

DESIGN, CONTROL AND IMPLEMENTATION OF AN AC MICROGRID

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**DEPARTMENT OF ELECTRICAL ENGINEERING
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DESIGN, CONTROL AND IMPLEMENTATION OF AN AC MICROGRID

by

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CERTIFICATE

This is to certify that the thesis entitled, “**Design, Control, and Implementation of an AC Microgrid**” being submitted by **Mr. Deepu Vijay M** for the award of the degree of **Doctor of Philosophy** is a record of bonafide research work carried out by him in the Department of Electrical Engineering of Indian Institute of Technology Delhi.

Mr. Deepu Vijay M has worked under our guidance and supervision and has fulfilled the requirements for the submission of this thesis, which to our knowledge has reached the requisite standard. The results obtained herein have not been submitted to any other University or Institute for the award of any degree.

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Deepu Vijay M

ABSTRACT

Limited fossil fuel resources, increased demand for electrical energy, increased population, impact on atmospheric conditions, greenhouse gas emissions, and insufficient centralized generation, have forced the world to go for distributed generation with renewable energy sources. The quest for reliable and stable solutions for the energy crisis seen by the world and known issues associated with the conventional utility grid, have resulted in a new concept known as microgrids. The commonly used renewable energy sources in a microgrid are solar PV generation and wind energy conversion system (WECS). The use of microgrids, enhances the reliability and resiliency of the system as it operates autonomously during grid outages. Investigations on different AC microgrid configurations with the solar PV array and WECSs are made in this thesis. For the microgrid applications, a new WECS with a position sensor-less synchronous reluctance generator (SynRG), is proposed in this thesis. The simple, brushless, compact structure of SynRG, along with a full-scale converter, makes it suitable for variable speed wind power generation. SynRG is economical and robust due to the absence of permanent magnets and windings in the rotor, thus eliminating rotor losses. The use of back-to-back connected configuration provides smooth grid synchronization and decoupled operation. The WECS and the grid are sharing a common DC-link through their respective voltage source converters (VSCs). The VSC connected to the machine side provides the required reactive power to the SynRG and operates it at a speed, decided by the maximum power extraction (MPE) algorithm. Rotor position/speed sensor-less field-oriented control with novel flux estimation techniques are implemented for controlling the SynRG.

In this research work, design, modeling and implementations of different AC microgrid configurations comprising a combination of solar PV array, SynRG based WECS and a battery, are carried out. A total of ten microgrid configurations are discussed in this thesis. Different control algorithms are also introduced for the successful operation of the microgrids during grid-connected and standalone modes of operation. The issues associated with the increased grid penetrations of renewable energy sources are also addressed. Harmonics are injected into the grid currents by the nonlinear loads connected at the point of common coupling (PCC). In addition to the increased cost of electricity per unit, the major challenge

faced by the utility companies, is the mitigation of power quality issues at the PCC for each consumer caused by the local loads. Efficient control algorithms are implemented for the grid side converter of all the proposed microgrid configurations, which enhance the power quality at the PCC as per the IEEE 519 standard as well as maintain unity power factor at the PCC. For quick dynamic performance during the variation in power generation from the solar PV array and WECS, feed-forward components are included in the control algorithms. Different synchronization controls are proposed for the seamless operation of the microgrid during grid outages/restoration. These improved techniques estimate the amplitude, frequency, and phase of the grid phase voltages in a fast and accurate manner, even for adverse grid conditions. Due to the intermittent nature of power generation from the solar PV array and WECS, battery banks are included in the microgrid configurations. For the protection and longevity of the battery, bidirectional converters are used. MATLAB[®]/ Simulink platform is used for the modeling and simulation of all the microgrid configurations and developed laboratory prototypes are used for the experimental validations. This research work is expected to make significant addition to the existing knowledge on the design, development, and control approach for PV-Wind and battery based AC microgrid.

सार

सीमित जीवाश्म ईंधन संसाधन, विद्युत ऊर्जा की बढ़ती मांग, बढ़ती जनसंख्या, वायुमंडलीय स्थितियों पर प्रभाव, ग्रीनहाउस गैस उत्सर्जन और अपर्याप्त केंद्रीकृत उत्पादन ने दुनिया को अक्षय ऊर्जा स्रोतों के साथ वितरित उत्पादन की ओर कार्य करने के लिए मजबूर किया है। विश्व द्वारा देखे गए ऊर्जा संकट के लिए विश्वसनीय और स्थिर समाधान की तलाश, तथा पारंपरिक ग्रिड से जुड़े ज्ञात मुद्दों ने माइक्रोग्रिड्स नामक एक नई अवधारणा को जन्म दिया है। माइक्रोग्रिड में आमतौर पर उपयोग किए जाने वाले अक्षय ऊर्जा स्रोत सौर पीवी उत्पादन और पवन ऊर्जा रूपांतरण प्रणाली हैं। माइक्रोग्रिड्स का उपयोग, सिस्टम की विश्वसनीयता और लचीलेपन को बढ़ाता है क्योंकि यह ग्रिड आउटेज के दौरान स्वायत्त रूप से संचालित होता है। इस थीसिस में सौर पीवी सरणी और डब्ल्यू०ई०सी०एस० के साथ अलग-अलग ए०सी० माइक्रोग्रिड कॉन्फिगरेशन पर जांच की जाती है। माइक्रोग्रिड अनुप्रयोगों के लिए, इस थीसिस में एक पोजीसन सेसर-लेस सिंक्रोनस रीलक्टेंस जेनेरेटर पर आधारित एक नयी डब्ल्यू०ई०सी०एस० प्रस्तावित है। फुल स्केल कन्वर्टर के साथ, सिंक्रोनस रीलक्टेंस जेनेरेटर की सरल, ब्रश रहित, सूक्ष्म संरचना, इसे बदलती पवन गति के तहत बिजली उत्पादन के लिए उपयुक्त बनाती है। रोटर में स्थायी मैग्नेट और वाइंडिंग की अनुपस्थिति के कारण सिंक्रोनस रीलक्टेंस जेनेरेटर किफायती और मजबूत है, इस प्रकार रोटर में होने वाली विद्युत हानि को समाप्त करता है। बैक-टू-बैक कनेक्टेड कॉन्फिगरेशन का उपयोग निर्बाध ग्रिड सिंक्रोनाइज़ेशन और डी-कपल्ड ऑपरेशन प्रदान करना है। डब्ल्यू०ई०सी०एस० और ग्रिड अपने संबंधित वोल्टेज सोर्स कन्वर्टर के माध्यम से एक डीसी-लिंक साझा कर रहे हैं। मशीन से जुड़ा वी०एस०सी०, सिंक्रोनस रीलक्टेंस जेनेरेटर को आवश्यक रिएक्टिव पावर प्रदान करता है, तथा इसे अधिकतम शक्ति निष्कर्षण (एम०पी०ई०) एल्गोरिदम द्वारा तय की गई गति पर संचालित करता है। सेंसर-लेस फील्ड ओरिएंटेड नियंत्रण नॉवेल फ्लक्स आकलन तकनीक का उपयोग रोटर स्थिति / गति का अनुमान लगाने के लिए किया गया है, जो सिंक्रोनस रीलक्टेंस जेनेरेटर की गति को नियंत्रित करने के लिए के कार्यान्वित किया जाता है।

इस शोध कार्य में, विभिन्न माइक्रोग्रिड विन्यासों के डिजाइन, मॉडलिंग और कार्यान्वयन किए जाते हैं, जिसमें सौर पीवी सरणी, सिंक्रोनस रीलक्टेंस जेनेरेटर आधारित डब्ल्यू०ई०सी०एस० और एक बैटरी का संयोजन शामिल है। इस थीसिस में कुल दस माइक्रोग्रिड कॉन्फिगरेशन सम्मिलित किए गए हैं। ग्रिड से जुड़े और स्टैंडअलोन मोड ऑपरेशन के दौरान माइक्रोग्रिड के सफल संचालन के लिए विभिन्न नियंत्रण एल्गोरिदम भी प्रस्तावित किए गए हैं। नवीकरणीय ऊर्जा स्रोतों के ग्रिड में वृद्धि के साथ जुड़े मुद्दों को भी संबोधित किया गया है। हार्मोनिक्स को पॉइंट ऑफ कामन कपलिंग (पी०सी०सी०) के बिंदु पर जुड़े

नॉनलाइनियर भार द्वारा ग्रिड धाराओं में इंजेक्ट किया जाता है। प्रति यूनिट बिजली की बढ़ी हुई लागत के अलावा, कंपनियों के सामने प्रमुख चुनौती स्थानीय भार के कारण प्रत्येक उपभोक्ता के लिए पी०सी०सी० में बिजली की गुणवत्ता को बरकरार रखना है। कुशल नियंत्रण एल्गोरिदम सभी प्रस्तावित माइक्रोग्रिड कॉन्फ़िगरेशनों के ग्रिड साइड कनवर्टर के लिए कार्यान्वित किए जाते हैं, जो पी०सी०सी० में बिजली की गुणवत्ता को आई०ई०ई०ई० 519 मानक के अनुसार बढ़ाते हैं और साथ ही पीसीसी पर यूनिटी पावर फैक्टर को बनाए रखते हैं। सौर पीवी सरणी और डब्ल्यू०ई०सी०एस० से बिजली उत्पादन में भिन्नता के दौरान त्वरित गतिशील प्रदर्शन के लिए, फीड-फॉरवर्ड घटकों को नियंत्रण एल्गोरिदम में शामिल किया गया है। ग्रिड आउटेज / बहाली के दौरान माइक्रोग्रिड के निर्बाध संचालन के लिए विभिन्न सिंक्रनाइज़ेशन नियंत्रण प्रस्तावित हैं। ये उन्नत तकनीक ग्रिड वोल्टेज के आयाम, आवृत्ति और फेज का अनुमान प्रतिकूल ग्रिड परिस्थितियों में त्वरित व सटीक तरीके से लगाती हैं। सौर पीवी सरणी और डब्ल्यू०ई०सी०एस० से बिजली उत्पादन की आंतरायिक प्रकृति के कारण, बैटरी बैंकों को माइक्रोग्रिड कॉन्फ़िगरेशन में शामिल किया गया है। बैटरी की सुरक्षा और दीर्घायु के लिए, द्विदिश कन्वर्टर्स का उपयोग किया जाता है। मैटलैब / सिमुलिक प्लेटफॉर्म का उपयोग मॉडलिंग और सभी माइक्रोग्रिड कॉन्फ़िगरेशन के सिमुलेशन के लिए किया जाता है और प्रयोगशाला में विकसित प्रोटोटाइप का प्रयोग प्रयोगात्मक मान्यताओं के लिए किया जाता है। यह शोध कार्य पीवी-विंड और बैटरी-आधारित एसी माइक्रोग्रिड के लिए डिजाइन, विकास और नियंत्रण के दृष्टिकोण पर मौजूदा ज्ञान को महत्वपूर्ण बनाने के लिए अपेक्षित है।

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LIST OF ABBREVIATIONS

AC	Alternating Current
ACLMK	Augmented Complex-Valued Least-Mean Kurtosis
ALA	Axially Laminated Anisotropic
ANN	Artificial Neural Network
BPF	Band-Pass Filter
BTB	Back-to-Back
DC	Direct Current
DER	Distributed Energy Resources
DFIG	Doubly-fed Induction Generator
DG	Distributed Generation
DSP	Digital Signal Processor
DSTATCOM	Distribution Static Compensator
ES	Energy Storage
FFE	Fourth-Order Flux Esimator
FLC	Fuzzy Logic Control
FLL	Frequency-Locked-Loop
FOC	Field Oriented Control
FOCV	Fractional Open-Circuit Voltage
FOGI	Fourth Order Generalized Integrator
FRT	Fault Ride Through
FSCC	Fractional Short-Circuit Current
GSC	Grid Side Converter
HCC	Hysteresis current controllers
HGI	Hybrid Generalized Integrator
IEEE	Institute of Electrical and Electronics Engineers
IG	Induction Generator
IGBT	Insulated Gate Bipolar Transistor
INC	Incremental Conductance

LMF	Least Mean Fourth
LPF	Low-Pass Filter
MAF	Moving Average Filter
MEPT	Maximum Electrical Power Tracker
MMPT	Maximum Mechanical Power Tracker
MPE	Maximum Power Extraction
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
MSC	Machine Side Converter
NN	Neural Network
PCC	Point of Common Coupling
PEI	Power Electronic Interface
PI	Proportional Integral
PLL	Phase-Locked-Loop
PMSG	Permanent Magnet Synchronous Generator
PSC	Positive Sequence Component
PV	Photovoltaic
RES	Renewable Energy Source
RG	Reluctance Generator
SCIG	Squirrel Cage Induction Generator
SECS	Solar Energy Conversion System
SOGI	Second-Order Generalized Integrator
SRF	Synchronous Reference Frame
STS	Synchronization Switch
S/H	Sample and Hold
SynRG	Synchronous Reluctance Generator
SynRM	Synchronous Reluctance Motor
THD	Total Harmonic Distortion
TSR	Tip Speed Ratio

UT	Unit Templates
VSC	Voltage Source Converter
VSWT	Variable Speed Wind Turbine
WECS	Wind Energy Conversion System
WRIG	Wound Rotor Induction Generator
WRSG	Wound Rotor Synchronous Generator
WT	Wind Turbine
ZCD	Zero Crossing Detection

LIST OF SYMBOLS

C_{dc}	DC-link capacitor (F)
C_f	Shunt ripple filter capacitor (F)
C_p	Power-Coefficient of Wind Turbine
D_b	Duty cycle of boost converter
D_{bdc}	Duty cycle of bidirectional converter
e_{ib}	DC-link voltage error
f_g	Grid frequency (Hz)
F_s	Sampling frequency (kHz)
h	Over loading factor
I_b	Battery current (A)
I_{cpv}	Solar feed-forward component (A)
I_{cw}	Wind feed-forward component (A)
I_{cl}	DC-link voltage regulation component
i_{g-max}	Maximum grid current (RMS)
I_l^m	Average magnitude of three phase fundamental load current components (A)
$I_{l1}^m, I_{l2}^m, I_{l3}^m$	Peaks of fundamental components of load currents (A)
i_{l1}, i_{l2}, i_{l3}	Three phase load currents (A)
i_{g1}, i_{g2}, i_{g3}	Three phase grid currents (A)
$i_{g1}^*, i_{g2}^*, i_{g3}^*$	Reference three phase grid currents (A)
$i_{gsc1}, i_{gsc2}, i_{gsc3}$	Three phase GSC currents (A)
$i_{gsc1}^*, i_{gsc2}^*, i_{gsc3}^*$	Reference three phase GSC currents (A)
I_g^m	Amplitude of reference grid currents
$i_{sy1}, i_{sy2}, i_{sy3}$	Stator currents of SynRG (A)
$i_{sy}^\alpha, i_{sy}^\beta$	Stator currents of SynRG in $\alpha - \beta$ domain (A)
I_{pv}	PV array current (A)
I_{mpp}	PV array maximum power point current (A)
I_{sc}	PV array short circuit current (A)
I_{sw-max}	Maximum peak current rating of GSC device
k_1	Variation of Energy in dynamics
K_p^θ, K_i^θ	Proportional gain of PI controller in $\Delta\theta$ control
K_d^p, K_i^i	Gains of DC-link voltage PI controller
K_p^θ, K_i^θ	Gains of phase generation PI controller
K_p^{ib}, K_i^{ib}	Gains of bidirectional converter controller
L_b	Boost converter inductor (H)

L_{bi}	BDC inductor (H)
L_f	Shunt compensator inductor (H)
L_m	Interfacing inductor (H)
L_{sy}^d, L_{sy}^q	Direct and quadrature axes inductances of SynRG (H)
M, ς	Coefficients of the SFE-FLL
m	Modulation index of shunt compensator
p	Number of pole pairs in SynRG
P_g	Instantaneous grid power (W)
P_l	Instantaneous load active power (W)
P_{pv}	PV array power (W)
P_{pv-max}	Maximum PV power (W)
P_τ	Mechanical power captured from wind turbine (W)
P_b	Battery power (W)
r_b	Blade Radius of Wind Turbine
R_f	Shunt ripple filter resistor (Ω)
r_s	Stator resistance of SynRG (Ω)
s	Laplace operator
S_x	Synchronization signal
T_e	Estimated SynRG torque (N-m)
T_s	Sampling time (s)
$\hat{T}_g$	Window length of HGI filter
u_{p1}, u_{p2}, u_{p3}	Three phase PCC voltage templates
V_b	Battery voltage (V)
V_{dc}	DC-link voltage (V)
V_{dc}^*	Reference DC-link voltage (V)
v_{l1}, v_{l2}, v_{l3}	Three phase instantaneous load phase voltages (V)
$v_{l1}^*, v_{l2}^*, v_{l3}^*$	Reference load phase voltages (V)
$v_{ll1}, v_{ll2}, v_{ll3}$	Three phase instantaneous load line voltages(V)
v_p^α, v_p^β	Three phase PCC voltages in $\alpha - \beta$ domain
V_{min}, V_{max}	Minimum and maximum limits of the PCC phase voltage peak (V)
V_{mpp}	PV array maximum power point voltage (V)
v_{p1}, v_{p2}, v_{p3}	Three phase instantaneous grid voltages (V)
$v_{p1}^+, v_{p2}^+, v_{p3}^+$	Three phase PSCs of grid voltages (V)
v_{p-min}	Lowest permissible PCC voltage
V_{oc}	PV array open circuit voltage (V)
V_p^m	Peak of grid phase voltages (V)

V_{pv}	PV array voltage (V)
$v_{sw(g)}$	Voltage rating of GSC devices
$v_{sw(m)}$	Voltage rating of MSC devices
$v_{sy1}, v_{sy2}, v_{sy3}$	Three phase instantaneous SynRG voltages (V)
$v_{sy}^{\alpha}, v_{sy}^{\beta}$	SynRG voltages in $\alpha - \beta$ domain (V)
$v_p^{\alpha'}, qv_p^{\alpha'}$	In-phase and quadrature component of grid voltage filter output (V)
$v_p^{\alpha+}, qv_p^{\beta+}$	Three phase fundamental positive sequence PCC voltages in $\alpha - \beta$ domain (V)
V_{wi}	Wind speed (m/s)
z	Z-domain operator
Z_s	Impedance of the grid
β	Pitch angle of Wind Turbine
$\hat{\beta}$	Forgetting factor of ACLMK
ζ_b	Status of battery
Δe_{vdc}	Change in DC-link voltage error
ΔI_r	Inductor Current Ripple
ΔP_{pv}	Change in PV array power
ΔD	Duty cycle step size
ΔV_{mpp}	Step change in solar PV array output voltage
μ_s	Step size of ACLMK
ϕ	Load power factor angle ($^{\circ}$)
$\psi_{sy}^{\alpha}, \psi_{sy}^{\beta}$	Stator flux linkages of SynRG in $\alpha\beta$ frame
θ_l	Load phase angle
θ_g	PCC voltage phase angle
$\theta_{min}, \theta_{max}$	Minimum and maximum limits of phase angle error
θ_{sy}^e	The angle of stator flux vector with respect to α axis
$\Delta\theta$	Phase angle error
ω_{τ}	Speed of Wind Turbine in (rad/s)
ω	Grid frequency (rad/s)
ω_{sy}^e	Speed of the flux linkage space vector of SynRG
κ	Filtering gain of HGI filter
κ_s	Filtering gain of C-SOGI filter
κ_1, κ_2	Filtering gains of C-FGI filter
λ	Tip Speed Ratio
λ_{opt}	Optimum Tip Speed Ratio
ρ	Air density (kg/m ³)