INVESTIGATIONS ON UTILITY SYNCHRONIZED MICROGRIDS WITH SOLAR-WIND-HYDRO GENERATION

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INVESTIGATIONS ON UTILITY SYNCHRONIZED MICROGRIDS WITH SOLAR-WIND-HYDRO GENERATION

by

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CERTIFICATE

It is certified that the thesis entitled "**Investigations on Utility Synchronized Microgrids with Solar-Wind-Hydro Generation**," being submitted by **Ms. Rohini Sharma** 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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Rohini Sharma

ABSTRACT

Resilience and reliability of the microgrids are a vital issue, as it not only decreases the power outage, but it allows high penetration of various distributed energy resources such as renewables (solar, wind, hydro) and battery energy storage. Microgrid (MG) is a small-scale power network that functions either in the grid-connected (GC) mode or an islanding (IS) mode. In both these modes of operation and transition from an IS mode to the GC mode and vice-versa, the distributed energy resources (DER) in microgrid (MG) are controlled by using various control techniques. Therefore, this thesis deals with the design, control and implementation of various configurations integrating solar PV, pico-hydro generation, wind energy conversion system, battery storage, grid/DG set and local loads. These configurations are segregated on the basis number of energy sources (one or multiple), the configuration of each source (single stage or double stage) and types of loads (single-phase, three-phase, dynamic loads). The solar and wind generations are intermittent and thus used in conjunction with pico-hydro generation to guarantee that the baseload is supplied at all times. This MG operates in multiple modes like islanded mode, grid-connected mode and DG set connected mode to facilitate uninterrupted power to local loads. Moreover, few configurations have DG set, irrespective of the fact that the DG set utilizes diesel, which is not clean. Diesel power provides reliability that supports critical loads (hospitals) when renewable energy and battery power are insufficient. However, the DG set operates in the fuel-efficient zone under load unbalance conditions as it is supported through a battery storage. The core objective of the system is to deliver power to critical loads even at the grid outage.

A prime research feature for a microgrid is its appropriate control, which assures uniform power as well as current allocation between distributed generation units while operating in different operating conditions. A single voltage source converter achieves significant roles like frequency and voltage regulation (in islanded and DG set connected mode), energy management between generating units and loads, compensating the harmonics current demand of local nonlinear load and dynamic reactive power demand of dynamic loads (Induction Motor). Therefore, the VSC control is the eminent part of the MG and for the satisfactory operation, it should be fast and robust. In this thesis, various control algorithms are implemented and these controls provide reduced steady-state error, enhanced convergence rate, DC offset rejection capability to achieve accurate extraction of the fundamental component of nonlinear load currents.

The satisfactory performance of these microgrids and their control algorithms are replicated through simulated results, which are modelled in MATLAB/Simulink platform using Simpower toolbox and test results on the developed hardware prototype. Simulated and test results are presented for adverse conditions like solar intensity change, wind speed change and unbalanced load conditions.

सार

माइक्रोग्रिड का लचीलापन और विश्वसनीयता एक महत्वपूर्ण मुद्दा है, क्योंकि यह न केवल बिजली की कमी को कम करता है, बल्कि यह विभिन्न वितरित ऊर्जा संसाधनों जैसे नवीकरणीय (सौर, पवन, हाइड्रो) और बैटरी ऊर्जा भंडारण के उच्च प्रवेश की अनुमति देता है। माइक्रोग्रिड (एमजी) एक छोटे पैमाने का बिजली नेटवर्क है जो या तो ग्रिड-कनेक्टेड मोड या एक आइलैंडिंग मोड में कार्य करता है। आइलैंडिंग मोड से ग्रिड-कनेक्टेड मोड में संचालन और संक्रमण के इन दोनों तरीकों में और इसके विपरीत, माइक्रोग्रिड (एमजी) में वितरित ऊर्जा संसाधन (डीईआर) को विभिन्न नियंत्रण तकनीकों का उपयोग करके नियंत्रित किया जाता है। इसलिए, यह थीसिस सौर पीवी, पिको-हाइड्रो उत्पादन, पवन ऊर्जा रूपांतरण प्रणाली, बैटरी भंडारण, ग्रिड / डीजी सेट और लोकल लोड को एकीकृत करने वाले विभिन्न विन्यासों के डिजाइन, नियंत्रण और कार्यान्वयन से संबंधित है। इन विन्यासों को ऊर्जा स्रोतों की संख्या (एक या एकाधिक), प्रत्येक स्रोत के विन्यास (एकल चरण या दोहरे चरण) और भार के प्रकार (एकल-चरण, तीन-चरण, गतिशील भार) के आधार पर अलग किया जाता है। सौर और पवन पीढ़ी रुक-रुक कर होती है और इस प्रकार पिको-हाइड्रो पीढ़ी के साथ संयोजन में उपयोग की जाती है ताकि यह सुनिश्चित हो सके कि हर समय बेसलोड की आपूर्ति की जाती है। यह MG कई मोड में काम करता है जैसे कि आईलैंडेड मोड, ग्रिड-कनेक्टेड मोड और DG सेट कनेक्टेड मोड, ताकि लोकल लोड को निर्बाध बिजली मिल सके। इसके अलावा, कुछ कॉन्फ़िगरेशन में डीजी सेट होता है, इस तथ्य के बावजूद कि डीजी सेट डीजल का उपयोग करता है, जो साफ नहीं है। डीजल विश्वसनीयता पावर प्रदान करती है जो नवीकरणीय ऊर्जा और बैटरी पावर अपर्याप्त होने पर महत्वपूर्ण लोड (अस्पतालों) का समर्थन करती है। हालांकि, डीजी सेट ईंधन-कुशल क्षेत्र में लोड असंतुलन स्थितियों के तहत संचालित होता है क्योंकि यह बैटरी स्टोरेज के माध्यम से समर्थित होता है। सिस्टम का मुख्य उद्देश्य ग्रिड आउटेज पर भी महत्वपूर्ण लोड को बिजली पहुंचाना है।.

एक माइक्रोग्रिड के लिए एक प्रमुख अनुसंधान विशेषता इसका उपयुक्त नियंत्रण है, जो विभिन्न परिचालन स्थितियों में काम करते हुए वितरित उत्पादन इकाइयों के बीच समान शक्ति के साथ-साथ वर्तमान आवंटन का आश्वासन देता है। एक एकल वोल्टेज स्रोत कनवर्टर आवृत्ति और वोल्टेज विनियमन (आइलैंडिंग मोड और डीजी सेट कनेक्टेड मोड में), उत्पादन इकाइयों और लोड के बीच ऊर्जा प्रबंधन, स्थानीय गैर-रेखीय लोड की हार्मोनिक्स वर्तमान मांग और गतिशील भार की गतिशील प्रतिक्रियाशील बिजली की मांग की भरपाई जैसी महत्वपूर्ण भूमिकाएं प्राप्त करता है। इसलिए, वीएससी नियंत्रण एमजी का प्रमुख हिस्सा है और संतोषजनक संचालन के लिए, यह तेज और भरोसेमंद होना चाहिए। इस थीसिस में, विभिन्न नियंत्रण एल्गोरिदम लागू किए गए हैं और ये नियंत्रण कम स्थिर-राज्य त्रुटि, बढ़ी हुई अभिसरण दर, डीसी ऑफ़सेट अस्वीकृति क्षमता प्रदान करते हैं ताकि गैर-रेखीय लोड धाराओं के मौलिक घटक के सटीक निष्कर्षण को प्राप्त किया जा सके।.

इन माइक्रोग्रिड और उनके नियंत्रण एल्गोरिदम के संतोषजनक प्रदर्शन को सिम्युलेटेड परिणामों के माध्यम से सत्यापित किये जाये है, जो कि सिमपॉवर टूलबॉक्स का उपयोग करके MATLAB/Simulink प्लेटफॉर्म में तैयार किए जाते हैं और विकसित हार्डवेयर प्रोटोटाइप पर परीक्षण के परिणाम हैं। सौर तीव्रता परिवर्तन, हवा की गति परिवर्तन और असंतुलित भार स्थितियों जैसी प्रतिकूल परिस्थितियों के लिए परीक्षण के परिणाम प्रस्तुत किए गए है।

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LIST OF ABBREVIATIONS

AAF-FLL	Advanced Adaptive FilterFrequency Locked Loop
3IMPL	Three Phase Improved Magnitude Phase Locked Loop
3MPLL	Three-Phase Modified Phase-Locked Loop
ADC	Analog Digital Converter
AGI-FLL	Advanced Generalized Integrator Frequency Locked Loop
AMLMS	Approximate Multiplier Least Mean Square
ANF	Adaptive Notch Filter
BDC	Bidirectional DC-DC Converter
BES	Battery Energy Storage
BLDCGs	Brushless DC Generators
CLO	Circular Limit Cycle Oscillator
CLO-FLL-WPF	Circular Limited Cycle Oscillator-Frequency Locked Loop-with Prefilter
D-EPLL	Damped Enhanced Phase-Locked Loop
DERs	Distributed Energy Resources
DFIGs	Doubly Fed Induction Generators
DG	Diesel Generator
DOD	Depth of Charge
EPLL	Enhanced Phase Locked Loop
ESOGI-FLL-WIF	Enhanced Second-Order Generalized Integrator with an in-Loop Filter
ESOGI-MFLL	Enhanced Second-Order Generalized Integrator with Modified Frequency Locked Loop
ESOGI-OLCFLL	Enhanced Second-Order Generalized Integrator Out-Loop Compensation Frequency Locked Loop
Ext-SOGI-FLL	Extended Second Order Generalized Integrator Frequency Locked Loop
FZA-APNCA	Flexible Zero Attracting Affine Projection Normalized Correlation Algorithm
GC	Grid Connected
HCC	Hysteresis Current Controllers
IAF-FLL	Improved Adaptive Filter Frequency Locked Loop
IGI-FLL	Improved Generalized Integrator Frequency Locked Loop
ILMS	Improved Least Mean Square
IMs	Induction Motors
INC	Incremental Conductance
ITOF- FLL	Improved Third-Order Filter Frequency Locked Loop
LF	Loss Factor
LMS	Least Mean Square
MDSOGI-FLL	Modified Damped Second-Order Generalized Frequency Locked Loop

MEPLL	Modified Enhanced Phase-Locked Loop
MFLL	Modified Frequency Locked Loop
MG	Microgrid
MMSOGI-FLL	Modified Multi Second-Order Generalized Frequency Locked Loop
MPPT	Maximum Power Point Tracking
MVSS INC	Modified Variable Step Size Incremental Conductance
PCC	Point of Common Coupling
PI	Proportional Integral
PID	Proportional Integral Derivative
PLL	Phase Locked Loop
PMSGs	Permanent Magnet Synchronous Generators
PQ	Power Quality
PR	Proportional Resonant
PV	Photovoltaic
PWM	Pulse Width Modulation
RES	Renewable Energy Sources
S&H	Sample and Hold
SEIG	Self-Excited Induction Generator
SOGI	Second-Order Generalized Integrator
SRF	Synchronous Reference Frame
SSS	Solid-State-Switch
SyRG	Synchronous Reluctance Generator
UC	Utility Connected
VCO	Voltage Controlled Oscillator
VSC	Voltage Source Converter
WECS	Wind Energy Conversion System
WTGS	Wind Turbine Generation System
ZCD	Zero Crossing Detector

LIST OF SYMBOLS

a	Overloading Factor
Ag	Battery Aging Factor
C_{dc}	DC link Capacitor
C_f	Capacitance Ripple Filter
C_{min}	Minimum Capacitance
D	Duty Cycle
D_{dc}	Duty Cycle of BDC
dI_r	Change in Wind Current
dV_r	Change in Wind Voltage
$\mathcal{E}_e$	Error Between Sums of Fundamental Component Extracted and the Input Load Current Fundamental Component
$\mathcal{E}_f$	Frequency Observe Error
f	Frequency
f_{sw}	Switching Frequency
γ	Gain of the FLL
h	Overload Factor
I_b	Sensed Battery Current
I_b*	Reference Battery Current
I_{ber}	Error of Reference Battery Current
i_{da}^*, i_{db}^*, i_{dc}^*	Reference DG Currents
i_{da}, i_{db}, i_{dc}	Sensed DG Current Values
i_{dae}, i_{dbe}, i_{dce}	DG Current Error Signals
I_{dg}	Net Active DG Current
I_{dgavg}	Average Fundamental DG Active Current Component
i_{dn}	DG Sensed Neutral Current
i_{dn}*	DG Reference Neutral Current
i_{fa}	Fundamental Load Current Component
i_{fabc}	Three Phase In-Phase Fundamental Load Current Component
I_{fp}	Frequency Based Loss Component
I_g*	Total Load Current Fundamental Component
i_{ga}^*, i_{gb}^*, i_{gc}^*	Grid Reference Currents
i_{ga}, i_{gb}, i_{gc}	Grid Current Sensed Values

i_{gae}, i_{gbe}, i_{gce}	Grid Current Error Signals
i_{gn}	Grid Sensed Neutral Current
i_{gn}*	Reference Grid Neutral Current
i_{La}*, i_{Lb}*, i_{Lc}*	Reference VSC Currents
i_{La}, i_{Lb}, and i_{Lc}	Sensed VSC Currents
i_{La}, i_{Lb}, i_{Lc}	Sense the Load Currents
I_{Lfa}, I_{Lfb}, I_{Lfb}	Active Components (Grid mode)
I_{Lpa}	Active Power Component of Phase a
I_{Lpavg}	Fundamental Active Load Current Component Average Output
I_{Lpb}	Active Power Component of Phase b
I_{Lpc}	Active Power Component of Phase c
I_{Lqa}	Reactive Power Component of Phase a
I_{Lqavg}	Average Value of Fundamental Reactive Load Current
I_{Lqb}	Reactive Power Component of Phase b
I_{Lqc}	Reactive Power Component of Phase c
I_m	Magnitude of the Fundamental Current Estimated
I_{mpp}	MPP Current of PV
I_{pnet}	Net Fundamental Component of Active Current
I_{pt}	PI controller based Frequency Regulator Output
I_{pv}	PV Current
I_{pvf}	PV Power Feed-Forward Term
I_{qnet}	Net Fundamental Reactive Current
I_{qt}	PI controller based volatge regulator output
I_r	Wind Current
i_{sa}^*, i_{sb}^*, i_{sc}^*	Reference Value of Currents
i_{sa}, i_{sb}, i_{sc}	Sensed Value of Currents
i_{sae}, i_{sbe}, i_{sce}	Current Error Signals
I_{scpv}	Short Circuit Current of PV
i_{sn}	Sensed Source Neutral Current
i_{sn}*	Reference Source Neutral Current
i_{spa}^*,i_{spb}^*,i_{spc}^*	In Phase Reference Source Currents
i_{sqa}^*,i_{sqb}^*,i_{sqc}^*	Quadrature Reference Source Currents
$I_{vmax,peak}$	Peak Maximum VSC Current
I_{vq}	Output of Voltage PID Controller

I_{vsc}	VSC Current Rating
I_{wf}	Wind Power Feed-Forward Term
k_l	Voltage Ripple
L_b	PV Boost Inductor
L_d	Direct Axis Inductance
L_{dc}	Inductor in BDC
L_f	Value of the Interfacing Inductor
L_o	Wind inductor value
L_q	Quadrature Axis Inductance
m	Modulation Index
P	Load on the Battery
P_{DGmax}, P_{DGmin}	Maximum and Minimum Diesel Generator Power Limits
P_i	Instantaneous Power
P_{mpp}	MPP Power of PV
P_w	Wind Power Generated
qi_{fabc}	Three Phase Quadrature Fundamental Load Current Component
R_f	Resistance of Ripple Filter
T_c	Temperature Correction Factor
t_r	Time of Recovery
T_s	Switching Time
u_{apd}, u_{bgd}, u_{cgd}	In-Phase Unit Templates in DG Connected Mode
u_{apg}, u_{bgs}, u_{cgs}	In-Phase Unit Templates in Grid Connected Mode
u_{aps}, u_{bps}, u_{cps}	In-Phase Unit Templates in Islanded Mode
u_{aqs}, u_{bqs}, u_{cqs}	Quadrature Unit Templates in Islanded Mode
VA_{VSC}	VA Rating of the VSC
V_b	Battery Voltage
v_{dab}, v_{dbc}	Sense DG Voltages
V_{dc}	DC link Voltage
V_{dcmin}	Minimum DC link Voltage
V_{dcref}	DC link Reference PV Volatge
v_{ea}, v_{eb}, v_{ec}	Error Signals
v_g	Rating of AC side voltage (line)
v_{gab}, v_{gbc}, v_{gca}	Sense Grid Voltages
v_{La}^*, v_{Lb}^*, v_{Lc}^*	Reference Three-Phase Voltage

v_{La}, v_{Lb}, v_{Lc}	Sensed Three Phase Voltage
v_{Lab}, v_{Lbc}	Sense Load Voltage
V_{min}	Minimum AC Side Voltage
V_{mpp}	MPP Volatge of PV
V_{ocpv}	Open Circuit Voltage of PV
V_{pv}	PV Volatge
V_r	Wind Voltage
V_{tm}	AC Supply Voltages
V_{tm}^*	Reference Voltage
V_{tmg}	Terminal Voltage of the Grid
V_{VSC}	Voltage Rating of the device (IGBT switch)
$w(k)$, $w(k-1)$, Δw	New, Old and Change in DC-link Reference PV Voltages
X_d.	Direct Axis Reactance
ΔI_L	Ripple Current in BDC
ΔI_o	Current Ripple at Rated Wind Speed
ΔI_{rms}	Allowable Current Ripple
$\Delta\theta$	Synchronization PI Controller Output
$\Delta\omega_n$	Change in Frequency
η	Efficiency of the Battery
θ_e	Phase Angle Difference Betweem Grid Voltage and Load Volatge
θ_g	Phase Angle of Grid Voltage
θ_L	Phase Angle of Load Voltage
θ_{new}	Modified Phase Angle
λ	Multiplication Factor
ω_c	Frequency Updated
ω_e	Frequency Error
ω_f^*	Updated Reference Frequency
ω_{ff}	Additional Frequency
ω_L	Sensed Frequency
ω_L*	Reference Frequency
ω_n	Fundamental Frequency
ω_{new}	New Frequency Deviation Component
ω_{ref}	Reference Frequency