Faculty of Electrical Engineering

VARIABLE SPEED CONTROL OF TWO-MASS WIND TURBINE SYSTEM VIA STATE FEEDBACK WITH ADAPTATION LAW

Nor Syaza Farhana binti Mohamad Murad

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NOR SYAZA FARHANA BINTI MOHAMAD MURAD

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DECLARATION

I declare that this thesis entitle "Variable Speed Control of Two-Mass Wind Turbine System via State Feedback with Adaptation Law" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature	:	…………………………..…………….
Name	:	Nor Syaza Farhana binti Mohamad Murad
Date	:	…………………………..…………….

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Electrical Engineering

Signature	:	………………..…………………..
Supervisor Name	:	Dr. Muhammad Nizam bin Kamarudin
Date	:	………………..…………………..

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DEDICATION

For my husband Mohd Nor Ilman bin Mahad.

For my parents Mohamad Murad bin Zabidi and Norhaidah binti Abdullah.

For my daughter Dhia Inas Safiya binti Mohd Nor Ilman.

ABSTRACT

Wind turbine convert kinetic energy from the wind to rotational energy and then to electrical energy. In a wind energy conversion system (WECS), its electrical power control (EPC) side demanded a maximum mechanical power from the mechanical power control (MPC) side despite any intermittent wind and seasonal interference. Therefore, it is necessary to develop a variable speed algorithm for a modern WECS. For a two-mass horizontal axis wind turbine, the rotor and generator stiffness is commonly being neglected in the system dynamic. The inclusion of stiffness in system dynamic introduces integral term in the system expression and hence, incur mathematical complexity in the controller design phase. Contrary, this study consider stiffness as unknown parameter in the wind turbine dynamic. In order to obtain the maximum output power, the design of an algorithm with adaptation law for the speed control of a two-mass wind turbine system with an unknown stiffness is proposed in this research. The algorithm is formulated using a full-state feedback. In pursuance of solving the tracking control as a regulation case, the speed of the turbine is bijective mapped into the error dynamic. The stability of the proposed algorithm is guaranteed by Lyapunov. The adaptation law used in the variable speed algorithm is to successfully acquire the adaptability of the algorithm towards an unknown stiffness. Therein, the estimated stiffness is augmented in the Lyapunov function. The Lie derivative of the function is made into a negative semi-definite via the non-negative control parameters. In order to control the rotor speed to sustain the optimum tip-speed ratio (TSR), as well as obtaining the maximum power output from the turbine, the proposed algorithm is constructed. A MATLAB with Simulink® toolbox is used to validate the effectiveness of the proposed control speed. The simulation result showed that the rotor speed achieved an asymptotic tracking towards the demanded rotor speed irrespective of the stiffness value. The error is proved to be minimized as the integral of absolute error (IAE) obtained for wind turbine with stiffness ranging from 134550 $Nmrad^{-1}$, 269100 $Nmrad^{-1}$, and 403650 $Nmrad^{-1}$ are recorded as 0.003088, 0.003063 and 0.003088 respectively. These IAE are slightly higher as compared to the IAE for the wind turbine without stiffness which has been recorded as 0.001552. According to the findings of the adaptation law, the algorithm can be adapted to various stiffness value in consequence of the estimated stiffness value. In conclusion, the optimum TSR and output power are acquired through the proposed controlled rotor speed.

ABSTRAK

Turbin angin menggunakan sistem penukaran tenaga angin untuk menukar tenaga kinetik dari angin ke tenaga berputar dan kemudian ke tenaga elektrik. Dalam sistem penukaran tenaga angin (WECS), pihak kuasa kawalan elektrik (EPC) memerlukan kuasa mekanik maksimum dari sisi kawalan mekanikal (MPC) walaupun terdapat gangguan angin dan gangguan bermusim. Oleh itu, adalah perlu untuk membangunkan algoritma kelajuan boleh ubah untuk WECS moden. Bagi turbin angin dua jisim paksi mengufuk, kekukuhan pemutar dan penjana biasanya diabaikan dalam sistem dinamik. Untuk mendapatkan kuasa output maksimum, reka bentuk algoritma dengan hukum penyesuaian untuk kawalan kelajuan sistem turbin angin dua jisim dengan kekukuhan yang tidak diketahui dicadangkan dalam kajian ini. Algoritma dirumuskan menggunakan kaedah suapbalik keadaan penuh. Bagi menyelesaikan kawalan penjejakan sebagai kes pengawalaturan, kelajuan turbin dipetakan secara bijeksi ke dalam ralat dinamik. Kestabilan algoritma yang dicadangkan dijamin oleh Lyapunov. Hukum penyesuaian yang digunakan dalam algoritma kelajuan boleh ubah adalah untuk memperoleh kesesuaian algoritma terhadap kekukuhan yang tidak diketahui. Di dalamnya, anggaran kekukuhan diperkuatkan dalam fungsi Lyapunov. Terbitan Lie bagi fungsi Lyapunov dibuat menjadi negatif-separa pasti melalui parameter kawalan bukan negatif. Bagi mengawal kelajuan pemutar untuk mengekalkan nisbah laju hujung yang optimum (TSR), serta mendapatkan output kuasa maksimum dari turbin, algoritma yang dicadangkan dibina. MATLAB dengan kotak alat Simulink® digunakan untuk mengesahkan keberkesanan kelajuan kawalan yang dicadangkan. Keputusan simulasi menunjukkan kelajuan pemutar mencapai pengesanan berasimptot ke arah kelajuan pemutar yang diminta tanpa mengira nilai kekukuhan. Terbukti ralat diminimumkan berdasarkan kamiran ralat mutlak yang diperoleh dari turbin angin dengan nilai kekukuhan 134550 Nmrad^{-1}, 269100 Nmrad^{-1}, dan 403650 Nmrad^{-1} iaitu 0.003088, 0.003063 dan 0.003088 yang sedikit lebih tinggi berbanding dengan 0.001552 yang direkodkan oleh kamiran ralat mutlak untuk turbin angin tanpa kekukuhan. Menurut penemuan hukum penyesuaian, algoritma boleh disesuaikan dengan pelbagai nilai kekukuhan akibat daripada nilai kekukuhan yang dianggarkan. Kesimpulannya, kawalan kelajuan pemutar yang dicadangkan berupaya menghasilkan TSR optimum sekaligus menghasilkan kuasa output yang optimum.

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LIST OF ABBREVIATIONS

ATF	-	Aerodynamic Torque Feedforward
BSMC	-	Backstepping Sliding Mode Control
EPC	-	Electrical Power Control
FSFP	-	Fixed Speed Fixed Pitch
FSVP	-	Fixed Speed Variable Pitch
HAWT	-	Horizontal Axis Wind Turbines
IAE	-	Integral of Absolute Error
ISE	-	Integral of Squared Error
ISMC	-	Integral Sliding Mode Control
LPV	-	Linear Parameter Varying
LQR	-	Linear Quadratic Regulator
MPC	-	Mechanical Power Control
MPPT	-	Maximum Power Point Tracking
PI	-	Proportional Integral
PMSG	-	Permanent Magnet Synchronous Generator
QFT	-	Quantitative Feedback Theory
SCIG	-	Squirrel Cage Induction Generator
SMC	-	Sliding Mode Controller
SOCP	-	Second-Order Cone Programming
SSE	-	Sum of Squared Error

TSR	-	Tip-Speed Ratio
VAWT	-	Vertical Axis Wind Turbines
VSFP	-	Variable Speed Fixed Pitch
VSVP	-	Variable Speed Variable Pitch
WECS	-	Wind Energy Conversion System
WRIG	-	Wind Rotor Induction Generator
WRSG	-	Wind Rotor Synchronous Generator

LIST OF SYMBOLS

$\dot{x}$	-	System differential equation
x	-	System dynamic
u	-	Control input
B	-	Unknown parameter
$\widehat{B}$	-	Estimated stiffness
$\dot{\widehat{B}}$	-	Adaptation law
v_{rated}	-	Rated wind speed
R	-	Rotor blade radius
v	-	Wind speed
ρ	-	Air density
$C_p(\lambda,\beta)$	-	Power coefficient
λ	-	Tip speed ratio
β	-	Pitch angle
γ	-	Gearing ratio
ω_r	-	Rotor speed
ω_g	-	Generator speed
J_r	-	Rotor inertia
J_g	-	Generator inertia
K_r	-	Rotor external damping
K_g	-	Generator external damping

B_r	-	Rotor stiffness
B_g	-	Generator stiffness
T_m	-	Aerodynamic torque
T_g	-	Generator torque
T_{hs}	-	High-speed shaft torque
T_{ls}	-	Low-speed shaft torque
θ_g	-	Generator-side angular deviation
θ_r	-	Rotor-side angular deviation
P_{wind}	-	Wind power
P_m	-	Aerodynamic power
$C_{p_{max}}$	-	Maximum power coefficient
λ_{opt}	-	Optimal tip-speed-ratio
πR^2	-	The swept area
ω_r^*	-	Desired rotor speed
R	-	State space region
r	-	Small region of state space
C	-	Feedback gain
$V(x)$	-	Scalar continuous function
$\delta(x)$	-	Uncertainty which is unbounded and observable
u_{nom}	-	Nominal control input
u_r	-	Robust control input
z	-	Rotor tracking error
$T_{g_{nom}}$	-	Nominal generator torque
T_{g_r}	-	Robust generator torque
C_1	-	Control law parameter

Γ^{-1}	-	Adaptation law parameter
ε	-	Saturation type-control parameter (epsilon)
α	-	Saturation type-control parameter (decay function)
$P_{generator}$	-	Generator power
η_g	-	Generator efficiency
η_{gb}	-	Gearbox efficiency

LIST OF PUBLICATIONS

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CHAPTER 1

INTRODUCTION

1.1 Introduction to Wind Energy Conversion System (WECS)

Nowadays, research and development in wind turbine technology is rather encouraging. However, in Southeast Asian continental, the development in wind turbine technology is rather slow. Few studies on evaluation of wind energy feasibility in Southeast Asian continental have been reported. For instance, wind turbine feasibility studies in Malaysia (Sanusi et al., 2016; Nor et al., 2014; Siti et al., 2011), Brunei (Padmanaban et al., 2015), Myanmar (Soe et al., 2015; Kyaw et al., 2011), and Indonesia (Hiendro et al., 2013). The studies prove that Southeast Asian continental have potential in developing wind farm for power generation.

Wind turbines are commonly categorized into horizontal axis wind turbines (HAWT) and vertical axis wind turbines (VAWT). The classification is made based on the structure and the rotor shaft orientation of such configuration. The main rotor shaft, the gearbox and the generator of HAWT are located on top of a tower with the main rotor shaft orientation is parallel to the wind direction. In VAWT, the main rotor shaft which perpendicular to the wind direction is located on top of the turbine while the generator and the gearbox are located near the ground (Onol and Yesilyurt, 2017; Agarwal et al., 2016; Parker et al., 2016; Malinowski et al., 2015; Njiri et al., 2015; Cheng et al., 2012; Manyonge et al., 2012).

Wind energy conversion system (WECS) consists of a mechanical power control (MPC) side and electrical power control (EPC) side. The WECS is dependent on wind flow dynamics which are highly nonlinear, non-deterministic and have chaotic behavior. Plus, the most striking characteristic of wind flow that bother control engineers is its variability (Kamarudin et al., 2015a). The EPC side of the system demanding maximum mechanical power from the MPC side despite wind intermittent and seasonal interference. As such, the need to develop a variable speed algorithm for a modern WECS is crucial.

In modern WECS, research in variable speed wind turbine is getting blossom. In a constant speed wind turbine, the rotor speed remain constant for all wind speeds. As the size of turbine increases and due to wind intermittent, the inherent problems of the constant speed wind turbine becomes more pronounced. On the other hand, variable speed wind turbine allows the rotor and wind speed to be matched in order to maintain its optimum tip-speed ratio (TSR) for maximum efficiency. TSR is defined as the ratio of the blade tip-speed and wind speed. Nowadays, variable speed wind turbine can either operates as variable pitch or fixed pitch approach. In a fixed pitch approach, the maximum power coefficient is determined by TSR. Whereas in variable pitch approach, the maximum power coefficient is determined by both TSR and pitch angle.

1.2 Problem Statement

The dynamics of a two-mass wind turbine system consists of a rotor-generator inertia, rotor-generator external damping, and rotor-generator stiffness. The rotor and generator stiffness originate from the vibration of turbine tower which is reflected by the wind resonance. Since the nacelle is located on top of the tower, it is also affected by the vibration and thus producing stiffness in the system dynamics. In a variable speed algorithm to date, the lumped stiffness has been neglected though the stiffness effect is count in the actual dynamic. The reason of neglecting the stiffness is to avoid the presence of the integral-term to the system dynamics that is difficult to handle by control engineers.