CONTROL OF MICROGRIDS EMPLOYING WIND DRIVEN SWITCHED RELUCTANCE GENERATOR AND PHOTOVOLTAIC ARRAY WITH SEAMLESS SYNCHRONIZATION

VIVEK NARAYANAN

DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
HAUZ KHAS, NEW DELHI – 110016, INDIA
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by

VIVEK NARAYANAN
Electrical Engineering Department

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CERTIFICATE

It is certified that the thesis entitled "**Control of Microgrids Employing Wind Driven Switched Reluctance Generator and Photovoltaic Array with Seamless Synchronization**," being submitted by **Mr. Vivek Narayanan** 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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(Prof. Bhim Singh)
Electrical Engineering Department
Indian Institute of Technology Delhi
Hauz Khas, New Delhi-110016, India

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ABSTRACT

Electrification and efficiency are essential drivers of the energy shift, made possible by renewables, hydrogen, and sustainable biomass. Due to falling prices, solar and onshore wind are forecasted to account for most renewable energy source (RES) growth, accounting for 43% and 26% of generation in 2050. The Intergovernmental Panel on Climate Change (IPCC) projects that "global net human-caused CO_2 emissions would need to be decreased by around 45% from 2010 levels by 2030, reaching 'net zero' around 2050" in order to limit global warming at 1.5^0C.

In this thesis, a number of grid-connected and standalone configurations of microgrids are designed for integrating renewable sources such as solar and wind based on areas, applications, type of energy sources, supply reliability, cost, and the power quality (PQ) aspects for providing uninterrupted power to the loads. Moreover, with battery energy storage (BES) and coordinated control, the proposed microgrid solves the problem of intermittent renewable generation. Here, a switched reluctance generator (SRG) is adopted for converting the mechanical power output from the wind turbine (WT) into electricity. Moreover, the SRG is operated with a sensorless technique to determine the position and speed for its effective control with the ability to harvest the peak power available in the wind energy.

The proposed microgrids address the problems related to electrification in the accessible areas of the electric grid and in regions with a weak or nonexistent grid. In grid-connected configurations, the power generated by the RES is shared between the local loads and the utility grid. In the standalone systems, the microgrid is combined with a diesel generator (DG) set to realize a reliable solution to provide uninterrupted electricity to local loads at remote places. Moreover, it is guaranteed through the control and the storage battery that the DG set is always utilized optimally by operating into the fuel-efficient zone, irrespective of the variation in the load demand.

The unbalanced, distorted, and failure of the utility grid are severe concerns in the microgrid. As a result, it must guarantee that the microgrid operates without generating any interruptions in supplying the critical loads. Moreover, substantial power electronics converter-based nonlinear loads are used in domestic applications, which have given rise to serious PQ issues, such as harmonics, unbalanced loading, poor power factor operation, voltage distortion, etc., and have drawn the most attention in distribution systems. This causes mal-operation of appliances, increased losses, and poor power factor on the grid. Therefore, algorithms are needed to manage the voltage source converter (VSC) with rapid reaction, fluctuation-free, and well-structured operation. In this thesis, robust control techniques are designed and developed for multimode operations of microgrids as well as to regulate the voltage and frequency of microgrids irrespective of the load condition and renewable sources availability. All microgrid configurations are modeled and simulated in the MATLAB/Simulink platform. Simulated performances are validated using an experimental microgrid setup developed in the laboratory. The results showcase the satisfactory performance of microgrids under different practical scenarios.

सार

विद्युतीकरण और दक्षता, ऊर्जा बदलाव के आवश्यक चालक हैं, जो नवीकरणीय ऊर्जा, हाइड्रोजन और टिकाऊ बायोमास द्वारा संभव बनाया गया है। गिरती कीमतों के कारण, अनुमान है कि 2050 में सौर और तटवर्ती पवन सबसे अधिक रिन्यूएबल एनर्जी सोर्स (आरईएस) की वृद्धि के लिए जिम्मेदार होंगे, जो 43% और 26% उत्पादन के लिए जिम्मेदार होंगे। इंटरगवर्नमेंटल पैनल ऑन क्लाइमेट चेंज (आईपीसीसी) का अनुमान है कि ग्लोबल वार्मिंग को 1.5^0C पर सीमित करने के लिए "वैश्विक शुद्ध मानव-जनित CO_2 उत्सर्जन को 2030 तक 2010 के स्तर से लगभग 45% कम करने की आवश्यकता होगी, जो 2050 के आसपास 'शुद्ध शून्य' तक पहुंच जाएगा"।

इस थीसिस में, माइक्रोग्रिड के कई ग्रिड-कनेक्टेड और स्टैंडअलोन कॉन्फ़िगरेशन को क्षेत्रों, अनुप्रयोगों, ऊर्जा स्रोतों के प्रकार, आपूर्ति विश्वसनीयता, लागत और पावर क्वालिटी (पीक्यू) पहलुओं के आधार पर सौर और पवन जैसे नवीकरणीय स्रोतों को एकीकृत करने के लिए डिज़ाइन किया गया है, लोड को निर्बाध बिजली प्रदान करने के लिए। इसके अलावा, बैटरी एनर्जी स्टोरेज (बीईएस) और समन्वित नियंत्रण के साथ, प्रस्तावित माइक्रोग्रिड आंतरायिक नवीकरणीय उत्पादन की समस्या को हल करता है। यहां, विंड टरबाइन (डब्ल्यूटी) से यांत्रिक बिजली उत्पादन को बिजली में परिवर्तित करने के लिए एक स्विच्ड रीलक्टन्स जनरेटर (एसआरजी) को अपनाया जाता है। इसके अलावा, एसआरजी को पवन ऊर्जा में उपलब्ध पीक पावर का दोहन करने की क्षमता के साथ इसके प्रभावी नियंत्रण के लिए स्थिति और गति निर्धारित करने के लिए सेंसर रहित तकनीक से संचालित किया जाता है।

प्रस्तावित माइक्रोग्रिड विद्युत ग्रिड के सुलभ क्षेत्रों और कमजोर या अस्तित्वहीन ग्रिड वाले क्षेत्रों में विद्युतीकरण से संबंधित समस्याओं का समाधान करते हैं। ग्रिड से जुड़े कॉन्फ़िगरेशन में, आरईएस द्वारा उत्पन्न बिजली को स्थानीय लोड और उपयोगिता ग्रिड के बीच साझा किया जाता है। स्टैंडअलोन सिस्टम में, दूरस्थ स्थानों पर स्थानीय लोड को निर्बाध बिजली प्रदान करने के लिए एक विश्वसनीय

समाधान का एहसास करने के लिए माइक्रोग्रिड को डीजल जनरेटर (डीजी) सेट के साथ जोड़ा जाता है। इसके अलावा, नियंत्रण और स्टोरेज बैटरी के माध्यम से यह गारंटी दी जाती है कि लोड मांग में भिन्नता के बावजूद, डीजी सेट को ईंधन-कुशल क्षेत्र में संचालित करके हमेशा इष्टतम उपयोग किया जाता है। उपयोगिता ग्रिड का असंतुलित, विकृत और विफलता माइक्रोग्रिड में गंभीर चिंता का विषय है। परिणामस्वरूप, उसे यह गारंटी देनी होगी कि माइक्रोग्रिड महत्वपूर्ण भार की आपूर्ति में कोई रुकावट पैदा किए बिना काम करता है। इसके अलावा, घरेलू अनुप्रयोगों में पर्याप्त पावर इलेक्ट्रॉनिक्स कनवर्टर-आधारित नॉनलाइनियर लोड का उपयोग किया जाता है, जिसने हार्मोनिक्स, असंतुलित लोडिंग, खराब पावर फैक्टर ऑपरेशन, वोल्टेज विरूपण इत्यादि जैसे गंभीर पीक्यू मुद्दों को जन्म दिया है और सबसे अधिक डिस्ट्रिब्यूटेड सिस्टम में ध्यान आकर्षित किया है। इससे उपकरणों का खराब संचालन, घाटा बढ़ना और ग्रिड पर खराब पावर फैक्टर होता है। इसलिए, तीव्र प्रतिक्रिया, उतार-चढ़ाव-मुक्त और अच्छी तरह से संरचित संचालन के साथ वोल्टेज सोर्स कनवर्टर (वीएससी) को प्रबंधित करने के लिए एल्गोरिदम की आवश्यकता होती है। इस थीसिस में, माइक्रोग्रिड के मल्टीमोड संचालन के साथ-साथ लोड की स्थिति और रिन्यूएबल सोर्स की उपलब्धता के बावजूद माइक्रोग्रिड के वोल्टेज और आवृत्ति को विनियमित करने के लिए मजबूत नियंत्रण तकनीकों को डिजाइन और विकसित किया गया है।

सभी माइक्रोग्रिड कॉन्फ़िगरेशन को MATLAB/Simulink प्लेटफ़ॉर्म में मॉडल और सिम्युलेटेड किया गया है। प्रयोगशाला में विकसित प्रायोगिक माइक्रोग्रिड सेटअप का उपयोग करके सिम्युलेटेड प्रदर्शनों को मान्य किया गया है। परिणाम विभिन्न व्यावहारिक परिदृश्यों के तहत माइक्रोग्रिड के संतोषजनक प्रदर्शन को दर्शाते हैं।

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

RES	Renewable energy sources
DER	Distributed energy resources
PV	Photovoltaic
MPP	Maximum power point
MPPT	Maximum power point tracking
P&O	Perturb and observe
IP&O	Improved perturb and observe
INC	Incremental-conductance
WEGS	Wind energy generation system
WT	Wind turbine
SRG	Switched reluctance generator
SCIG	Squirrel cage induction generator
DFIG	Doubly fed induction generator
SG	Synchronous generator
PMSG	Permanent magnet synchronous generator
SynRG	Synchronous reluctance generator
AHB	Asymmetric half-bridge
SMPO	Sliding mode position observer
PSO	Particle swarm optimization
ITAE	Integral time absolute error
ITSE	Integral time square error
ITE	Integral absolute error
ISE	Integral square error
HCM	Hysteresis or chopping mode
SPM	Single pulse mode
TSR	Tip speed ratio
DG	Diesel generator
AVR	Automatic voltage regulator
BES	Battery energy storage
SOC	State of charge
BDC	Bidirectional DC-DC converter
VSC	Voltage source converter
IGBT	Insulated-gate bipolar transistor
PCC	Point of common coupling
DSTATCOM	Distribution static compensator
DBR	Diode bridge rectifier
PQ	Power quality
THD	Total harmonic distortion
UPF	Unity power factor
GCM	Grid-connected mode
SAM	Standalone mode
DGM	Diesel generator mode
CCM	Current control mode
VCM	Voltage control mode
STS	Solid transfer switch
PI	Proportional-integral

LPF	Low pass filter
BPF	Band pass filter
HPF	High pass filter
HCC	Hysteresis current controller
PWM	Pulse width modulation
PLL	Phase-locked loop
FLL	Frequency-locked loop
PSC	Positive sequence component
IRPT	Instantaneous reactive power theory
SRFT	Synchronous reference frame theory
SOGI	Second-order generalized integrator
SOSOGI	Second-order second-order generalized integrator
CSOGI	Cascaded second-order generalized integrator
CNISOGI	Cascaded non-identical second-order generalized integrator
MNF-SOGI	Modified notch filter-second order generalized integrator
ISOGI-FLL	Improved second-order generalized integrator-frequency locked loop
SOGI-FLL-WDCRC	Second-order generalized integrator-frequency locked loop with DC-offset rejection capacity
TOGI	Third-order generalized integrator
TOGI-FLL-WDL	Third-order generalized integrator frequency-locked loop with DC-loop
MSTOGI	Mixed second and third-order generalized integrator
MTFOGI	Mixed third–fourth order generalized integrator
FOGI	Fifth-order generalized integrator
EAF	Enhanced adaptive filter
LMS	Least mean square
LMF	Least mean fourth
VSSMCLMS	Variable step size modified clipped least mean square
RNLMAT	Robust normalized least mean absolute third
WZA-LLMS	Weighted zero-attracting leaky least mean square
IVZA-LMS	Improved variable zero-attracting least mean square
JLHCAF	Joint logarithmic hyperbolic cosine adaptive filter
VLMS/F	Volterra least mean square/fourth
RLMLS	Robust least mean logarithmic square
VSS-ℓ0-NLMS	Variable step-size ℓ0-norm normalized least mean square
MLLMS	Modified leaky-least mean square

LIST OF SYMBOLS

V_{pv}	PV array voltage
I_{pv}	PV array current
P_{pv}	PV array power
V_{oc}	Open circuit PV voltage
I_{sc}	Short circuit PV current
$V_{mpp}, I_{mpp}, P_{mpp}$	PV array MPP voltage, current, and power
L_b	Boost inductance
V_{dc}, V^*_{dc}, V_{de}	Sensed and reference DC-link voltage and their error
C_{dc}	DC-link capacitor of VSC
m	Modulation index
a	Overloading factor
V_b	Battery voltage
I_b, I^*_b, I_{be}	Sensed and reference battery current and their error
L_{bb}	BDC inductance
V_{vsc}, I_{vsc}	VSC switch voltage and current
k	Safety factor
L_f	Interfacing inductor
R_f, C_f	Ripple filter
v_{gab}, v_{gbc}	Sensed grid line voltages
v_{ga}, v_{gb}, v_{gc}	Grid phase voltages
$v_{g\alpha}$, $v_{g\beta}$	Grid voltages in $\alpha\beta$ frame
$v^+_{g\alpha}$, $v^+_{g\beta}$	PSCs of grid voltages in $\alpha\beta$ frame
v^+_{ga}, v^+_{gb}, v^+_{gc}	PSCs of grid voltages in *abc* frame
u_{gpa}, u_{gpb}, u_{gpc}	In-phase unit templates of PSCs of grid voltages
u_{gqa}, u_{gqb}, u_{gqc}	Quadrature unit templates of PSCs of grid voltages
V_{tg}	Amplitude of PSCs of grid voltages
i_{ga}, i_{gb}, i_{gc}	Sensed grid currents
i^*_{ga}, i^*_{gb}, i^*_{gc}	Reference grid currents
v_{Lab}, v_{Lbc}	Sensed PCC line voltages
v_{La}, v_{Lb}, v_{Lc}	PCC phase voltages
v^*_{La}, v^*_{Lb}, v^*_{Lc}	Reference PCC voltages
V^*_{tL}, ω_L	Amplitude and frequency of reference PCC voltages
i_{La}, i_{Lb}, i_{Lc}	Sensed load currents
P_L	Load power
i_{vsc}, i^*_{vsc}	VSC currents and reference VSC currents
v_{dga}, v_{dgb}, v_{dgc}, V_{tdg}	DG set voltages and their amplitude
u_{dgpa}, u_{dgpb}, u_{dgpc}	In-phase unit templates of DG set voltages
u_{dgqa}, u_{dgqb}, u_{dgqc}	Quadrature unit templates of DG set voltages
i_{dga}, i_{dgb}, i_{dgc}	Sensed DG currents
i^*_{dga}, i^*_{dgb}, i^*_{dgc}	Reference DG currents
θ_g, θ_{dg}, θ_L	Phase angles of grid, DG, and load voltages
f_g, f_{dg}	Frequency of grid and DG voltages
W_{pv}	Feed-forward weight of PV power
W_{La}, W_{Lb}, W_{Lc}	Fundamental active weights of load currents of phase ‘a’, ‘b’, and ‘c’
W_{Lavg}	Average fundamental active weight of load currents
W_g, W_{dg}	Amplitude of grid and DG currents

K_{pv}, K_{iv}, K_{pi}, K_{ii}	Proportional and integral gains of outer and inner PI controllers of BDC
ρ	Air-specific density
A	Area occupied by the WT blades
C_p	Power coefficient
λ	Tip speed ratio
β	Pitch angle
V_w	Wind speed
I_A, I_B, I_C, I_D	SRG phase currents
V_A, V_B, V_C, V_D	SRG phase voltages
ω_r	SRG speed
T	Torque
P_w	Power output from WEGS
W_W	Feed-forward weight of wind power
L_a	Aligned inductance
L_u	Unaligned inductance
R	Winding resistance
J	Inertia
B	Friction coefficient
θ_{on}	Turn-on angle
θ_{off}	Turn-off angle
ψ	Flux-linkage
ψ_m	Measured flux-linkage
ψ_{est}	Estimated flux-linkage
ψ_e	Flux-linkage error
σ_s	Sliding surface
ω_{est}, θ_{est}	Estimated speed and position
k_α, k_ω, k_θ	SMPO gains
e_θ, e_ω, e_α	Estimate errors for position, speed, and acceleration