slip speed
$\omega_{r\_\max}$	-	Maximum rotor speed
α	-	Incidence angle
v_t	-	Turbulence wind speed
v_m	-	Mean wind speed
σ, σ_v	-	Standard deviation
v_F	-	Amplification factor
v_t'	-	Colored noise
φ_i	-	Phase angle
ω_t	-	Turbine rotor speed
ω_n	-	Natural frequency
ξ	-	Damping factor
$\hat{\psi}_r, \hat{\psi}_m$	-	Rotor and air gap flux
ψ_{dr}, ψ_{qr}	-	Rotor flux for direct and quadrature axes

LIST OF ABBREVIATIONS

ARE	-	Algebraic Riccati Equation
ASD/VSD	-	Adjustable or variable speed drive
AT	-	After retuning
BT	-	Before retuning
C1	-	Case 1
C2	-	Case 2
DC	-	Direct current
EID	-	Equivalent input disturbance
FS	-	Fixed speed
HAWT	-	Horizontal Axis Wind Turbine
HSS	-	High speed shaft
IVC	-	Indirect vector control
LPV	-	Linear parameter varying
LQ	-	Linear quadratic
LQR	-	Linear quadratic regulator
LQG	-	Linear quadratic Gaussian
LSS	-	Low speed shaft
LTR	-	Loop transfer recovery
MPC	-	Model Predictive Control
MPPT	-	Maximum power point tracking
MRAC	-	Model reference adaptive control
OP	-	Operating point
OTR	-	Optimally tracking rotor
PI	-	Proportional Integral
PID	-	Proportional Integral Derivative

PMSG	-	Permanent Magnet Synchronous Generator
SCIG	-	Squirrel Cage Induction Generator
SRFSWT	-	Stall regulated fixed speed wind turbine
SRVSWT	-	Stall regulated variable speed wind turbine
SRWT	-	Stall regulated wind turbine
U.S.	-	United states
VPVSWT	-	Variable Pitch Variable speed wind turbine
VS	-	Variable speed
WECS	-	Wind energy conversion system
WEF	-	Wind energy Foundation
WTG	-	Wind turbine generation

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CHAPTER 1

INTRODUCTION

1.1 Background of study

Recently, the conventional fossil-based resources are continuously depleting. Thus, the implementation of renewable energy as additional generating units is a viable option. Many countries are already implementing renewable energy as their alternative generation. In United States (U.S), they have already provided 36.5% of renewable energy as their new generating capacity between years 2008 and 2012. Moreover, U.S is targeting to increase their renewable energy to more than 55% as theirs additional generation capacity. Among other renewables, wind energy shows a great potential to generate electricity with 42% in expected generation capacity. Thus, this shows that the wind energy conversion is the dominant renewable technology so far. Through technology advancement, the wind turbine size, which is directly correlated to the amount of power produced, becomes larger and larger. The growth in the size of wind turbine is shown in Figure 1.1.

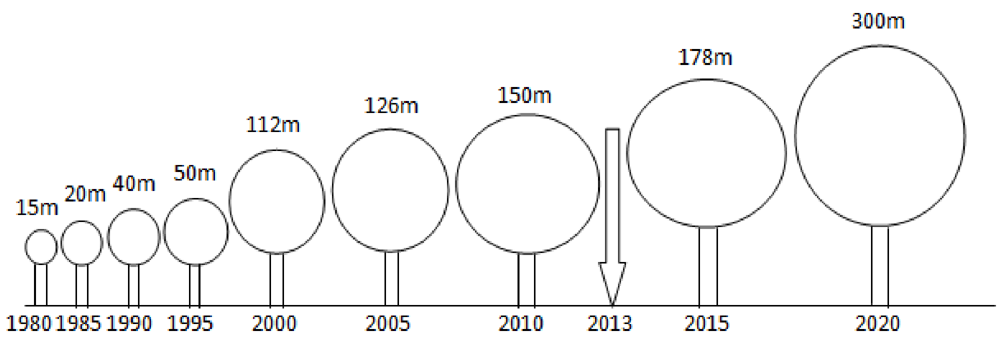

Figure 1.1 Growth in size of wind turbines

The growth in the size of wind turbine follows the times. In early 1980s wind turbines technology is established, where the diameter of the rotor is small and its generation ranged from 20 kW to 30 kW. During that time only a simple fixed-speed stall-regulated wind turbines with basic asynchronous generators were introduced [1]. However, the cost per kW installed of small wind turbine then was more expensive than the large one [2]. Then at mid-to late 1980s, the diameter of the rotor became large and generator ratings were also increased [3]. According to [4], as the rotor diameter increased, the hub height and generator rating also increased. This is due to the higher output can be achieved when a taller tower was used since it can intercept higher velocity winds. Now, the development of wind turbine industries, especially in the developed countries is expanding very fast [5].

Although, the wind turbine generation (WTG) has different capacity sizes, the construction of WTG must also consider finding a location with continuous wind sources albeit with low wind speed. Since Malaysia is located at the area with significantly low wind velocity, small-sized wind turbines are the most likely candidate to be utilized. The wind turbine chosen for this study is low cost type, which is a small-sized Stall-Regulated Variable-Speed Wind Turbine (SRVSWT). However, the practical application of SRVSWT, especially with variable speed drive performance has not been thoroughly tested. Hence, a feasibility study of variable speed drives performance on a small-scale wind turbine for Malaysian condition needs to be done. Through this research, the behaviour of power optimization during low wind velocity region can be studied.

1.2 Problem statement

Nowadays, the wind turbine market is conquered by Variable-Pitch Variable-Speed Wind Turbine (VPVSWT) because it can generate better power regulation compared to Stall-Regulated Wind Turbine (SRWT). However, VPVSWT has some drawbacks which are more complex; incur high maintenance, more expensive and too heavy due to the extra electronics utilities for the blade alteration and yawing purposes. Thus, the variable speed of SRWT is introduced since such turbine is less complex, lower in cost; construction and maintenance, due to its unaltered blade. Modelling works representing SRVSWT system are available in numbers of papers. Nonetheless, there is no modelling of the SRVSWT based on the dynamic equations that controlled using a Linear Quadratic Regulator (LQR) control method is available in the literature. Most of the LQR control approach was proposed for the VSPVSWT system, in which usually used in the aerodynamic model

1.3 Objectives

The objectives of this research are:

i. Model development of a small-sized Stall Regulated Variable Speed Wind Turbine (SRVSWT) based on several dynamic equations using Matlab Simulink.
ii. To develop the Linear Quadratic Regulator (LQR) controller to control the electric power generation of the developed SRVSWT with SCIG.
iii. To perform comparative study with respect to Malaysia's weather condition between the LQR controller with an integral action and PI controller with speed loop control.

1.4 Scope of study and its limitation

According to Malaysia's weather condition, a small size wind turbine of Stall-Regulated Variable-Speed Wind Turbine (SRVSWT) with size of 6kW is used throughout this study. The proposed wind turbine is used with the Squirrel Cage Induction Generator (SCIG). The control of the generated power of SRVSWT is accomplished by using LQR controller. For comparison purpose, the results from LQR controller will be compared to the PI controller. The power control is only cover for low wind speed region based on Malaysia's wind condition.

1.5 Thesis outline

This thesis consists of six chapters. Chapter 1 describes the overview of the study which includes the problem statement, objectives and scope of the study. Meanwhile, Chapter 2 will review the wind turbine control, its operation for fixed speed and variable speed, and also the small-sized wind turbine system. All related approach proposed by the previous researches in order to improve the performance of wind turbines are discussed in this chapter.

Chapter 3 presents the modelling work of a small-sized SRVSWT system. This chapter covers the detailed modelling of each subsystem, including the variable wind speed model, aerodynamic model, drive train model and generator model. Then, the complete model of a small-sized SRVSWT system is presented for the final simulation purpose.

The description of controllers is discussed in Chapter 4. In this chapter, methods for implementing the PI controller and LQR controller are described in detail. Each controller has a different algorithm depending on its control objectives. For the PI controller, the main objective is to control the mechanical speed, while, the LQR controller is used to control the generated torque.

Then, the performance analysis for each controller is discussed in Chapter 5. The analysis of the comparison performance covering the generated power, generated torque, mechanical speed, tip speed ratio and power coefficient is presented. Lastly, the conclusion of the study and several future works are suggested in Chapter 6 in order to improve the current work.

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