CONTROL OF RENEWABLE ENERGY BASED GRID INTERACTIVE MICROGRIDS WITH SQUIRREL CAGE INDUCTION GENERATOR

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DEPARTMENT OF ELECTRICAL ENGINEERING

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by

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Department of Electrical Engineering

Submitted

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CERTIFICATE

It is certified that the thesis entitled "**Control of Renewable Energy Based Grid Interactive Microgrids with Squirrel Cage Induction Generator**," being submitted by **Ms. Seema** 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: January 11, 2021

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Seema

ABSTRACT

There are still many villages in India, which are not yet electrified and the residents of those villages are not getting the electricity even for the lighting loads. This is due to the fact that commissioning new transmission lines to those places are very difficult and costly too. Therefore, one comes up with next obvious solution that the renewable energy sources such as solar PV array, wind energy and hydro as the best option for the electrification. However, each of the renewable energy source has their own limitations. For example, the solar PV array generation is not available in night, when it is most needed. The wind energy generation is also uncertain due to the varying wind speeds. On the contrary, the hydro based power generation is always available, however, the large land mass requirement, huge initial investment and their suitability for only hilly areas are the limiting factors for the rural electrification.

To solve the aforementioned problems and to ensure the electricity to the far flung homes, in this thesis, a number of configurations of microgrids are designed for integrating the renewable sources such as solar, wind and hydro, storage battery, the grid and DG (Diesel Generator) set. These configurations are segregated on the basis of number of energy sources, and configurations of every energy sources in the microgrid. Moreover, the application of these microgrids (farming, lighting, small industries or critical loads such as hospitals), and types of loads (single phase, three phase and dynamic loads etc.), are also considered for designing the microgrid. For example, the pico-hydro in conjunction with solar, wind and battery based configurations are presented for the areas where canal small tributaries or the river are available. Therefore, the proposed configurations solve the huge space and massive investment requirement of the hydro generator. Moreover, due to the continuous power generation using the pico-hydro generator, the proposed microgrid configurations ensure that the base load always gets supply, which means the proposed

microgrid configurations solve the problem of complete black out in night when the solar power and wind generation are not available. Moreover, with the use of storage battery and the coordinated control, the proposed model also solves the problem of intermittent renewable generation. Few configurations are also dedicated to operate the microgrid without storage battery yet supplying power to the loads instead of completely shutting down the microgrid under fault in the battery. Similarly, for ensuring the continuous supply to the critical loads such as hospitals, some microgrid configurations have used DG set, despite knowing the fact that the DG set does not use the power from the clean sources of energy. However, 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.

Apart from various configurations of the microgrids, the control of the microgrid is also designed to operate in multimode such as islanded, grid connected and DG (Diesel Generator) set connected mode, so that the utilization of energy source increases and the probability of continuous supply to the loads increases. Another major contribution in this thesis is that, only a single voltage source converter is controlled for achieving various tasks such as delivering continuous power to the loads, injecting the surplus renewable generation into the grid, voltage and frequency regulation at PCC (in islanded and DG set connected modes), compensating the harmonics current demand of nonlinear loads and dynamic reactive power demand of the dynamic loads (Induction Motor), and maintaining the active power balance during the disturbances using the storage battery and the voltage sources converter. Therefore, the VSC control should be fast and robust, which contributes to achieve the above mentioned tasks.

Hence, in this thesis, various robust and fast VSC control algorithms are implemented. The presented algorithms offer DC-offset rejection, fast convergence and low steady state oscillations for fast tracking of reference signals. In these designed microgrids, the control requires the local parameters such as PCC voltages, load currents, grid currents, PV voltage and current, to monitor the status of generation and loads. According to the situation of the real parameters, the controller takes the decision and controls the power flow within the microgrid.

सारांश

भारत में अभी भी कई गाँव ऐसे हैं, जो अभी तक विद्युतीकृत नहीं हैं और उन गाँवों के निवासियों को प्रकाश के भार के लिए भी बिजली नहीं मिल रही है। यह इस तथ्य के कारण है कि उन स्थानों पर नई ट्रांसमिशन लाइनों को चालू करना बहुत मुश्किल है और महंगा भी है। इसलिए, अक्षय ऊर्जा स्रोत जैसे कि सौर ऊर्जा, पवन ऊर्जा और पनबिजली विद्युतीकरण के लिए सबसे अच्छा विकल्प है। हालांकि, अक्षय ऊर्जा स्रोत में से प्रत्येक की अपनी सीमाएं हैं। उदाहरण के लिए, सौर ऊर्जा रात में उपलब्ध नहीं होती है, जबकि इसकी सबसे अधिक आवश्यकता उस समय होती है।अलग-अलग हवा की गति के कारण पवन ऊर्जा उत्पादन भी अनिश्चित है। इसके विपरीत, पनबिजली पर आधारित बिजली उत्पादन हमेशा उपलब्ध होता है, हालांकि, बड़े पैमाने पर भूमि की आवश्यकता, विशाल प्रारंभिक निवेश और केवल पहाड़ी क्षेत्रों के लिए उनकी उपयुक्तता ग्रामीण विद्युतीकरण के लिए सीमित कारक हैं।

उपरोक्त समस्याओं को हल करने के लिए और दूर दराज के घरों में बिजली सुनिश्चित करने के लिए, इस शोध-प्रबन्ध में, सौर, पवन और जल, जैसे अक्षय ऊर्जा स्रोतों को एकीकृत करके, माइक्रोग्रिड के कई विन्यास डिज़ाइन किए गए हैं, जिसमे भंडारण बैटरी, ग्रिड और डीजी (डीजल) जनरेटर सेट भी एकीकृत किये गये हैं। इन माइक्रोग्रिड के विन्यासों को ऊर्जा स्रोतों की संख्या के आधार पर और हर ऊर्जा स्रोतों के विन्यासों के आधार पर अलग किया जाता है। इसके अलावा, इन माइक्रोग्रिड्स के अनुप्रयोग (जैसे , खेती, प्रकाश, छोटे उद्योग या अस्पताल जैसे महत्वपूर्ण भार), और लोड के प्रकार (एकल चरण, तीन चरण और गतिशील भार आदि) को माइक्रोग्रिड डिजाइन करने के लिए माना जाता है। उदाहरण के लिए, सौर, पवन और बैटरी आधारित विन्यास के साथ पिको-हाइड्रो उन क्षेत्रों के लिए प्रस्तुत किया जाता है जहां नहर की छोटी सहायक नदियाँ या नदी उपलब्ध हैं। इसलिए, प्रस्तावित कॉन्फ़िगरेशन हाइड्रो जनरेटर के विशाल स्थान और बड़े पैमाने पर निवेश की आवश्यकता को हल करते हैं। इसके अलावा, पिको-हाइड्रो जनरेटर का उपयोग करने वाली निरंतर बिजली उत्पादन के कारण, प्रस्तावित माइक्रोग्रिड कॉन्फ़िगरेशन यह सुनिश्चित करता है कि आधार लोड हमेशा पूर्ति प्राप्त करे, जिसका अर्थ है कि प्रस्तावित माइक्रोग्रिड कॉन्फ़िगरेशन सौर शक्ति, पवन और पिको-हाइड्रो जनरेटर से बिजली उत्पादन करके रात में पूर्ण ब्लैक आउट की समस्या को हल करते हैं।

इसके अलावा, भंडारण बैटरी और समन्वित नियंत्रण के उपयोग के साथ, प्रस्तावित मॉडल भी आंतरायिक अक्षय ऊर्जा की समस्या को हल करता है। कुछ कॉन्फ़िगरेशन स्टोरेज बैटरी के बिना माइक्रोग्रिड को संचालित करने के लिए समर्पित हैं। इसी तरह, अस्पतालों जैसे महत्वपूर्ण भार को निरंतर पूर्ति सुनिश्चित करने के लिए, कुछ माइक्रोग्रिड कॉन्फ़िगरेशन ने डीजी सेट का उपयोग किया है, इस तथ्य को जानने के बावजूद कि डीजी सेट ऊर्जा के स्वच्छ स्रोतों से बिजली का उपयोग नहीं करता है। हालांकि, नियंत्रण और स्टोरेज बैटरी के माध्यम से इसकी गारंटी दी जाती है कि डीजी सेट हमेशा लोड डिमांड में भिन्नता के बावजूद ईंधन कुशल क्षेत्र में काम करके बेहतर रूप से उपयोग किया जाता है। माइक्रोग्रिड्स के विभिन्न विन्यासों के अलावा, माइक्रोग्रिड का नियंत्रण भी मल्टीमोड में संचालित करने के लिए डिज़ाइन किया गया है जैसे कि स्टैंडअलोन, ग्रिड कनेक्टेड और डीजी (डीज़ल जेनरेटर) सेट, ताकि ऊर्जा स्रोत का उपयोग बढ़े और निरंतर पूर्ति की संभावना बढ़े।

इस शोध-प्रबन्ध में एक अन्य प्रमुख योगदान यह है कि, केवल एक ही वोल्टेज स्रोत कनवर्टर को विभिन्न कार्यों को प्राप्त करने के लिए नियंत्रित किया जाता है जैसे कि लोड पर निरंतर बिजली पहुंचाना, अधिशेष अक्षय ऊर्जा को ग्रिड में इंजेक्ट करना, पीसीसी वोल्टेज और आवृत्ति (स्टैंडअलोन और डीजी में) नियमन करना, नॉनलाइनर लोड्स के डायनामिक्स और डायनेमिक लोड्स (इंडक्शन मोटर) की डायनामिक रिएक्टिव पॉवर डिमांड की भरपाई, और स्टोरेज बैटरी और वोल्टेज सोर्स कनवर्टर का उपयोग करके गड़बड़ी के दौरान सक्रिय पावर बैलेंस बनाए रखना। इसलिए, वीएससी नियंत्रण तेज और मजबूत होना चाहिए, जो उपरोक्त कार्यों को प्राप्त करने में योगदान देता है। इसलिए, इस शोध-प्रबन्ध में, विभिन्न मजबूत और तेज़ वीएससी नियंत्रण एल्गोरिदम लागू किए जाते हैं। प्रस्तुत एल्गोरिदम संदर्भ संकेतों के तेजी से ट्रैकिंग के लिए डीसी-ऑफसेट अस्वीकृति, तेजी से अभिसरण और कम स्थिर राज्य दोलन प्रदान करते हैं। इन डिज़ाइन किए गए माइक्रोग्रिड्स में, नियंत्रण के लिए पीसीसी वोल्टेज, लोड धाराओं, ग्रिड धाराओं, पीवी वोल्टेज और धारा जैसे स्थानीय मापदंडों की आवश्यकता होती है, ताकि विद्युत शक्ति और भार की स्थिति की निगरानी की जा

सके। वास्तविक मापदंडों की स्थिति के अनुसार, नियंत्रक निर्णय लेता है और माइक्रोग्रिड के भीतर विद्युत प्रवाह को नियंत्रित करता है।

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AC	Alternating Current
DC	Direct Current
DG	Diesel Generator
SCIG	Squirrel Cage Induction Generator
RES	Renewable Energy Sources
BES	Battery Energy Storage
UPF	Unity Power Factor
PCC	Point of Common Coupling
IEEE	Institute of Electrical and Electronics Engineers
DERs	Distributed Energy Resources
CIGRE	International Council on Large Electric Systems
CERTS	Consortium for Electric Reliability Technology Solutions
IS	Islanded
GC	Grid Connected
VSC	Voltage source Converter
MPPT	Maximum Power Point Tracking
PV	Photovoltaic
BDC	bidirectional DC-DC converter

IGBT	Insulated Gate Bipolar Transistor
HCC	Hysteresis Current Controller
INC	Incremental Conductance
SRF-PLL	Synchronous Reference Frame Phase Locked Loop
GI	generalized integrator
ZCD	Zero Crossing Detector
PI	Proportional Integrator
ADC	Analog Digital Converter
MC	Machine side converter
LC	load side converter
SSS	solid state switch
SOGI	Second Order Generalized Integrator)
AVR	Automatic Voltage Regulator
PR	Proportional Resonant
EPLL	Enhanced Phase Locked Loop
IM	Induction Motor
IGFEPLL	Improved Generalized Filter Enhanced Phase Locked Loop
IIFWEPLL	Improved in-loop filter with enhanced phase locked loop
VF	voltage and frequency
LMS	Least Mean Square

I-RZA-QLMS	Improved Reweighted Zero-Attracting Quaternion-Valued Least Mean Square
LMS-Sign-VS	Least Mean Square with Signum Variable Step
IMLMS	improved Momentum LMS
LMAT	Least Mean Absolute Third
VFD	Variable Frequency Drive
WT	Wind-Turbine
FOC	Field Oriented Control
P&O	Perturb and Observe
THD	Total Harmonic Distortion
ANF	Adaptive Notch Filter
DANF	Double Adaptive Notch Filter
DSP	Digital Signal Processor
AANF	Amplitude Adaptive Notch Filter
MAANF	Modified adaptive notch filter
PM	Proportional Multiresonant
VSWG	variable speed wind generator

LIST OF SYMBOLS

a	Overloading Factor
V_{dc}	DC-Link Voltage
C_{dc}	DC-Link Capacitor
$R_f C_f$	Passive RC Filter
P_{mp}, V_{mp} and I_{mp}	Solar Peak Power, Peak Voltage and Peak Current
L_b	Boost Inductor
L_f	Interfacing Inductor
L_{dc}	Bidirectional Converter Inductor
Vb	Battery Voltage
v^*_{La}, v^*_{Lb}, v^*_{Lc}	Reference Load Phase Voltages
v_{Lab}, v_{Lbc}, v_{Lca}	Sensed Line Voltages of PCC
i_{La}, i_{Lb}, i_{Lc}	Sensed Load Currents
θ_e	Phase Angle Error Grid And PCC Voltages
θ_g, θ_L and θ_s	Phase Angle of Grid, PCC And DG Set Voltages
X	Switching Signal for SSSs
i_{ga}^*, i_{gb}^* and i_{gc}^*	Reference Grid Currents
i_{sa}^*, i_{sb}^* and i_{sc}^*	Reference DG Set Currents
i_{hya}^*, i_{hyb}^* and i_{hyc}	Reference Hydro Generator Currents
I_{pvff}, I_{wiff} and I_{hyff}	PV, Wind and Hydro Feedforward Current Component
i_{gn}, i_{sn}, i_{hyn} and i_{Ln}	Grid, Source, Hydro Generator and Load Neutral Current
I_{Lpavg}	Net Active Weight Component of Load Current
I_{dc}	Loss Component for DC-Link Regulation

k_{pi}, k_{pp}, k_{pib} and k_{ppb}	Gains of Voltage and Current PI Controllers for BDC
K_{vi}, k_{vp}, k_{pf} and k_{pf}	Gains of Voltage and Current PI Controllers for Voltage and Frequency Regulation
i_{va},i_{vb} and i_{vc}	VSC Currents For Phase ‘a’, ‘b’ and ‘c’
u_{pa},u_{pb} and u_{pc}	in-Phase Unit Templates
ω_L^*	Reference Frequency of Load Voltage
I_{bff}	Battery Feedforward Term
I_b^{ref}	Reference Battery Current
I_b	Sensed Battery Current
θ_{est}	Estimated rotor flux position of SCIG
N_{est}	Estimated rotor speed of SCIG
$\psi_{\alpha r}$ *and* $\psi_{\beta r}$	Estimated rotor flux in αβ reference frame
R_r and L_r	rotor resistance and rotor inductance of SCIG
i_{wa}, i_{wb} and i_{wc}	Wind generator current of phase ‘a’, ‘b’ and ‘c’