INVESTIGATIONS ON DOUBLY FED INDUCTION GENERATOR BASED MICROGRID USING RENEW ABLE ENERGY RESOURCES

SHAILENDRA KUMAR TIWARI

DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI

OCTOBER 2018

INVESTIGATIONS ON DOUBLY FED INDUCTION GENERATOR BASED MICROGRID USING RENEW ABLE ENERGY RESOURCES

by

SHAILENDRA KUMAR TIWARI

DEPARTMENT OF ELECTRICAL ENGINEERING

Submitted

in fulfillment of the requirements of the degree of Doctor of Philosophy

to the

INDIAN INSTITUTE OF TECHNOLOGY DELHI INDIA

OCTOBER 2018

CERTIFICATE

It is certified that the thesis entitled **"Investigations on Doubly Fed Induction Generator based Microgrid Using Renewable Energy Resources,"** being submitted by **Mr. Shailendra Kumar Tiwari** 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 her under our supervision and guidance. The matter embodied in this thesis has not been submitted for award of any other degree or diploma.

Dated: October 29, 2018

(Dr. Bhim Singh)
Professor
Electrical Engineering Department
Institute of Technology Delhi
Hauz Khas, New Delhi-110016, India

(Dr. P.K. Goel)
Commissioner
South Delhi Municipal Corporation
Dr. Shyama Prasad Mukherjee Civic Centre
New Delhi-110002

ACKNOWLEDGEMENTS

I am extremely grateful to Prof. Bhim Singh and Dr. Puneet K. Goel for providing guidance to me in pursuit of knowledge through this research work. Prof. Bhim Singh's pursuance, perseverance and patience acted as great source of inspiration and motivation for me in completing this work. My supervisors' suggestion to work in the area of renewable energy has immensely benefitted me. The discussion with Dr. Goel on various issues of renewable energy resources and his deep insight into various aspects of this area gave me innovative ideas to bring novelty in this work.

My supervisors' suggestion to work in the area of renewable energy has immensely benefited me and I am really satisfied with the knowledge I acquired and contributed through this work. I am indeed indebted to both my supervisors for their guidance and support.

I also express my gratitude to all the SRC members, i.e., Prof. Sukumar Mishra, Prof. T. S. Bhatti, Dr. N. Senroy and Prof. Bhuvneshwari. With their probing questions and valuable suggestions, I was enthused to go deeper into the various issues of the research area.

I am really obliged to my office superiors, Mr. S.S. Mishra, Mr. M.K. Jha, Mr. B. Kamath and Mr. D. Joshi for their perpetual and unrelenting support during this work. I am also thankful to my previous departmental heads Mr. R.K. Sikri, Mr. N.C. Gurung and Mr. G. Venu for their support.

The camaraderie amongst the students of Prof. Bhim Singh is a real boon to a research scholar working in that environment. I also got immensely benefited from the environment working in P.G. machine lab for their positive attitude and support during my work. I would like to extend my sincere thanks to Dr. Vashist Bisht, Dr. Geetha Pathank, Dr. Rajan Kumar Sonkar, Dr. Ikhlaq Bohru, Mr. Shailendra Dwivedi, Mr. Aniket Anand, Mr. Anshul Varshney, Mr. Piyush Kant, Mr.

Anjanee Kumar Mishra, Mr. Utkarsh Sharma, Mr. Saurabh Shukla, Mr. Subir Karmakar and Mr. Shadab Murshid for their valuable aid support. My sincere and special thanks to Dr. N.K. Swami Naidu, Mr. P. Sambhasivaiah, Ms Seema Kewat, Mr. Manish Kumar Singh and Mr. Anjeet Verma for co-operation and support in pursuing experimental work. I am likewise thankful to those who directly or indirectly helped me to finish my dissertation study.

The project and research work of the students can't be completed without the active co-operation from the laboratory and other staff of the concerned Department. I want to express my sincere thanks to staff of P.G. Machine Lab, Sh. Shrichand, Sh. Puran Singh and Sh. Jitendra of the Department of Electrical Engineering for their support.

This section can't be complete without mention of the support I always get from my wife, Priti, in pursuit of academic excellence. Her faith and belief in my potential has always given me inspiration to accept higher goals and challenges on the academic front, despite the pressure of my job. My son Samagra and daughter Shrishti were very much conscious of my difficulties and showed lot of maturity and understanding, whenever I was not able to devote enough time on them. I am sure I would be able to make up for this loss.

My deepest love, appreciation and indebtedness go to my parents for their ambitions, sacrifices and whole hearted support. I must appreciate my brothers Arvind and Sunil who were always behind me to provide the moral support for achieving this academic level.

I truly thank Almighty for giving me mental strength and support to take up and complete this research work.

Dated: October 29, 2018 (Shailendra K. Tiwari)

IIT Delhi, New Delhi

ABSTRACT

This research work deals with design and implementation of wind energy based microgrid using power electronics converters with or without other energy sources e.g. solar and diesel. The machine used as a wind energy generator is the doubly fed induction generator (DFIG). With intelligent control, the microgrid is able to provide a quality power to the consumers for all type of loads. Some of the power quality issues faced by the consumer fed from a microgrid are unbalanced load, harmonics, sag and swell of voltage etc. The wind and solar energy sources need to be operated at maximum power point tracking (MPPT).

Various control algorithms are implemented for satisfactory performance of these microgrids under steady state and dynamic conditions. These control algorithms provide voltage regulation, harmonics and unbalanced currents compensation as well as MPPT. The control algorithm through PE converters also helps to meet the unpredictable and varying load demand with the help of battery energy storage. The MPPT used for wind energy generator is tip speed ratio (TSR), hill climb search (HCS) and adaptation methods.

Multi-source microgrid increases the reliability as well as reduces battery storage requirements. Multi-source generation also reduces rating of electrical and power electronics components. This work also presents the sizing criteria of the components used in the system. In case of wind and solar based power generation, the control has been presented so as both the sources operate at MPPT. The MPPT of the solar PV power generation is realised using perturb and observe (P&O) and incremental conductance (INC) approaches.

Multi-source generation involving wind-diesel microgrid, the pooling of power from both sources is done in AC side. With the help of the control algorithm, voltage profile is maintained at disconnection and re-connection of wind energy generator is achieved. Control algorithms have been presented so as all the electrical parameters remain within requirements of applicable standards.

Another important function of the microgrid is its synchronization and de-synchronization to the utility grid. Control apporaches are presented for seamless connection to the microgrid, in case of availability of the grid. Vice-versa, in case of sudden outage of the grid, the control algorithm continues to provide the power within the requirement of applicable standards.

Microgrids comprising of various configuration are presented, which are capable for provide voltage and frequency control in all operating mode. The satisfactory performances of these microgrids are demonstrated with simulation results obtained using developed models in MATLAB/Simulink and their validation is done with experimental results obtained on the developed prototypes in the laboratory.

सार

यह शोध कार्य पवन एवम अन्य अक्षय उर्जा स्रोतों पर आधरित माइक्रोग्रिड के डिज़ाइन एवम क्रियान्वयन पर आधरित है। पवन उर्जा के लिए ड्बली फैड इंडक्शन जनरेटर का प्रयोग किया गया है। माइक्रोग्रिड गुणवत्ता विद्युत उर्जा देने मे सक्षम है। विद्युत उर्जा के ग्राहकों द्वरा अनबैलेंस्ड लोड, वोलटेज का सैग, स्वेल्ल, हार्मोनिक्स जैसे समस्याओं का प्राय: सामना करना पड्ता है। पवन एवम सौर उर्जा स्रोतों को अधिकतम उत्पादन हेतु मेक्सिम्म पावर पोइंट ट्रैकींग(एम.पी. पी. टी.) पर कार्य करने की आवश्यकता है। कई कन्ट्रोल अल्गोरिथिम का कार्यान्वित कर माइक्रोग्रिड का स्टडी स्टेट एवम डयनेमिक अवस्था का संतोषजनक प्रदर्शन किया गया है। कन्ट्रोल अल्गोरिथिम वोलटेज रेगुलेश्न, हर्मोनिक्स एवम अनबैलेंस्ड करैन्ट का कौम्पेंसेशन कर पावर क्वालिटि समस्याओं का निवारण करता है। कन्ट्रोल अल्गोरिथिम पावर इलेक्ट्रोनिक कनवर्टर के द्वरा अप्रत्याशित एवम निरंतर बदलते लोड पर विद्युत उर्जा प्रदान करता है। पवन अक्षय कनवर्सन के लिए टिप स्पिड रेशियो, हिल क्लाइम्ब सर्च एवम अडैप्टेशन विधि का प्रयोग किया है।

बहु-स्रोत माइक्रोग्रिड बैटरी स्टोरेज के साथ विद्युत उर्जा की विश्वसनीयता मे सुधार करता है। बहु-स्रोत उत्पादन प्रणाली विद्युत एवम पवर इलेक्ट्रोनिक कनवर्टर का रेटिंग भी कम रखता है। शोध कार्य, उर्जा प्रणाली में प्रयोग होने वाले सभी घटको का की

साइज़िंग क्राईटीरिया भी प्रस्तुत किया गया है। पवन एवम सौर उर्जा प्रणाली का नियंत्रण एम.पी. पी. टी. पर कार्य करता है। सौर उर्जा का एम.पी. पी. टी. कन्ट्रोल परटर्ब एंड औबसर्ब एवम इंक्रिमेंट कनंडक्टेंस विधि पर आधारित है।

पवन-डीजल माइक्रोग्रिड में दोनो स्रोतो का पूलिंग ए.सी टर्मिनल पे किया जाता है। कन्ट्रोल अल्गोरिथिम के सहयोग से प्रणाली, पवन उर्जा स्रोत का संयोजन एवम वियोग पर भी वोलटेज प्रोफाइल को स्वीकार्य सीमा में रखने में सक्षम है।

कन्ट्रोल अल्गोरिथिम प्रस्तुत किया गया है जो की विद्युत पैरामीटर को उपयुक्त स्टेंड्ड में रखता है। माइक्रोग्रिड का वांछनीय आवश्यक्ता ग्रिड के साथ सिंक्रोनाइजेस्न एवम डि-सिंक्रोनाइजेस्न भी है। माइक्रोग्रिड प्रणाली, अपने कनट्रोल अल्गोरिथिम के द्वारा ग्रिड उपलब्ध्अता पर स्वत: निर्बाध रुप से सम्बंध स्थापित कर लेता है। इसी तरह ग्रिड की आउटेज की स्थिति में पावर क्वालिटि को बनाए रखता है।

इस शोध कार्या मे माइक्रोग्रिड के कई कॉन्फ़िगरेशन प्रस्तुत किया गया है जो कि सभी अवस्था में वोल्टेज एवम फ्रिक्वेंसी कंट्रोल करने में सक्षम है। माइक्रोग्रिड का संतोषजनक प्रदर्शन मैट्लैब/सिमुलिंक के द्वारा सिमुलेशन परिणाम एवम इसका प्रायौगिक सत्यापन भी प्रयोगशाला मे प्रोटोटाइप के द्वरा किया गया है।

TABLE OF CONTENTS Page No.

LIST OF FIGURES

LIST OF TABLES

LIST OF ABREVIATION

ADC	Analog to Digital Converter
AH	Ampere-Hour
BES	Battery Energy Storage
DG	Diesel Generator
DFIG	Doubly Fed Induction Generator
FEZ	Fuel Efficient Zone
EESG	Electrically Excited Synchronous Generator
GCB	Generator Circuit Breaker
GHG	Green House Gasses
HCS	Hill Climb Search
InC	Incremental Conductance
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
MRAS	Model Reference and Adaptive System
LSC	Load Side Converter
PCB	Printed Circuit Board
PE	Power Electronic
PES	Power Electronics Switch
PI	Proportional and Integral
P&O	Perturb and Observe
PV	Photovoltaic
PCC	Point of Common Connection

PMSG	Permanent Magnet Synchronous Generator
PMBLDCG	Permanent Magnet Brushless DC Generator
RE	Renewable Energy
RSC	Rotor Side Converter
SCIG	Stator Controlled Induction Generator
S-MPPT	MPPT for Solar PV Array
STC	Standard Test Condition for Solar PV Module
SOC	State of Charge of Battery bank
TSR	Tip Speed Ratio
VFC	Voltage and Frequency Control
VSCs	Voltage Source Converters
W-MPPT	MPPT for Wind Energy Generator
WEG	Wind Energy Generator
WECS	Wind Energy Conversion System
WSM	Wind Solar Micro-grid
WDM	Wind Diesel Hybrid System
WDSM	Wind-Diesel-Solar Microgrid
DMWM	Dual Mode Wind Based Microgrid
GCWSM	Grid Connected Wind Solar Microgrid

LIST OF SYMBOLS

C_p	Coefficient of power
C_{pr}	Coefficient of power at rated wind speed
D	Duty Ratio of Converter
D_1/D_2	Duty ratio in buck and boost mode respectively for buck-boost converter
E_w	Energy generated by WEG for a specified period
E_s	Energy generated by solar array for a specified period
E_{net}	Net energy generated by WEG & Solar array (if applicable)
E_{con}	Energy consumed through connected loads and losses
f_L	Load frequency
f_g	Grid frequency
f_{sw}	Switching frequency
G	Solar Radiation in kW/m^2
I_{pv}	Solar array current
I_{sc}	Short Circuit Current of cell or module
I_{mpp}	Short Circuit current of cell or module
i_{drs}	Rated current of devices used in Solar PV system
I_{ms0}	No-load DFIG magentising current at DC reference
I_{dr}	Direct axis rotor current
I_{qr}	Quadrature axis rotor current
I_{qrs}	Steady state value of I_{qr} after sampling
I_{ds}	Direct axis stator current
I_{qs}	Quadrature axis stator current

I_{bd}	Direct axis RSC current in battery charging mode
I_{dcp}	load component of current at the point of interconnection(converter side)
I_{dcp}	quadrature component of current at the point of interconnection (converter side)
i_{gabc}	Grid currents
i_{labc}	Load currents
i_{sabc}	Stator current of DFIG
i_{rabc}	Rotor current of DFIG
i_{cabc}	Converter current
i_{rpl}	Ripple current
I_{LSC}	LSC current at rated condition
I_{RSC}	RSC current at rated condition
L_{b1}/L_{b2}	Inductance requirement in buck and boost mode respectively for buck-boost converter
L_b	Value of input Inductance DC-DC converter
m_i	Modulation index of converter
N_c	Number of cell in a solar PV string
Q_s	Reactive in p.u.
r	turbine rotor length
T	Ambient Temperature
V_{dcm}	Minimum DC bus Voltage
V_{DCTH}	DC bus threshold voltage
V_{drs}	Rated voltage of devices used in Solar PV system
V_{occ}	Open circuit voltage of cell

V_{ocamax}	Maximum allowable open circuit voltage of solar PV array
V_{mppc}	Cell voltage at MPP
V_{mpp}	Module voltage at MPP
$V_{mppamin}$	Minimum allowable MPP voltage of solar PV array
$V_{mppamax}$	Maximum allowable MPP voltage of solar PV array
V_m	Module operating voltage
V_{pv}	Solar PV array voltage
V_{Pw}	Amplitude of the voltage of wind energy generator
V_{PL}	Amplitude of the system (or load) Voltage
v_{Labc}	Phase voltages of load
v_{sabc}	Stator Voltage of wind energy generator
V_w	Wind Speed
V_{wr}	Rated Wind Speed
V_{wm}	Maximum wind speed upto which Turbine operates in MPPT
W_{bat}	Ampere-Hour Capacity of BES
ρ	Density of air
P_m	Mechanical power output of wind turbine
P_s	Stator power of DFIG
P_a	Air gap power of WEG
P_{smax}	Stator power of DFIG at rated load conditions
P_r	Rotor power of DFIG
P_{rmax}	Rotor power of DFIG at rated load conditions
P_{er}	Rated Electrical power of DFIG

P_w	Gross Power output of WEG
P_{mr}	Rated Mechanical Power of Wind turbine
P_b	Battery power
P_{sol}	Power from PV array
P_L	Active power of load
P_{exp}	Exported power to the grid
Q_g	Reactive power fed to the grid
I_{qs}, I_{ds}	Direct axis and quadrature axis stator current
i_b	Battery current
i_{qrs}	Steady state current of i_{qr}
p	Number of poles
s_{pmax}	slip at maximum power
u_{ap}, u_{bp}, u_{cp}	In-phase unit template
u_{aq}, u_{bq}, u_{cq}	Quadrature unit template
V_{Labc}	Load phase voltages
V_{Lr}	rms value of line to line load voltage
V_{dc}	DC link voltage
V_r	rms value of phase voltage
V_b	Battery voltage
ΔP_a	Change of air gap power of WEG
ΔT_{TH}	Temperature rise to cell/module due to incident solar radiation
η	Gear ratio
λ	Tip speed ratio

ω_r	Rotor angular speed
θ_r	Rotor position
$\theta_{statorflux}$	Stator field angle
θ_{mech}	Rotor mechanical angle
θ_{slip}	Rotor slip angle
θ_{TR}	Transformation angl for RSC
θ_{TL}	Transformation angl for LSC
Superscripts	
*	Reference value
Subscript	
d, q	d-axis and q-axis component
err	error
G	Gear train
L	Load
Lr	Line r.m.s
m	Mechanical
sol	Solar
rm	rotor parameter at maximum rang of W-MPPT
r, s	Rotor or stator quantities
T	Turbine
w	Wind