CONTROL AND IMPLEMENTATION OF SINGLE-PHASE GRID INTERFACED SOLAR PV-WIND AND BES BASED MICROGRID WITH GRID SYNCHRONIZATION

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by

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CERTIFICATE

It is certified that the thesis entitled "**Control and Implementation of Solar-Wind and Battery based Single Phase Microgrid with Grid Synchronization**," being submitted by Mrs. Yashi Singh 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 our supervision and guidance. The matter embodied in this thesis, has not been submitted for the award of any other degree or diploma.

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ABSTRACT

This research work focuses on the development of a grid-interactive, multifunctional single-phase PV-BES (Photovoltaic-Battery Energy Storage) system for residential and rooftop applications. To enhance system reliability, configurations integrating battery energy storage (BES) at the DC link are presented, both with and without a bidirectional converter. The functionality of the microgrid in various operating modes is thoroughly discussed. A seamless transition logic, combined with an islanding detection technique, enables smooth transitions between off-grid and grid-interactive modes. In grid-interactive mode, the system effectively provides power quality (PQ) solutions, including harmonics elimination, power factor correction and reactive power compensation. In off-grid mode, the control objectives shift to maintaining voltage and frequency regulation at the point of common coupling (PCC). The primary goal of this system is to ensure uninterrupted power delivery to local critical loads, even during grid outages.

The primary aim of integrating battery energy storage (BES) into the microgrid is to enhance coordination with distributed generation, ensuring a reliable supply of electricity. By integrating BES, the reliability of peak load management is improved, along with the power quality of renewable energy production and the management of distributed and off-grid power systems.

This research work also includes on the development of a grid-interactive multifunctional wind energy generation system (WEGS), objective even during grid outages. Owing to the complementary profiles of renewable sources like wind and solar, this work emphasizes the development of a multifunctional microgrid employing a wind turbine based permanent magnet brushless DC generator (PMBLDCG) and a solar photovoltaic (PV) array. The functionality of the microgrid during various operating modes is discussed. A seamless transition logic, combined with an islanding detection technique, is incorporated for transitioning between off-grid and grid-interactive modes.

This study explores various topologies for parallel solar PV inverter-based microgrids, both with and without BES, aimed at enhancing reliability and accessibility in remote areas. These topologies consist of DG units, BES, and local loads, with each DG unit incorporating inverters connected to a PV array through an output interfacing inductor and coupling lines linked in parallel at the PCC. A microgrid is deemed efficient if it performs effectively in both standalone and grid-tied modes, ensuring a smooth power transition. When a PV inverter operates in

islanding mode, the PV power should not exceed the load demand to maintain system stability. However, this can lead to either wasted PV power or underutilization of available PV power. To address this, additional solar panels are connected to other energy sources, such as batteries, to create a parallel PV inverter-based system, making it feasible to effectively harness power from each source.

The microgrid structures and control algorithms are used in microgrid and these are modelled and simulated with MATLAB/Simulink toolbox. Following satisfactory simulation results, a prototype microgrid incorporating a solar PV array, wind turbine driven PMBLDCG, and BES is developed. Test performances of multiple parallel PV inverter-based microgrids are validated on the RT-LAB platform using a real-time controller OP4510. The simulation and testing results are presented under various challenging conditions, including variations in solar insolation, loads, voltage distortion, and mode transition. Notably, the wind and solar power systems track the maximum power point. Finally, performance of the microgrid in both off-grid and grid-interactive modes, with seamless transitions between these modes, is demonstrated in detail.

सार

यह शोध कार्य एक ग्रिड-संयुक्त, बहुउद्देशीय एकल-चरणीय सौर-ऊर्जा एवं बैटरी ऊर्जा भंडारण प्रणाली के विकास पर आधारित है, जिसे विशेष रूप से घरेलू एवं छत पर स्थापित अनुप्रयोगों के लिए विकसित किया गया है। प्रणाली की विश्वसनीयता बढ़ाने के उद्देश्य से बैटरी ऊर्जा भंडारण को दिष्ट धारा संधि बिंदु पर एक-दिशीय तथा द्वि-दिशीय परिवर्तकों के साथ तथा बिना संयोजन के विभिन्न विन्यासों में प्रस्तुत किया गया है। इस सूक्ष्मबिजली तंत्र की विभिन्न कार्यप्रणाली स्थितियों में संचालन क्षमता का विस्तृत अध्ययन किया गया है।

एक सुगम संक्रमण युक्ति तथा द्वीपीकरण पहचान तकनीक के माध्यम से ग्रिड तथा स्वतंत्र रूप से संचालित मोड के बीच निर्बाध परिवर्तन सुनिश्चित किया गया है। ग्रिड-संयुक्त मोड में यह प्रणाली विद्युत गुणवत्ता सुधार हेतु हार्मोनिक घटाना, शक्ति गुणांक सुधारना तथा प्रत्यावर्ती शक्ति क्षतिपूर्ति जैसे कार्य करती है। स्वतंत्र मोड में प्रणाली का नियंत्रण उद्देश्य संयुक्त युग्मन बिंदु पर वोल्टता एवं आवृत्ति को स्थिर बनाए रखना होता है, जिससे विद्युत आपूर्ति में किसी भी प्रकार की बाधा आने पर भी आवश्यक स्थानीय भारों को सतत ऊर्जा प्राप्त हो सके।

इस प्रणाली में बैटरी ऊर्जा भंडारण को सम्मिलित करने का प्रमुख उद्देश्य है - वितरित ऊर्जा स्रोतों के साथ समन्वय स्थापित करना, ताकि आपूर्ति की विश्वसनीयता सुनिश्चित हो सके। इसके अतिरिक्त यह पीक लोड प्रबंधन, नवीकरणीय ऊर्जा गुणवत्ता तथा दूरवर्ती एवं स्वतंत्र विद्युत तंत्रों के प्रबंधन को भी बेहतर बनाता है।

यह शोध कार्य एक बहुउद्देशीय ग्रिड-संयुक्त पवन ऊर्जा उत्पादन प्रणाली के विकास को भी सम्मिलित करता है। सौर एवं पवन ऊर्जा स्रोतों की पूरक प्रकृति को ध्यान में रखते हुए एक संयुक्त सूक्ष्मबिजली तंत्र विकसित किया गया है, जिसमें स्थायी चुम्बकीय रहित-वलय दिष्ट धारा उत्पादक से चालित पवन टरबाइन एवं सौर ऊर्जा पटल सम्मिलित हैं। इसमें भी सुगम संक्रमण युक्ति तथा द्वीपीकरण पहचान तकनीक का प्रयोग किया गया है।

यह अध्ययन बैटरी ऊर्जा भंडारण सहित तथा बिना, समानांतर सौर ऊर्जा इन्वर्टर आधारित सूक्ष्मबिजली तंत्र की विभिन्न संरचनाओं का विश्लेषण करता है, जो दूरदराज़ क्षेत्रों में विद्युत आपूर्ति की उपलब्धता और विश्वसनीयता बढ़ाने में सहायक हैं। इन संरचनाओं में वितरित ऊर्जा इकाइयाँ, ऊर्जा भंडारण प्रणाली और स्थानीय भार शामिल होते हैं, जहाँ प्रत्येक इकाई को सौर पटल, आउटपुट संयोजक और इन्वर्टर के माध्यम से युग्मन बिंदु पर समानांतर रूप में जोड़ा गया है। एक प्रभावशाली सूक्ष्मबिजली तंत्र वही होता है, जो ग्रिड-संयुक्त तथा स्वतंत्र दोनों स्थितियों में कुशलता से कार्य कर सके। स्वतंत्र संचालन के दौरान

यदि सौर ऊर्जा उत्पादन भार की मांग से अधिक हो जाता है, तो प्रणाली की स्थिरता पर प्रभाव पड़ता है। इसे रोकने हेतु अतिरिक्त सौर पटल को ऊर्जा भंडारण तथा अन्य स्रोतों से जोड़ा जाता है, जिससे प्रत्येक स्रोत से प्राप्त ऊर्जा का समुचित उपयोग हो सके।

समस्त सूक्ष्मबिजली संरचनाओं एवं नियंत्रण कलन विधियों को सांख्यिकी गणना सॉफ्टवेयर के माध्यम से मॉडलित एवं अनुकरण किया गया है। संतोषजनक अनुकरण परिणामों के पश्चात एक प्रायोगिक प्रतिरूप तैयार किया गया है, जिसमें सौर पटल, पवन टरबाइन तथा बैटरी ऊर्जा भंडारण को सम्मिलित किया गया है। इस प्रणाली का परीक्षण वास्तविक समय नियंत्रण यंत्र की सहायता से किया गया है। विभिन्न जटिल परिस्थितियों जैसे - सौर विकिरण में परिवर्तन, भार में उतार-चढ़ाव, वोल्टता विकृति एवं संचालन मोड में परिवर्तन की स्थिति में प्राप्त परीक्षण परिणामों का प्रस्तुतीकरण किया गया है। विशेष रूप से सौर एवं पवन दोनों प्रणालियाँ अधिकतम ऊर्जा बिंदु का सफलतापूर्वक अनुसरण करती हैं तथा ग्रिड और स्वतंत्र संचालन मोड के मध्य निर्बाध परिवर्तन को प्रभावी रूप से प्रदर्शित करती हैं।

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LIST OF ABBREVIATIONS

ADO	Adaptive Disturbance Observer
AIF	Adaptive Integrator Filter
ANI	Active Noise Isolation
APF	Active power Filter
APC	Adaptive Power Control
AQSG	Adaptive Quadrature Signal Generator
BES	Battery Energy Storage
BPF	Band Pass Filter
CCM	Current Control Mode
DBC	DC-DC Bidirectional Converter
DOD	Depth of discharge
DSP	Digital Signal Processor
DER	Distributed Energy Resource
DFIG	Double-Fed Induction Generator
DFT	Discrete Fourier transformation
ES-SOGI	Extant State Second Order Generalized Integrator
FADO	frequency adaptive disturbance observer
FLL	Frequency Locked Loop
FSFP	Fixed Speed Fixed Pitch
FSVP	Fixed Speed Variable Pitch
GF-EPLL	General Filtering based Enhanced Phase Locked Loop
GI	Generalized Integrator
GTM	Grid Tied Mode
HE	Harmonic Extractor
HSC	Hysteresis Switching Controller
HVCC	Hybrid Voltage and Current Control
IAM	Islanding Mode
IGBT	Insulated Gate Bipolar Transistor
InC	Incremental Conductance
ITOAI	Improved Third-Order Adaptive Integrator
LMF	Least Mean Fourth

LMS	Least Mean Square
MACNE	Multi Adaptive Circular Noise Estimation
MNSOGI	Modified Novel Second Order Generalized Integrator
MCVF	Modified Complex Variable Filter
MOGI	Mixed Order Generalized Integrator
MPP	Maximum Power Point
MPE	Maximum Power Extraction
MADO	Multi Adaptive Disturbance Observer
NDZ	Non-Detection Zones
PCC	Point of Common coupling
PMBLDCG	Permanent Magnet Brushless DC Synchronous Generator
P&O	Perturb and observe
PI	Proportional Integral
PLL	Phase Locked Loop
PQ	Power Quality
PV	Photovoltaic
PVI	Photovoltaic Inverter
QSG	Quadrature Signal Generator
RTDS	Real Time Digital Simulator
RES	Renewable Energy Source
SOC	State of Charge
S&H	Sample and Hold
SOGI	Second Order Generalized Integrator
SOGI-QSG	Second Order Generalized Integrator with Quadrature Signal Generator
SRFT	Synchronous Reference Frame Theory
STS	Static Transition Switch
THD	Total Harmonic Distortion
TF	Transfer Function
TOGI	Third Order Generalized Integrator
TSP	Tip Speed Ratio
UPF	Unity Power Factor
UPS	Uninterruptible Power Supply

VCM	Voltage Control Mode
VSVP	Variable Speed Variable Pitch
VSC	Voltage Source Converter
VSFP	Variable Speed Fixed Pitch
WEGS	Wind Energy Generation System
WT	Wind Turbine
ZCD	Zero Crossing Detector

LIST OF SYMBOLS

a	Overloading factor
β	Blade pitch angle
A_g	Battery ageing factor
C_p^{opt}	optimum power coefficient
C_{dc}	DC link capacitor
C_p	power coefficient
C_f	Ripple filter capacitance
D	Duty cycle of the bidirectional converter
D_{bs}	Duty cycle of the boost converter
ΔI_g	Ripple in the grid current
ΔI_b	Minimum ripple in the battery
ΔP_W	Change in wind power
ΔI_{WT}	Change in wind turbine current
ΔV_{WT}	Change in wind turbine voltage
ΔP_{PV}	Change in PV power
ΔV_{PV}	Ripple in the PV voltage,
ΔI_{PV}	Ripple in the PV current,
$\Delta\theta$	Phase angle error between the phase angle of grid and load voltage
f_g	Grid Frequency
f_{gmin}, f_{gmax}	Minimum and maximum AC side frequency
G	Solar Insolation
I_{MP}	Maximum PV Current
I_{IGBT}	Current rating of IGBT devices
I_{dc}	DC link current
I_{PV}	PV Current
I_{sc}	Short circuit current
I_{wT}	Rectifier wind current
i_{wa}	Stator phase ‘a’ current
I_{VSCmax}	Maximum VSC current
I_b	Battery current
I_b^*	Reference battery current

i_c	VSC current
I_{vd}, I_{vq}	VSC current in DQ frame
$i_{s\alpha}$, $i_{s\beta}$	Reference grid current in αβ-reference frame
i_L	Load currents
$i_{\alpha L}$, $i_{\beta L}$	Load current in αβ-reference frame
$i_{\alpha Ls}$, $i_{\beta Ls}$	Reference load current in αβ-reference frame
I_{drg} , I_{drg}	Reference grid current in DC frame
I_{ld}, I_{Lq}	Reference load current in DC frame
I_{PVFF}	PV Feedforward term
I_{WTFF}	Wind Feedforward term
I_{Loss}	DC loss component
I_{pL}	Active fundamental component of load current
I_{gr}	Net reference grid current
i_{gref}	Reference grid current
J	Equivalent moment of inertia
K	Derating Factor
K_0, K_1, K_2 and K_3	Internal gain parameters in GL-EPLL
L_{bc}	Boost converter inductor
L_b	bidirectional converter inductor
L_f	Interfacing Inductor
m	Modulation Index
N_{P_PV}	Number of parallel solar PV panels
N_{S_PV}	Number of series solar PV panels
P_{PV}	PV power
P_L	VSC power
P_g	Grid power
P_{cgr}	Constant grid power
P_W	Wind power
R_f	Ripple filter Resistance
R_b	Turbine blade radius
S_{STS}	Synchronization signal
S_{vf}	Safety factor for calculating voltage rating of IGBT devices

S_{if}	Safety factor for calculating current rating of IGBT devices
T_c	Temperature correction factor
T	Solar temperature
V_{dcm}	Minimum DC link voltage
u_{pg}, u_{pq}	In-phase and quadrature phase unit templates
V_{IGBT}	Voltage rating of IGBT devices
V_{dc}	DC link voltage
V_{PV}	PV voltage
V_{oc}	Open circuit voltage
V_{dcr}	Reference DC link voltage
v_g	Grid voltage
$v_{\alpha g}$, $v_{\beta g}$	Grid voltage in αβ-reference frame
V_d, V_q	Grid voltage in DQ frame
V_t	Magnitude of grid voltage
$V_{tmin,}$ V_{tmax}	Minimum and maximum AC grid voltage
v_L	Load voltage
V_{Ld}, V_{Lq}	Load voltage in αβ-reference frame
V^*_{ld}, V^*_{lq}	Reference load voltage in αβ-reference frame
V_t	Terminal voltage
v_{wT}	Rectifier wind voltage
v_{wa}	Stator phase ‘a’ voltage
ω_o	Nominal value of grid frequency
ω	grid frequency
X_g	Grid status signal
θ_L	Phase angle of grid voltage
θ_g	Phase angle of load voltage
λ_{opt}	Tip speed ratio