ADVANCED MODELING AND CONTROL OF DFIG BASED WIND TURBINE SYSTEMS

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by

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Submitted

in the fulfilment of the requirements of the degree of Doctor of Philosophy

to the

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Dedicated

to

My Parents, Wife and Kids

CERTIFICATE

This is to certify that the thesis entitled **"Advanced Modeling and Control of DFIG based Wind Turbine Systems"** submitted by **Mr. Ganesh Prasad Prajapat**, to Indian Institute of Technology Delhi for the award of degree of **Doctor of Philosophy** is a bona fide record of research work carried out by him under my supervision. The contents of this thesis have not been submitted to any other institute or university for the award of any degree or diploma.

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Abstract

This thesis mainly concentrates on a model formulation of the structural and mechanical dynamics of the DFIG based wind turbine systems (DFIG-WT) for the investigation of the grid-structure interaction, modeling and impact of the gear-train backlash and its estimation for the purpose of the monitoring. Further, the enhancement of the damping through an optimal control approach, wind speed based enhanced MPPT scheme for maximum energy capture and a wind speed based control scheme for the smooth operation of the DFIG-WT have also been proposed in this thesis. Several aspects of modelling and control of the DFIG-WT, investigated in this thesis are as follows-

1) A model has been proposed to investigate the electro-mechanical interaction of the grid connected DFIG-WT with special attention on the structural dynamics of the wind turbine. The Euler–Lagrangian approach has been used for the structural dynamics of the wind turbine while the driving input mechanical power to the wind turbine has been modelled by the Blade Element Momentum (BEM) method.

2) A model of the gear-train with backlash has been presented to observe its impact on the system dynamics. The proposed model has also been used for the estimation of the backlash for its monitoring which may help to develop equipment maintenance strategies as well as updating the control schemes. Unscented Kalman filter (UKF) has been used for the purpose of estimation. The estimation was enabled by the bad-data detection.

3) Stability enhancement of a grid connected DFIG-WT through an optimal control approach i.e. a Linear Quadratic Regulator (LQR) has been suggested for low inertia DFIG-WT exhibiting prolonged oscillations when subjected to an electrical disturbance. The proposed damping strategy has also been compared with the conventional power system stabilizer (PSS) and concluded that LQR performs quite good since it uses less control effort and state energy. The LQR control also works well with multi-machine system.

4) A wind speed based control strategy to capture the additional energy out of the variable wind through enhancing the MPPT scheme of the DFIG-WT has also been proposed. The UKF based estimation of the wind speed embedded with the proposed control scheme makes it a sensor-less and hence cost effective method.

5) A wind speed based control strategy for the smooth operation of the DFIG-WT running

under turbulent wind is suggested. Essentially, the proposal is to make the reference torque such that it suppress the acceleration and deceleration of the turbine due to the change in wind speed and make the maximum power tracking slow so that the generator speed responds smoothly. The estimation of the wind speed by UKF also relaxed from the need of an additional sensor.

Keywords: DFIG, Wind Turbine, Euler–Lagrangian approach, BEM, gear-train backlash, LQR, Unscented Kalman Filter, State and Parameter Estimation, Maximum Power Point Technique, Wind Speed Estimation.

सार

यह शोध प्रबंध मुख्य रूप से ग्रिड-स्ट्रक्चर इंटरैक्शन, मॉडलिंग और गियर-ट्रेन बैकलैश के प्रभाव की जांच के लिए डीएफआईजी आधारित पवन टरबाइन सिस्टम (डीएफआईजी-डब्ल्यूटी) की संरचनात्मक और यांत्रिक गतिशीलता के मॉडल फॉर्मूलेशन पर केंद्रित है। इसके अतिरिक्त, एक अनुकूल नियंत्रण दृष्टिकोण के माध्यम से अवमन्दक की वृद्धि, अधिकतम ऊर्जा को पकड़ने के लिए पवन गति आधारित उन्नत एमपीपीटी योजना और डीएफआईजी-डब्ल्यूटीटी के सुचारु संचालन के लिए हवा की गति आधारित नियंत्रण योजना भी इस शोध में प्रस्तावित की गई है। इस सिद्धांत में जांच की गई डीएफआईजी-डब्ल्यूटीटी के मॉडलिंग और नियंत्रण के कई पहलू इस प्रकार हैं-

1) पवन टरबाइन की संरचनात्मक गतिशीलता पर विशेष ध्यान देने के साथ ग्रिड से जुड़े डीएफआईजी-डब्लूटी के इलेक्ट्रो-मैकेनिकल इंटरैक्शन की जांच के लिए एक मॉडल का प्रस्ताव दिया गया है। यूलर-लैंगांगियन दृष्टिकोण का उपयोग पवन टरबाइन की संरचनात्मक गतिशीलता के लिए किया गया है जबकि पवन टरबाइन के लिए ड्राइविंग इनपुट यांत्रिक शक्ति को ब्लेड एलिमेंट मोमेंटम (बीईएम) विधि द्वारा मॉडलिंग किया गया है।
2) बैकलैश के साथ गियर-ट्रेन का एक मॉडल सिस्टम गतिशीलता पर इसके प्रभाव का निरीक्षण करने के लिए प्रस्तुत किया गया है। प्रस्तावित मॉडल का उपयोग इसकी निगरानी के लिए बैकलैश के आकलन के लिए भी किया गया है जो उपकरण रखरखाव रणनीतियों को विकसित करने और नियंत्रण योजनाओं को अद्यतन करने में मदद कर सकता है। अनसेंटेड कलमैन फ़िल्टर (यूकेएफ) का अनुमान लगाने के उद्देश्य से उपयोग किया गया है। अनुमान खराब डेटा पहचान द्वारा सक्षम किया गया था।
3) एक इष्टतम नियंत्रण दृष्टिकोण के माध्यम से एक ग्रिड से जुड़े डीएफआईजी-डब्लूटीटी की स्थिरता वृद्धि यानी एक लीनियर क्वाड्रैटिक रेगुलेटर (एलक्यूआर) को कम जड़ता डीएफआईजी-डब्ल्यूटीटी के लिए लंबे समय तक बिजली के अशांति के अधीन लंबे समय तक चलने वाले ऑसीलेशन के लिए सुझाव दिया गया है। प्रस्तावित डंपिंग रणनीति की तुलना पारंपरिक पावर सिस्टम स्टेबलाइज़र (पीएसएस) के साथ की गई है और निष्कर्ष निकाला है कि एलक्यूआर काफी अच्छा प्रदर्शन करता है क्योंकि यह कम नियंत्रण प्रयास और राज्य ऊर्जा का उपयोग करता है। एलक्यूआर नियंत्रण मल्टी-मशीन सिस्टम के साथ भी अच्छी तरह से काम करता है।
4) डीएफआईजी-डब्ल्यूटीटी की एमपीपीटी योजना को बढ़ाने के माध्यम से परिवर्तनीय हवा से अतिरिक्त ऊर्जा को पकड़ने के लिए एक पवन गति आधारित नियंत्रण रणनीति भी प्रस्तावित की गई है। प्रस्तावित नियंत्रण योजना के साथ एम्बेडेड हवा की गति के

यूकेएफ आधारित आकलन ने इसे सेंसर-कम और इसलिए लागत प्रभावी विधि बना दिया है।

5) अशांत हवा के नीचे चल रहे डीएफआईजी-डब्ल्यूटी के सुचारू संचालन के लिए एक पवन गति आधारित नियंत्रण रणनीति का सुझाव दिया जाता है। अनिवार्य रूप से, प्रस्ताव रिफरेन्स टार्क बनाना है कि यह हवा की गति में बदलाव के कारण टरबाइन के त्वरण और मंदी को दबाएगा और अधिकतम पावर ट्रैकिंग धीमा कर देगा ताकि जनरेटर की गति सुचारू रूप से प्रतिक्रिया दे। यूकेएफ द्वारा हवा की गति का आकलन अतिरिक्त सेंसर की आवश्यकता से भी कम हो गया।

Content

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS AND SYMBOLS

DFIG-WT	Doubly Fed Induction Generator based Wind Turbine system
WECS	Wind Energy Conversion System
SMIB	Single Machine Infinite Bus system
DAE	Differential-Algebraic-Equations
ODE	Ordinary-Differential-Equations
PMSG	Permanent Magnet Synchronous Generator
FRC	Full Rated Converter
RSCC	Rotor Side Converter Controller
GSCC	Grid Side Converter Controller
TSR	Tip Speed Ratio
MPPT	Maximum Power Point Tracking
BEM	Blade Element Momentum method
E-L	Euler–Lagrangian equation
MBC	Multi-blade Coordinate Transformation
LQR	Linear Quadratic Regulator
PSS	Power System Stabilizer
UKF	Unscented Kalman Filter
PCS	Proposed Control Strategy
FAST	Fatigue, Aerodynamic, Structural and Turbulence simulator
NREL	National Renewable Energy Laboratory, Department of Energy, U.S.
PMU	Phasor Measurement Unit
WSCC	Western System Coordinating Council
H_t	Turbine inertia constant
H_g	Generator inertia constant
ω_t	Turbine angular speed
ω_r	Generator angular speed
θ_{tw}	Shaft twist angle
ω_B	Base electrical speed
$P_{t_{pu}}$	Turbine power

T_s	Shaft torque
T_e	Generator electrical torque
T_t	Turbine torque
c_d	Shaft damping coefficient
k_s	Stiffness of the shaft
V_w	Wind speed
ρ	Air density
A	Area swept by the turbine blades
C_p	Power coefficient
$C_{p_{pu}}$	Per unit Power coefficient
β	Pitch angle
λ	Tip-speed ratio
V_{dc}	DC link voltage
$\boldsymbol{V_s}$	Stator terminal voltage
$\boldsymbol{V_b}$	Infinite bus voltage
X_T	Transmission line reactance
X_C	Grid side converter transformer reactance
P_e	Generator active power
Q_e	Generator reactive power
V_{dcREF}	Reference DC-link voltage across capacitor
Q_{rREF}	Reference rotor reactive power
V_{sREF}	Reference stator voltage
P_{eREF}	Reference active power
T_{eREF}	Reference electromagnetic torque of generator
T_{eREFm}	Modified reference electromagnetic torque
k_{pn}	Proportional gain of n^{th} PI controller
k_{in}	Integral gain of n^{th} PI controller
θ_t	Angular position of the turbine shaft
θ_r	Angular position of the generator shaft
V_{qs}, V_{ds}, V_{qr} *and* V_{dr}	*q-axis* and *d-axis* stator and rotor voltages, respectively

I_{qs}, I_{ds}, I_{qr} and I_{dr}	*q-axis* and *d-axis* stator and rotor currents, respectively
C	Capacitance of DC-link capacitor
δ	Backlash in gear-train
$\boldsymbol{q}(t)$	Generalized variable considered as states
$\boldsymbol{M}(\omega_t, t)$	Mass matrix of rotating blades and tower
$\boldsymbol{C}(\omega_t, t)$	Damping matrix of rotating blades and tower
$\boldsymbol{K}(\omega_t, t)$	Stiffness matrix of rotating blades and tower
$\boldsymbol{F_{wind}}(t)$	Tangential force on blades
$\boldsymbol{F_g}(t)$	Gravitational force on blades
$\boldsymbol{F_{\dot{\omega}(t)}}(t)$	Accelerating force on blades
y_j	Edgewise displacement of blade *j*
l	Radial distance of an element of a blade from hub
$\bar{l}$	Fractional length of the blade, $\bar{l} = l/L$
L	Length of a blade
$\mu(l)$	Mass per unit length of a blade
$\varphi(l)$	Mode shape along the blade length depending on stiffness and inertia
$\Psi_1(t)$	Azimuth angle of a blade at time, *t* with vertical upward position
V_{rel}	Relative wind velocity
i_a	Axial induction factor
i_t	Tangential induction factor
$\phi(l, t)$	Flow angle
$\alpha(l, t)$	Angle of attack
$\boldsymbol{f}$	Set of state equations
$\boldsymbol{g}$	Set of algebraic equations
$\boldsymbol{h}$	Set of output equations
$\boldsymbol{y}$	Measurable output vector
$\boldsymbol{X}, \boldsymbol{X}^-$	System state and predicted state vector
$\boldsymbol{U}$	Input vector
$\boldsymbol{w}$	Process/model noise
$\boldsymbol{v}$	Measurement noise

$\boldsymbol{R_u}$	Measurement covariance
$\boldsymbol{Q_u}$	Process covariance
$\boldsymbol{R}$	State weighted matrices used in LQR
$\boldsymbol{Q}$	Control weighted matrices used in LQR
$\boldsymbol{P}, \boldsymbol{P}^{-}$	State covariance and predicted state covariance matrix
$\boldsymbol{\chi}, \boldsymbol{\chi}^{-}$	Sigma points and predicted sigma points
$\boldsymbol{Y}^{-}$	Predicted measurement sigma points
$\boldsymbol{M}$	Measurement covariance matrix
C	Cross covariance of χ^{-} and Y^{-}
$\boldsymbol{K}$	Kalman gain matrix
"^"	Estimated value of the respective variable
$Subscript\ pu$	Per unit value of the respective variable
$Subscript\ REF$	Reference value of the respective variable