ANALYSIS, DESIGN AND CONTROL OF DOUBLY FED INDUCTION GENERATOR FOR WIND ENERGY CONVERSION SYSTEMS

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by

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CERTIFICATE

It is certified that the thesis entitled "**Analysis, Design and Control of Doubly Fed Induction Generators for Wind Energy Conversion Systems**," being submitted by **Mr. N Krishna Swami Naidu** for award of the degree of **Doctor of Philosophy** in the Department of Electrical Engineering, Indian Institute of Technology Delhi, is a record of the student work carried out by him under my supervision and guidance. The matter embodied in this thesis has not been submitted for award of any other degree or diploma.

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ABSTRACT

Population growth and industrialization are the main reasons for the exponential increase in the electrical power demand. The major sources of the power generation are fossil fuels like coal, petroleum and gas which are depleting at a faster rate. The major concerns with these fossil fuels are the greenhouse emissions which in turn leads to climate change. Therefore, there is need to increase in the power generation from the renewable energy sources like solar, wind and bio mass. With latest technological advancements, wind energy is becoming the cheapest among all renewable energy sources. Doubly fed induction generators (DFIGs) are typically used as a variable speed wind energy conversion systems (WECSs) due to the reduction in the size of the power converters and also the converter losses. Therefore, this DFIG based WECS has the share about 50% of the total installed WECS all over the world. The DFIG based variable speed grid interfaced WECS are used for the power generation.

Normally, the voltage at the remote locations is not regulated at the desired value. This research aims the voltage regulation at the remote locations with the proper control of DFIG without adding any extra reactive power compensators. Attempts are made for achieving voltage regulation at the grid by the coordinated control of rotor side converter (RSC) and grid side converter (GSC) in addition to the conventional DFIG functionalities such as maximum power point tracking, decoupled control of active and reactive powers.

This research work also aims to investigate the solutions for volatile power generation from the grid connected WECS and also the power quality problems at the grid. The variation in the power generation prevails when the wind energy penetration increases in the total power due to its intermittent nature of wind. Therefore battery energy storage systems (BESS) is integrated with DFIG based grid connected WECS for smoothening the power and also for regulating the power

feeding to the grid irrespective of the wind speed. Attempts are also made for achieving the regulated power output by modifying the control algorithm of the GSC and also by the proper selection of BESS using the wind data of the proposed system.

A new topology of grid connected DFIG based WECS is investigated by removing the GSC and by integrating BESS in the DC link of RSC. The advantages of single voltage source converter (VSC) based DFIG are compared with the conventional double VSC based DFIG. Investigations are made on the proposed single VSC based DFIG using vector control and direct power control algorithms for the variations in the wind speed. Attempts are made for eliminating the rotor position sensor to improve the reliability and to reduce the cost. The stator flux based model reference adaptive system control and simple position sensorless algorithms are used for estimating rotor position and speed of the DFIG.

Poor power quality is another major concern for the consumers as well as generating companies. Investigations are made for improving power quality in the distribution system with DFIG based WECS. Harmonic mitigation of loads connected at PCC has been achieved by modifying the control algorithm of GSC of DFIG based WECS. Working of this DFIG as an active filter is proposed even at wind turbine stalling condition. A grid connected DFIG with BESS is also verified for both power smoothening and active filter capabilities without adding any extra power electronics component.

Detailed performance of all these configurations of grid connected DFIG based WECS for the power quality improvement are verified by the developed prototype in the laboratory using digital signal processor (DSP-dSPACE DS1103) based controller. The proposed control algorithms of DFIG are validated on a developed prototype for the dynamic changes in wind speeds.

Still there are some areas, where the electricity through the grid connection is not feasible due to geo-graphic and economic constraints. In this research work, DFIG is also used for feeding standalone consumer loads. DFIG based standalone WECS is investigated under variety of consumer loads such as linear, nonlinear and dynamic loads. A mechanical sensorless algorithm is used for estimating the rotor position and speed. DFIG based SWECS is investigated with and without BESS. A prototype of the DFIG based SWECS is developed to demonstrate the performance under different variety of loads at varying wind speeds. The performance of this DFIG based SWECS is observed for maximum power point tracking, load leveling, load balancing, a neutral current compensation and harmonic elimination while feeding different types of loads.

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LIST OF ABBREVIATIONS

AC	Alternating Current
BESS	Battery Energy Storage System
DC	Direct Current
DFIG	Doubly Fed Induction Generator
DPF	Displacement Power Factor
DSP	Digital Signal Processor
DTC	Direct Torque Control
GSC	Grid Side Converter
LSC	Load Side Converter
MPPT	Maximum Power Point Tracking
MRAS	Model Reference Adaptive System
PCC	Point of Common Coupling
PF	Power Factor
PI	Proportional and Integral
PMSM	Permanent Magnet Synchronous Machine
PWM	Pulse Width Modulation
RSC	Rotor Side Converter
SWECS	Standalone Wind Energy Conversion System
STATCOM	Static Compensator
THD	Total Harmonic Distortion
UPF	Unity Power factor
VC	Vector Control
VSC	Voltage Source Converter
WECS	Wind Energy Conversion System
WRIM	Wound Rotor Induction Machine

LIST OF SYMBOLS

i_{sa}, i_{sb}, i_{sc}	Three phase stator currents (i_{sabc})
i_{ra}, i_{rb}, i_{rc}	Three phase rotor currents(i_{rabc})
i_{ga}, i_{gb}, i_{gc}	Three phase grid currents (i_{gabc})
i_{la}, i_{lb}, i_{lc}	Three phase load currents (i_{labc})
i_{sta}, i_{stb}, i_{stc}	LSC currents in standalone WECS
i_{gsca}, i_{gscb}, i_{gscc}	Three phase grid side converter currents (i_{gscabc})
$i_{r\alpha}$, $i_{r\beta}$	Components of rotor currents in rotor co-ordinates
$i_{rs\alpha}$, $i_{rs\beta}$	Components of rotor currents in stator co-ordinates
i_{ms}	Magnetizing current
$i_{ms\alpha}$, $i_{ms\beta}$	Components of i_{ms} in stator co-ordinates
$i_{s\alpha}$, $i_{s\beta}$	Components of Stator currents in stator co-ordinates
i_{dr}^{*}	Direct axis rotor reference current
i_{qr}^{*}	Quadrature axis rotor reference current
i_{dr}	Direct axis rotor current
i_{qr}	Quadrature axis rotor current
v_{gab}, v_{gbc}, v_{gca}	Three phase grid line voltages(v_{gabc})
v_{ab}, v_{bc}, v_{ca}	Three phase stator line voltages (v_{abc})
v_r	Rotor Voltage
v_{dr}*	Direct axis reference rotor voltages
v_{qr}*	Quadrature axis reference rotor voltages
P_{rmax}	Maximum rotor active power
P_g	Grid Active Power
P_l	Load Active Power
P_s	Stator Active Power
P_{gsc}	GSC Active Power
P_{st}	LSC Active Power in standalone WECS
Q_g	Grid Reactive Power
Q_l	Load Reactive Power

Q_s	Stator Reactive Power
Q_{gsc}	GSC Reactive Power
Q_{st}	LSC Active Power in standalone WECS
$(\omega_r)_{act}$	Actual speed in rad/sec
$(\omega_r)_{est}$	Estimated speed in rad/sec
N_r	Actual Speed in rpm
N_r^*	Reference Speed in rpm
V_{dc}	DC Link voltage or BESS voltage
v_ω	Wind Speed in m/sec
θ_r	Angle of rotor current vector wrt rotor axis
θ_m	Rotor position (angle of rotor axis wrt stator axis)
θ_e	Angle of stator flux vector wrt stator axis
θ	Angle of stator voltage vector wrt stator axis
λ	*Tip Speed Ratio*
β	*Pitch Angle*
S	*Slip*
L_m	Magnetizing inductance
$\hat{\theta}_r$	estimated rotor position
S_P	active power switching states
S_Q	Reactive power switching states
$\Psi_{s\alpha}$, $\Psi_{s\beta}$	stationary frame stator flux linkages
C_p	Power Coefficient
η	Gear box ratio