CONTROL SYSTEM DESIGN AND TRANSIENT ANALYSIS OF A GRID INTEGRATED WIND TURBINE

by

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A thesis submitted in fulfilment of the requirements for the degree of Master of Science

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UNIVERSITI MALAYSIA PERLIS

2014

ACKNOWLEDGEMENT

My deepest thanks to the Almighty Allah S.W.T. (Alhamdulillah), the Omnipotent, the Merciful and the Compassionate, for giving me the strength, patience and determination in compiling this research. Then, I would like to express my gratefulness to my supervisor, Prof. Madaya Shamshul Bahar bin Yaakob, co-supervisor Prof. Madaya Dr. Mohd. Abdur Rashid and for his valuable and Ms. Adawati binti Yusof constructive suggestions thought this thesis that enabled it to run smoothly. I also deeply grateful to the Ministry of Higher Education, Malaysia, for providing financial support for most part of this research work under the grant RAGS 9018-00023. I would like to share this moment of contentment and express the appreciations to my parents who were encouraged at every step in my life. I am very much indebted to Md. Abdullah Al Humayun, for his guidance and great source of motivation in my higher study. I owe a special gratitude to the Bangladesh community in Perlis for their mental support. Finally, I thank everyone else who has facilitated the making of this thesis, including other colleagues.

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LIST OF ABBREVIATIONS

AC	Alternating Current
AWEA	American Wind Energy Association
DC	Direct Current
DFIG	Doubly Fed Induction Generator
EMF	Electro-Motive Force
GWEC	Global Wind Energy Council
HAWT	Horizontal Axis Wind Turbine
LQG	Linear-Quadratic-Gaussian
MPPT	Maximum Power Point Tracking
O&M	Operation and Maintenance
P&O	Perturbation and Observe
PMSG	Permanent Magnet Synchronous Generator
PI	Proportional-Integral
PID	Proportional-Integral-Derivative
PWM	Pulse Width Modulated
SCIG	Squirrel Cage Induction Generator
SG	Synchronous Generators
VSWT	Variable Speed Wind Turbine
VAWT	Vertical Axis Wind Turbine
WECS	Wind Energy Conversion Systems
WRIG	Wound Rotor Induction Generator
WRSG	Wound Rotor Synchronous Generator

LIST OF SYMBOLS AND VARIABLES

A		Area of Cross Section
A_i		Amplitude of The Wind Fluctuations
$C_{V\beta}$		Coefficient For Speed Controller
C_p		Input Power Coefficient
C_t		Torque Coefficient
J_{eq}		Equivalent Moment of Inertia.
K_b		Specific Gas Constant
K_i		Integral Constant
K_p		Proportional Constant
L'_{1r}		Leakage Inductance
L_{1s}		Leakage Inductance
L_m		Magnetizing Inductance
L'_r		Total Rotor Inductance;
L_s		Total Stator Inductance
P_{Betz}		Maximum Extractable Energy From Wind
P_e		Electric Output Power
P_{mech}		Mechanical Power
P_p		No. of Pole Pairs
P_w		Available Wind Power
R		Turbine Radius
R'_r		Rotor Resistance
R_s		Stator Resistance
S		Generator Slip

$S(\omega_n)$		Spectral Density Function
T		Temperature
T_e		Electric Torque.
T_f		Final Torque
T_m		Mechanical Torque
T_{wind}		Turbine Input Torque
V_{ds}		D Axis Stator Voltage
V_{qs}		Q Axis Stator Voltage
V_w		Wind Speed
$V_\omega(t)$		Instantaneous Wind Speed
e_w		Error Signal
f_s		Pulsation Frequency Of Supply Voltage
g		Gravity Constant
h		Turbine Hub Height
i_{ds}		d Axis Stator Current
i_{qs}		q Axis Stator Current
k		Optimal MPPT Constant
z		Altitude Above Sea Level
Ω		Friction Coefficient
Ω_r		Rotor Flux
Ω_s		Synchronous Speed
$\Omega_{V\beta}$		Time Constant of Pitch Actuator
β_d		Pitch Gain
υ_m		Mean Wind Speed
ψ_{ds}		D Axis Flux Linkage

ψ_{pm}		Permanent Magnetic Flux
ψ_{qs}		Stator Q Flux Linkage
ω_m		Mechanical Speed
ω_{ni}		Frequency of Wind Fluctuations Over 'N' Samples
ω_{opt}		Optimal Rotational Speed
ω_w		Angular Speed of The Turbine
$\rho(z)$		Air Density As Function of Altitude
ρ_0		Standard Sea Level Atmospheric Density
ΔT		Torque Variation From Reference Value
β		Blade Pitch Angle
$\delta\ (\Delta T)$		Deviation During A Sampled Time
θ		Perturbation Value
λ		Tip Speed Ratio

Rekabentuk Sistem Kawalan dan Analisis tentang Gangguan daripada Turbin Angin Grid Bersepadu

ABSTRAK

Kuasa angin adalah sumber tenaga boleh diperbaharui yang berkesan dan maju. Bahagian kuasa angin dengan jumlah kapasiti kuasa yang dipasang semakin meningkat di seluruh dunia. Oleh itu, ia kini lebih penting bagi para penyelidik untuk memberi lebih tumpuan kepada peningkatan teknikal sistem penukaran tenaga angin. Sebuah turbin angin yang berkelajuan boleh ubah biasanya menggunakan algoritma pengesan kuasa maksimum bagi mengoptimumkan pengambilan tenaga daripada angin. Dalam tesis ini, maksimum mata kuasa algoritma pengesan baru untuk sistem penukaran tenaga angin telah dicadangkan. Algoritma ini adalah berdasarkan kepada hubungan yang optimum antara kuasa aktif dan voltan arus terus. Kuasa arus terus dikira berdasarkan voltan dan arus, yang diukur menggunakan alat pengesan elektrik. Kaedah usikan konvensional telah diubah suai dengan memperkenalkan parameter usikan baru untuk mengurangkan masa pengiraan dan sistem yang rumit. Sistem yang dicadangkan ini juga mengandungi sudut kawalan lapang Fuzzy-PI untuk menganalisis ciri-ciri kuasa pengeluar untuk penjana angin berdasarkan kelajuan angin yang masuk ke kelajuan yang ditetapkan. Model terperinci elektromekanik turbin angin dengan kelajuan boleh ubah dan kawalan lapang boleh ubah dibangunkan menggunakan perisian Matlab / Simulink untuk menganalisis prestasi sistem kawalan yang dicadangkan. Model yang dicadangkan juga dibandingkan dengan sistem konvensional dan keputusan menunjukkan bahawa sistem yang dicadangkan dapat meningkatkan penyerapan kuasa dengan jumlah yang besar. Kajian ini juga mengkaji kestabilan gangguan sistem kuasa hibrid dengan peningkatan kadar penembusan turbin angin bagi mengetahui ciri-ciri kerosakan arus pada penjana angin grid bersepadu. Dengan peningkatan kadar penembusan tenaga angin, sistem kuasa yang didominasikan oleh mesin segerak akan mengalami perubahan ciri-ciri dinamik dan beroperasi. Daripada kenyataan ini, pendekatan yang sistematik telah dibangunkan untuk menganalisis kesan bagi meningkatkan kadar kestabilan gangguan sistem berkuasa besar. Asas utama kaedah ini adalah untuk menukarkan penjana induksi setara dengan penjana angin rotor bulat segerak yang biasa. Dalam hal ini, kedua-dua kaedah yang mengganggu dan bermanfaat boleh terjejas disebabkan kerosakan arus yang dikenal pasti. Kerja-kerja penyelidikan ini menghasilkan kaedah baru untuk memaksimumkan pengeluaran tenaga daripada angin. Ia juga mengenal pasti kesan terhadap kestabilan grid pada penjana angin. Perbincangan telah dibuat daripada keputusan yang diperoleh dan beberapa faktor telah disenaraikan. Penemuan ini membantu dalam mencadangkan pengubahsuaian berguna untuk meningkatkan prestasi sistem ini.

Control System Design and Transient Analysis of a Grid Integrated Wind Turbine

ABSTRACT

Wind power is one of the most reliable and developed renewable energy source. The share of wind power with respect to total installed power capacity is increasing worldwide. It is now more significant that the researchers focus more on technical improvements of wind energy conversion system. A variable speed wind turbine typically uses a maximum power tracking algorithm in order to optimize energy acquisition from wind. Although many algorithms has been introduced by the researchers in the past, to enhance the power extraction capability but they all fall short when it comes to computational simplicity and convergence time. In this thesis, a new maximum power point tracking algorithm for wind energy conversion systems has been proposed to get rid of these problems. The algorithm is based on the optimum relationship between active power and dc link voltage. The dc power is calculated from voltage and current, which are read by the algorithm. The conventional perturbation approach has been modified by introducing a new perturbing parameter to reduce computational time and system complexity. The proposed system also include a Fuzzy-PI pitch angle controller in order to analyze the output power characteristic of wind generator from cut-in wind speed to rated wind speed. A detail electromechanical model of a wind turbine with variable speed and variable pitch control is developed in Matlab/Simulink environment in order to analyze the performance of the proposed control system. The proposed model is also compared with conventional system and the comparison results show that the proposed system increases power absorption by five to seven percent. This research also investigates the transient stability of the hybrid power system with increased penetration level of wind turbine in order to find out the fault current behaviour of a grid integrated wind generator. With increasing penetration of wind power, the power system dominated by synchronous machines experience a change in dynamics and operational characteristics. Given this assertion, a systematic approach has been developed to analyze the impact of increased penetration on transient stability of a large power system. The primary basis of the method is to replace the induction generators with equivalent conventional round rotor synchronous wind generators. In this regard, the modes that are both detrimentally and beneficially affected by fault current have been identified. The results for transient stability analysis show that inducing synchronous wind generator increases transient stability of a system. This research work resulted in a new way to maximize energy extraction from wind. It also identifies the effect of wind generators on grid stability. Discussions of the obtained results were made and several factors were listed. These findings helped in proposing useful modifications for the system in order to enhance its performance.

CHAPTER 1

INTRODUCTION

1.1 Background

Even though the phenomenon of electricity generation using wind energy is well known since late 19th century, the low price and adequate availability of contemporary energy sources had forced wind to be an unattractive option at that time. However, the oil crisis of 1973 has pushed researchers to look into wind as a probable option for electricity production (Alpanda & Alva 2010). The prime focus of research during that period was to make bigger turbines so as to supply electricity at cheaper rate. It led to the development of huge wind turbines with cost efficient technologies (Assmann, Laumanns & Routledge, 2006). Typical assembly of wind energy conversion systems (WECS) at that time included a wind turbine with three fixed blades, a generator, a gearbox and available analog control techniques. Asynchronous generators were the inevitable choice as wind generators due to their simple construction, low cost and excellent robustness. These turbines used to be connected to the generator through a gearbox and their common shaft was made to rotate at a fixed speed. Soon, the researchers tried to invent technology for small wind turbines so that individuals could buy them at a reasonable price. These small turbines typically rated around several tens of kilowatts (Hoffmann & Mutschler, 2000).

After decades of research on this field, it is possible to produce wind power at a larger scale. The turbine manufacturing industries have gained a lot of experience in this time and they have come up with efficient ways to increase the physical and electrical size of the system. In the early days of WECS, the blade diameter was limited to 10~15 meters and the generator power rating in the region of 10 to 60 KWs. The turbines 1980's were much bigger in size with electrical capacity up to 200 KW and blade diameter up to 25 meter. The height of the turbine structure also increased proportionately. Increased wind capture was insured by these large structures considering the fact that wind flow increases with height. After years of successful invention, the generator power rating is now increased to 2MW with rotor span of up to 80 meter. Statistics conducted by the American Wind Energy Association (AWEA) show that today the generation of wind power has increased by 120 times if compared to the actual design of 1970's. However this rapid increase in generator has a mere effect on the Operation and Maintenance (O&M) costs, which has made it possible to supply wind power at a cheaper rate. The cost of electricity production has dropped to 3/4 cents per KWh (Thresher, Robinson & Veers, 2007). As a result, wind power has become an integral part of present power system.

The introduction of new types of generator has also increased the performance of WECS. After 1993, few researchers and manufacturers suggested using synchronous generator in place of asynchronous generators while others opted to use doubly-fed asynchronous generators instead (Ali & Wu, 2010).

The advances in control system designing has led the development of WECS. The use of state of the art controllers and converters have allowed manufacturers to try out different techniques and designs. The variable speed configuration is one of those recent techniques. Use of power electronic converters also allowed both higher power handling capability and lower price per KW (Franquelo, et al. 2006). There are some techniques that allow us to control the speed and power of a wind turbine, namely; stall control, pitch control, active stall control (Hansen, 2013). As a result this is expected that the use of power electronics will increase further in coming decades.

Since numerous ways have been invented and applied on wind turbines, a comparison among electrical, mechanical and economical aspects of those technologies is inevitable. The comparison among the constant speed and variable speed configuration is one of those much studied cases. All of those studies show, in terms of power capturing capabilities variable speed configuration is much suitable although a lot more complex than constant speed configuration (Sandhu, Vadhera & Sandhu, 2014). Studies show that the use of variable speed approach increases the power production of wind turbine by 20% (Lin & Hong, 2010). Some approaches are based on calculating the wind speed to optimize wind turbine performance (Fakharzadeh & Talebnezhad, 2011). Other controllers use an extensive searching method to find the maximum power for a given wind (Bououdena, Filalib & Chadlic, 2013; Wang, & Chang, 2004). However the wind power optimization algorithms that are available in the literature are not quite up to the mark yet as the full potential of wind power is yet to be exploited. Beside that, the existing algorithms has some technical issues, like computational complexity and convergence time; that requires more studies and pin point scrutinization.

1.2 Problem statement

Even though the field of wind energy is promising considering growing energy concerns and environmental apprehensions, a lot has to be improved in order to make most out of available wind energy. Preliminary studies have identified the parameters which are to be controlled to maximize energy production from wind turbine. Although a lot of researches have already been done on this topic, but, a simple effective way to accomplish the goal is yet to be formulated.

1) Protection from high wind gust

   A high wind flow across the face of turbine can be catastrophic for the mechanical structure, if it is not controlled properly. For smooth operation of the turbine a controller needs to be designed so that it assists the start up of wind turbine and provide provision for emergency stop.

2) Maximize energy extraction

   It has been reported by Badawi (2013), that the energy conversion laws allow only 59.3% of available wind energy to be converted to mechanical energy. Of this 59.3%, a lot of energy is lost as mechanical friction before it is converted to electrical energy. The presence of mechanical gearbox also adds to the mechanical loss. Considering these constraints, an assembly has to be designed that will make the most of available wind energy. The use of electrical device in place of mechanical equipments will reduce energy loss and increase system performance. The use of permanent magnet synchronous generator (PMSG) in place conventional induction generator allows a direct drive configuration. The PMSG also has direct mathematical relationship between output power and dc link voltage. As a result an algorithm for maximum power point tracking (MPPT) can be formulated that would not require mechanical rotary sensors.

3) Transient stability

The transient stability study deals with the effect of sudden large fault current in a stable current. A system is said transiently stable if the generators in the system can remain synchronism even after occurrence of a large fault or sudden load change or outage of line. The transient study of all the generators in a system is significant since it determines certain things such as the nature of relaying needed by the system, critical clearing time of circuit breaker, voltage level of the system and transfer capability between systems. Recently, the variable speed wind turbine (VSWT) driving a doubly fed induction generator (DFIG) or a direct drive PMSG has become popular. It has been found in the literature that the transient behavior of DFIG has been studied meticulously but the transient analysis for PMSG's is not sufficient enough.

4) The effect of penetration level of wind power

The injection of wind power into a stable system may disrupt stability since the dynamic behavior of wind generator is different from typical generator. It is possible that penetration of wind power up to certain limit is fine but further increase of wind power may cause the system to go into instability. So, the impact of wind power penetration has to be studied carefully in order to determine the limit of wind power limit.

1.3 Research Objective

The aim of this research is to design a pitch angle controller and a MPPT controller, so that maximum energy can be extracted from available wind flow. The transient response of the wind generator is then investigated in order to find out whether the designed controllers and chosen generator types has any impact on the stability of the grid.

The objectives of this research is to;

1) Investigate the pitch angle dependence of generator output power oscillation of a grid integrated wind turbine and design a new fuzzy logic controller incorporated with proportional-integral (PI) so that the controller induced oscillations can be eradicated.

2) Design a new algorithm in order to increase power extraction from wind without requiring any mechanical sensors.

3) Finally the performance of a wind turbine as a part of integrated hybrid power generation system has to be investigated to understand the effect of wind power penetration in a stable power system.

It is significant to study the blade construction and forces acting on the blade while designing pith controllers and MPPT controllers so that their effect on the turbine output power can be understood. A control system has to be developed to control pitch angle in such a way that it reduces stress on the blade in presence of turbulent wind speed and at the same time reduces controller induced oscillation. The proposed pitch control system should be capable of getting most out of available wind energy by changing blade pitch gradually from cut-in to cut off wind speed and also facilitate an emergency stop when needed.

Analyzing the governing parameters in obtaining maximum power from wind turbine such as tip speed ratio, power coefficient, dc link voltage, rotor speed and electromagnetic torque, is also included in the research objective since they affects the overall output power from turbine. An MPPT controller needs to be developed as to maximize the power extrcation. And then finally, a through transient analysis is to be performed in order to completely understand the effect of adding wind power into a stable gird.

1.4 Research Scope

The scope of this research includes understanding the physical characteristics and properties of wind turbine. The physical properties that influence energy production of a wind turbine are studied extensively in order to design a control algorithm that would maximize power extraction. The transient performance of a wind generator is another excruciating factor before connecting wind power into existing power system. The transient performance analysis reveals the fault current behavior of the system thus dictates the stability and viability of wind power injection. Finally the impact of wind power penetration is studied to draw a conclusion on the stability of wind power.

1.5 Thesis Organization

This thesis is organized with five distinct chapters. Contatents of each chapter is as described below:

Chapter 1 presents a brief background of the topic, problem statements, objectives and a brief methodology along with the organization of this thesis.

Chapter 2 illustrates an extensive literature review on wind turbine characteristics, construction and control algorithm. The present energy situation is also reviewed in this chapter and the research motivation in light of the continuous energy crisis has been explained. The control methods that have been adopted by the researchers up unit ill now to fix the issues stated in the problem statement are briefly described.

Chapter 3 describes the materials and methods developed in this research to protect the turbine from gust wind. It also explains the equations and fuzzy systems adopted to maximize the extracted power from available wind. Lastly, the method employed to analyze the transient stability is presented.

Chapter 4 explains the numerical results of different characteristics of wind turbine. The effect of proposed control methods on the performance of wind turbine has also been explained in this chapter.

Chapter 5 covers the conclusions and research findings with the recommendation of future work.