DESIGN AND CONTROL OF PV-WIND ENERGY BASED MICROGRIDS WITH ISLANDING AND RESYNCHRONIZATION

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DESIGN AND CONTROL OF PV-WIND ENERGY BASED MICROGRIDS WITH ISLANDING AND RESYNCHRONIZATION

by

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CERTIFICATE

It is certified that the thesis entitled “**Design and Control of PV-Wind Energy Based Microgrids with Islanding and Resynchronization**,” being submitted by **Mrs. Farheen Chishti** 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 my supervision and guidance. The matter embodied in this thesis has not been submitted for award of any other degree or diploma

Dated:

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ABSTRACT

This thesis presents the design and control of solar photovoltaic array and wind energy generation based microgrids with seamless transfer of operating modes for the electrification of rural communities as the prime motive. The combination of solar energy and wind energy generation increases the power reliability and provides energy surety as both the resources complement each other and cut down the reserve or storage requirements. The challenge is imposed as the renewable resources are dominated by their intermittency and geographic location availability. The variability of the energy supply is overcome by the use of energy storage systems, like battery energy storage (BES) or utility interconnection of the microgrid. The rural electrification is carried out either by grid interconnection or by incorporating the storage battery with the renewables to fulfill the community load demand. The first option is not viable for rural areas as site affordability acts as the key barrier. Secondly, the battery energy storage (BES) is worthwhile when specific conditions are fulfilled, which in return makes the value proposition of storage greater than the cost of installing it. BES is an expensive option but it meets all the aspects of integration challenges such as the uncertainty during demand rise and power sufficiency.

Here, in this work, BES control is deployed either connected directly at the DC link or through a bidirectional DC-DC converter. It controls the discharging and charging of the battery. The wind conversion systems also suffer from harmonics injection, degradation of minimum fault current and sudden voltage disruptions due to wind speed intermittency. These encountered challenges are resolved by utilizing full rated voltage source converters (VSCs) as an interface between the machine and the utility grid. Two back to-back connected VSCs, i.e., AC/DC converter, named as machine side VSC (MSC), a DC link, and a DC/AC inverter named as load side VSC (LSC) are implemented for variable speed operation of the system. The MSC regulates the synchronous

generator (SG) output power. It adjusts the current and torque of the SG. The LSC upholds the DC link voltage and synchronizes the AC generated power by the wind turbine driven SG with the power of the utility grid. The encoder-less field oriented control (FOC) with speed and position estimation is utilized for the SG. Depending upon the requirement, the solar PV array is configured as single stage or two stage configurations utilizing a boost converter. This work focuses upon the development and implementation of the advance control techniques for the successful operation of the microgrids during grid-connected mode or standalone operating mode. Even under adverse grid conditions, these improved approaches assess the amplitude, frequency, and phase of grid phase voltages quickly and accurately. All of the microgrid configurations have efficient control algorithms for the load side converter, which improve power quality at the PCC while maintaining unity power factor, provides harmonics elimination, grid currents balancing, reactive power compensation, neutral current compensation and power factor correction. The continuity of supply to the local consumer loads is ensured. The solar PV array and wind energy feed-forward terms express the power sharing mechanism to the utility and provides fast tracking under dynamic condition. The maximum power point extraction schemes for wind generation and solar PV array track the optimal power even under adverse solar insolation and wind speed conditions. The core objective is also to provide continuous supply to the critical loads even under grid outage scenarios. However, renewable generation loss and battery with low state of charge are also the conditions that need to be addressed for the continuity of supply during standalone operating mode. To overcome this shortcoming, the diesel generator set is brought into action for a short period of time and operated under maximum fuel efficiency zone to cater to the emergency load demand. All microgrid configurations are categorized in accordance to single phase, three phase three wire and three phase four wire distribution networks. The consumer requirement decides the type of the microgrid to be selected for specific applications. For investigating the performance, these microgrids are modelled and simulated using the MATLAB®/ Simulink platform, and experimental validations are carried out using developed laboratory prototypes. This study is intended to contribute significantly to existing knowledge on the design, development, and control of PV-wind energy based microgrids with islanding and resynchronization capabilities.

सार

यह थीसिस मुख्य उद्देश्य के रूप में ग्रामीण समुदायों के विद्युतीकरण के लिए ऑपरेटिंग मोड के निर्बाध हस्तांतरण के साथ सौर फोटोवोल्टिक पैनल और पवन ऊर्जा उत्पादन आधारित माइक्रोग्रिड के डिजाइन और नियंत्रण को प्रस्तुत करता है। सौर ऊर्जा और पवन ऊर्जा उत्पादन का संयोजन बिजली की विश्वसनीयता बढ़ाता है और ऊर्जा सुनिश्चितता प्रदान करता है क्योंकि दोनों संसाधन एक दूसरे के पूरक हैं और रिजर्व या भंडारण आवश्यकताओं को कम करते हैं। चुनौती इसलिए लगाई गई है क्योंकि अक्षय संसाधनों पर भौगोलिक स्थिति की उपलब्धता का बोलबाला है। ऊर्जा भंडारण प्रणालियों के उपयोग से ऊर्जा आपूर्ति की परिवर्तनशीलता को दूर किया जाता है, जैसे बैटरी ऊर्जा भंडारण (BES) या माइक्रोग्रिड इंटरकनेक्शन। ग्रामीण विद्युतीकरण या तो ग्रिड इंटरकनेक्शन द्वारा किया जाता है या सामुदायिक भार की मांग को पूरा करने के लिए नवीकरणीय ऊर्जा के साथ भंडारण बैटरी को शामिल करके किया जाता है। पहला विकल्प ग्रामीण क्षेत्रों के लिए व्यवहार्य नहीं है क्योंकि साइट की सामर्थ्य प्रमुख बाधा के रूप में कार्य करती है। दूसरे, बैटरी ऊर्जा भंडारण तब सार्थक होता है जब विशिष्ट शर्तें पूरी होती हैं, जो बदले में भंडारण के मूल्य प्रस्ताव को इसे स्थापित करने की लागत से अधिक बनाता है। BES एक महंगा विकल्प है लेकिन यह एकीकरण चुनौतियों के सभी पहलुओं जैसे मांग वृद्धि और बिजली की पर्याप्तता के दौरान अनिश्चितता को पूरा करता है।

यहां, इस कार्य में, BES नियंत्रण या तो सीधे डीसी लिंक पर या एक द्विदिश डीसी-डीसी कनवर्टर के माध्यम से जुड़ा हुआ है। यह बैटरी की डिस्चार्जिंग और चार्जिंग को नियंत्रित करता है। पवन रूपांतरण प्रणालियां भी हार्मोनिक इंजेक्शन, न्यूनतम फॉल्ट करंट की गिरावट और हवा की गति रुक-रुक कर होने के कारण अचानक वोल्टेज व्यवधान से ग्रस्त हैं। इन चुनौतियों का समाधान मशीन और उपयोगिता ग्रिड के बीच इंटरफेस के रूप में पूर्ण रेटेड वोल्टेज स्रोत कन्वर्टर्स (VSC) का उपयोग करके किया जाता है। दो बैक टू बैक कनेक्टेड VSC, यानी AC/DC कन्वर्टर, जिसे मशीन साइड वीएससी (MSC), एक डीसी लिंक और एक DC/AC इन्वर्टर को लोड साइड वीएससी (LSC) के रूप में नामित किया गया है, को चर गति संचालन के लिए लागू किया गया है। MSC सिंक्रोनस जनरेटर (SG) आउटपुट पावर को नियंत्रित करता है। यह SG के करंट और टॉर्क को एडजस्ट करता है। LSC डीसी लिंक वोल्टेज को बनाए रखता है और उपयोगिता ग्रिड की शक्ति के साथ पवन टरबाइन संचालित SG द्वारा AC उत्पन्न बिजली को सिंक्रनाइज़ करता

है। गति और स्थिति अनुमान के साथ एन्कोडर-रहित क्षेत्र उन्मुख नियंत्रण (FOC) का उपयोग SG के लिए किया जाता है। आवश्यकता के आधार पर, सोलर पीवी ऐरे को बूस्ट कन्वर्टर का उपयोग करते हुए सिंगल स्टेज या टू स्टेज कॉन्फ़िगरेशन के रूप में कॉन्फ़िगर किया गया है। यह कार्य ग्रिड से जुड़े मोड या स्टैंडअलोन ऑपरेटिंग मोड के दौरान माइक्रोग्रिड के सफल संचालन के लिए अग्रिम नियंत्रण तकनीकों के विकास और कार्यान्वयन पर केंद्रित है। प्रतिकूल ग्रिड परिस्थितियों में भी, ये बेहतर दृष्टिकोण ग्रिड चरण वोल्टेज के आयाम, आवृत्ति और चरण का जल्दी और सटीक आकलन करते हैं। सभी माइक्रोग्रिड कॉन्फ़िगरेशन में लोड साइड कन्वर्टर के लिए कुशल नियंत्रण एल्गोरिदम होते हैं, जो यूनिटी पावर फैक्टर को बनाए रखते हुए PCC में पावर क्वालिटी में सुधार करते हैं, हार्मोनिक्स एलिमिनेशन, ग्रिड करंट बैलेंसिंग, रिएक्टिव पावर, न्यूट्रल करंट और पावर फैक्टर करेक्शन प्रदान करते हैं। स्थानीय उपभोक्ता भार की आपूर्ति की निरंतरता सुनिश्चित की जाती है। सौर पीवी ऐरे और पवन ऊर्जा फीड-फॉरवर्ड, उपयोगिता के लिए बिजली साझाकरण तंत्र को व्यक्त करते हैं और गतिशील स्थिति के तहत तेजी से ट्रैकिंग प्रदान करते हैं। पवन उत्पादन और सौर पीवी ऐरे के लिए अधिकतम बिजली निष्कर्षण योजनाएं प्रतिकूल सौर सूर्यातप और हवा की गति की स्थिति के तहत भी इष्टतम शक्ति को ट्रैक करती हैं। मुख्य उद्देश्य ग्रिड आउटेज परिदृश्यों के तहत भी महत्वपूर्ण भार को निरंतर आपूर्ति प्रदान करना है। हालांकि, अक्षय उत्पादन हानि और कम चार्ज वाली बैटरी भी ऐसी स्थितियां हैं जिन्हें स्टैंडअलोन ऑपरेटिंग मोड के दौरान आपूर्ति की निरंतरता के लिए संबोधित करने की आवश्यकता है। इस कमी को दूर करने के लिए, डीजल जनरेटर सेट को थोड़े समय के लिए चालू किया जाता है और आपातकालीन भार की मांग को पूरा करने के लिए अधिकतम ईंधन दक्षता क्षेत्र के तहत संचालित किया जाता है। सभी माइक्रोग्रिड कॉन्फ़िगरेशन को सिंगल फेज, थ्री फेज थ्री वायर और थ्री फेज फोर वायर डिस्ट्रीब्यूशन नेटवर्क के अनुसार वर्गीकृत किया गया है। उपभोक्ता की आवश्यकता विशिष्ट अनुप्रयोगों के लिए चुने जाने वाले माइक्रोग्रिड के प्रकार को तय करती है। प्रदर्शन की जांच के लिए, इन माइक्रोग्रिड को MATLAB® / सिमुलिंक प्लेटफॉर्म का उपयोग करके मॉडलिंग और सिम्युलेटेड किया जाता है, और विकसित प्रयोगशाला प्रोटोटाइप का उपयोग करके प्रयोगात्मक सत्यापन किया जाता है। इस अध्ययन का उद्देश्य पीवी-पवन ऊर्जा आधारित माइक्रोग्रिड के डिजाइन, विकास और नियंत्रण पर मौजूदा ज्ञान में महत्वपूर्ण योगदान देना है, जिसमें द्वीपीय और पुन: सिंक्रनाइज़ेशन क्षमताएं हैं।

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RESs	Renewable Energy Resources
PV	Photovoltaic
REC	Rural Electrification Corporation
BES	Battery Energy Storage
DERs	Distributed Energy Resources
DG	Diesel Generator
PCC	Point Of Common Coupling
NDZ	Non-Detection Zone
VSCs	Voltage Source Converters
PLLs	Phase Locked Loops
SG	Synchronous Generator
MPPT	Maximum Power Point Tracking
WECS	Wind Energy Conversion System
PMSG	Permanent Magnet Synchronous Generator
DFIG	Doubly Fed Induction Generator
SCIG	Squirrel-Cage Induction Generator
WEGS	Wind Energy Generation System
PEC	Power Electronic Converters
P & O	Perturb And Observe
INC	Incremental Conductance
FLC	Fuzzy Logic Control
FOC	Field Oriented Control
PQ	Power Quality
LMS	Least Mean Square
LMF	Least Mean Fourth
SOGI	Second Order Generalized Integrators
ANF	Adaptive Notch Filters
FLLs	Frequency Locked Loops
WEGU	Wind Energy Generation Unit
VSWEGU	Variable Speed Wind Energy Generation
SPG	Single Phase Grid
TPTWG	Three Phase Three Wire Grid
TPFWG	Three Phase Four Wire Grid
MSC	Machine Side Converter
LSC	Load Side Converter
UPF	Unity Power Factor
BEMF	Back Electromotive Force

TLMS	Total Least Mean Square
CGI-PLL	Combined Generalized Integrator Based Phase Locked Loop
HCC	Hysteresis Current Controller
SCSS	Self-Correcting Sign-Sign
BGI-PLL	Binary Generalized Integrator Based Phase Locked Loop
LMLS	Least Mean Logarithmic Square
SOAP-FLL	Synchronous Observer Aided Preprocessing Based Frequency Locked Loop Filter
PR	Proportional Resonant Regulator
MTPA	Maximum Torque Per Ampere Control
DSP	Digital Signal Processing
DACs	Digital-To-Analog Converters
IGBT	Insulated Gate Bipolar Transistor
BDC	Bidirectional DC–DC Converter
SOC	State Of Charge
INSR-LMS	Improved Normalized Sign Regressor Least Mean Square
FLL-AVF	Frequency Locked Loop Unified Adaptive Vectorial Filter
MLEF	Maximum-Likelihood Estimator Framework
FADO-FLL	Frequency Adaptive Disturbance Observer Based Frequency Locked Loop
PWM	Pulse Width Modulated
LLAD	Least Logarithmic Absolute Difference
SA	Sign Algorithm
EMSE	Excess Mean Square Error
APF-FLL	All Pass Filter Based Frequency Locked Loop
THD	Total Harmonic Distortion
S	Synchronization Switches
SE-LMS	Sign-Error Least Mean Square
FAHO-FLL	Frequency Adaptive Harmonic Oscillator Based Frequency Locked Loop Filter
NAAP	Normalized Adaptive All Pass Filter
eSOGI-FLL	Extended Second Order Generalized Integrator Based Frequency Locked Loop
M-AAPL	M-Approximated Affine Projection Like Adaptive Filter
AP	Affine Projection
LPF	Low Pass Filters
PI	Proportional Integrator
MNF-SOGI-FLL	Modified Notch Filter Based Second Order Generalized Integrator-Frequency Locked Loop
BTB	Back To Back

AVR	Automatic Voltage Regulator
SEIG	Self-Excited Induction Generator
LMMN	Least Mean Mixed Norm
MSE	Mean Square Error
DO-PLL	Disturbance Observer Based Phase Locked Loop
MLMS	Momentum Based Least Mean Square
MBAF-PLL	Modified Binate Adaptive Filter Integrated To A Phase Locked Loop
MANF	Modified Adaptive Notch Filter
RNMN	Robust Normalized Mixed Norm Adaptive Algorithm
SRLMS	Stochastic Gradient Sign Error Least Mean Square Algorithm
DMGI-PLL	Dual Modified Generalized Integrator Based Phase Locked Loop

LIST OF SYMBOLS

β, r	Wind turbine pitch angle, blade radius
v_{wind}, , ω_{rm}	Wind speed, speed of wind turbine
P_t, λ, $C_p(\lambda,\beta)$	Mechanical power, Tip speed ratio, coefficient of turbine power
V_{dc}, V_{dcref} C_{dc}	Sensed DC link voltage, Reference DC link voltage, DC link capacitor
R_f, C_f	Ripple filter
L_f	Interfacing inductor
u_p, V_{gm}	Unit template, amplitude of voltage (single phase)
w_{Lp}, ϑ,	Weight component, step size
w_{cp}	VSC DC loss component
w_{wff}, P_{wind}	Wind feed-forward term, Wind power
w_{sp}	Peak value of net active load weight component
i_g, $i_{g\ ref}$*	Grid current, reference grid current for single phase microgrid
v_L,i_L	Load voltage, load current
S, S_2	Grid synchronization switch, DG synchronization switch
θ_g, θ_L, θ_e	Grid voltage phase angle, Load voltage phase angle, phase angle error
θ_s	operating voltage angle for standalone control
$I_{q\ ref}$, $I_{d\ ref}$	Reference quadrature axis current of SG, reference direct axis current of SG
$\omega_{gen\ est}$, $\omega_{gen\ ref}$	Estimated SG speed, reference SG speed
i_{gena} i_{genb}, i_{genc}	Sensed SG stator currents
$\theta_{\ est}$	Estimated rotor position of SG
$i_{genaref}$, i_{genref}, i_{genref}	Reference SG stator currents
v_{ga}, v_{gb}, v_{gc}	Phase voltages of the three phase grid
v_{gab}, v_{gbc}	Sensed line voltages of the grid
V_t	Amplitude of the PCC terminal voltage
u_a, u_b, u_c	In-phase unit templates
w_a,	Weight component of the load current of phase ‘a’
w_{loss}	DC loss component
i_{ga}, i_{gb}, i_{gc}	Sensed three phase grid currents
$i_{ga\ ref}$, $i_{gb\ r\ ef}$, $i_{gc\ ref}$	Reference three phase grid currents
v_{La}, v_{Lb}, v_{Lc}	Sensed load voltages
i_{La}, i_{Lb}, i_L	Sensed load currents
i_{Laref}, i_{Lbref}, i_{Lcref}	Reference load currents
I_{gn}, i_{Ln}, i_{LSCn}	Neutral currents of grid, load and LSC converter
P_{grid}, P_{Load}	Grid power, Load power

V_{pv}, I_{pv}, P_{pv}	Solar PV array voltage, current and power
V_b, I_b, P_b	Battery voltage, current and power
D/ δ	Duty ratio of bidirectional converter
L_{bdc}	bidirectional converter inductor
w_{Lp}	active weight component of the load current
w_{Load}	average weight component of the load current
w_{net}	net weight component of load current
v_{sa}^*, v_{sb}^*, v_{sc}^*	Three phase reference phase voltages of load
P_{mpp}, V_{mpp}, $_{mpp}$	Peak power, MPP voltage, MPP current of solar PV array
L_{BC}	Boost converter inductor
N_s, N_p	No. of solar cells in series and parallel
f_{sw}	Switching frequency
i_{Lafil}, i_{Lbfil}, i_{Lcfil}	Filtered load currents
V_{dg}, i_{dg}	SEIG DG set voltage and current
V_{dga}, V_{dgb}, V_{dgc}, i_{dga} i_{dgb} i_{dgc}	SG based DG set voltages and currents
P_{dg}	Power of DG set
$i_{dga\ ref}$, $i_{dgb\ ref}$, $i_{dgc\ ref}$	Reference DG currents