

CONTROL OF WIND-DRIVEN-DFIG-SPV ARRAY- BATTERY BASED MICROGRIDS WITH SYNCHRONIZATION

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**DEPARTMENT OF ELECTRICAL ENGINEERING
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by

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Submitted

in fulfilment of the requirements of the degree of
DOCTOR OF PHILOSOPHY

to the



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*Dedicated to My Parents
and My Mentors*

CERTIFICATE

It is certified that the thesis entitled “**Control of Wind-Driven-DFIG-SPV Array-Battery Based Microgrids With Synchronization,**” being submitted by **Mr. Subhadip Chakraborty** for 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. Subhadip Chakraborty has worked under our guidance and supervision and has fulfilled the requirements for the submission of this thesis, which to my knowledge has reached the required standard. The results obtained herein have not been submitted to any other University or Institute for the award of any degree.

Dated: June 30, 2025

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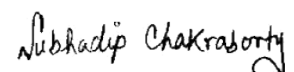
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ABSTRACT

The global shift toward sustainable energy sources has driven significant advancements in renewable energy technologies, particularly in wind and solar power. As these sources become increasingly integrated into global energy grid, challenges related to stability, power quality, and efficient management of energy resources in microgrids have emerged. Microgrids, especially deployed in distribution systems and in remote and semi-urban areas, have gained considerable attention due to their ability to integrate renewable energy sources, offer localized control, and enhance grid support functionalities. Among various renewable energy technologies, wind energy, particularly through doubly fed induction generators (DFIG), has gained prominence due to absence of costly rare earth magnets and potential for bulk power generation with partially rated power converters, while solar photovoltaic (SPV) arrays are a key renewable source due to their widespread availability, low cost, and minimal maintenance requirements due to absence of rotating parts. However, integration of these sources leads to power variability at point of common coupling (PCC) and fluctuations in PCC voltage parameters associated with voltage phase angle jumps and amplitude fluctuations. Moreover, loads demanding currents polluted with harmonics, negative sequence, and reactive currents further demean system power quality increasing line copper losses and degrading wind transformer performance. Such currents challenge fundamental estimation capabilities required for inverter control. Additionally, voltage disturbances propagate through inter-coupled estimation loops of phase and frequency locked loops (PLLs/FLLs), necessitating implementation of sophisticated control strategies with advanced filters for fast and accurate fundamental signal estimation to enhance inverter control. To address these issues, multimode, multifunctional control strategies are essential for ensuring reliable operation, improved power quality and seamless system transition among various operating modes with smooth synchronization performance.

To address evolving needs of solar photovoltaic (SPV) array and wind driven DFIG-based microgrids, various topological advancements are explored in this thesis, each offering specific advantages in terms of power quality, reliability, and energy management. Initially, batteryless single-stage SPV microgrids offered a cost-effective and simple design by eliminating intermediate converters and energy storage. However, they struggled with DC link fluctuations that may lead to operation of solar inverter in overmodulation zone. Further, varying DC link voltage also increases inverter losses, which is reduced with a two stage or double stage configuration with an intermediate DC-DC boost converter that ensures adaptive DC link

voltage to ensure optimal DC link voltage regulation with grid voltage to ensure optimal losses within inverter. Further, transitioning from a three-phase three-wire (3P3W) to a three-phase four-wire (3P4W) configuration has addressed critical issues related to unbalanced and single-phase loads, which caused phase overloading and voltage instability in 3P3W systems. 3P4W AC systems, with a neutral conductor, has provided better load balancing and voltage regulation across loads, ensuring safe operation of sensitive equipment. However, burden on neutral conductor during connected nonlinear loads leads to neutral overloading or overheating and possible bursting of neutral wire, necessitating neutral current compensation with the solar inverter alongside load harmonics, negative sequence, and reactive power compensation. Despite these improvements, absence of energy storage in batteryless configurations limited their capability during periods of low solar irradiance or grid outages. Integrating a battery energy storage system (BES), particularly with a bidirectional converter (BDC), has enabled regulated power supply by storing excess energy and providing backup during peak demand or nighttime, thereby enhancing system self-sufficiency and power quality. BDC also minimized 100Hz ripple currents, reducing stress on both BES and SPV array. Moreover, transition to dual-stage SPV architectures—with dedicated converters for SPV array and BES has allowed independent control and optimized power processing. These systems could flexibly switch between grid-forming (GFM) and grid-following (GFL) modes, enabling better compensation for harmonics, negative sequence currents, and load imbalances in both grid-tied and standalone operations. The need for improved resilience and multi-source integration has led to configurations combining SPV arrays with DFIG-based wind energy systems (WECS). These systems have enabled hybrid renewable operation across four modes—grid-connected or islanded, with DFIG stator connected or disconnected—allowing eight possible transition states. Control strategies ensure fast synchronization with grid or DFIG stator to support seamless transitions and continuous power delivery. More advanced microgrid topologies are also analysed incorporating an alternate power converter (APC) to reduce WECS transformer rating and burden of load harmonics, reactive and neutral current and ensure continuous load neutral and harmonics compensation.

The research presented in this thesis employs both experimental hardware results and simulation studies to validate the proposed solutions into the explored microgrid topologies. Through comprehensive hardware testing, the thesis demonstrates effectiveness of the proposed control algorithms in improving system reliability with improved power quality performance. Simulation results are presented to support experimental findings.

सार

स्थायी ऊर्जा स्रोतों की ओर वैश्विक बदलाव ने अक्षय ऊर्जा प्रौद्योगिकियों, विशेष रूप से पवन और सौर ऊर्जा में महत्वपूर्ण प्रगति को प्रेरित किया है। जैसे-जैसे ये स्रोत वैश्विक ऊर्जा ग्रिड में तेजी से एकीकृत होते जा रहे हैं, माइक्रोग्रिड में ऊर्जा संसाधनों की स्थिरता, बिजली की गुणवत्ता और कुशल प्रबंधन से संबंधित चुनौतियाँ उभरी हैं। माइक्रोग्रिड, विशेष रूप से वितरण प्रणालियों और दूरदराज और अर्ध-शहरी क्षेत्रों में तैनात, अक्षय ऊर्जा स्रोतों को एकीकृत करने, स्थानीय नियंत्रण प्रदान करने और ग्रिड समर्थन कार्यक्षमताओं को बढ़ाने की उनकी क्षमता के कारण काफी ध्यान आकर्षित कर रहे हैं। विभिन्न अक्षय ऊर्जा प्रौद्योगिकियों में, पवन ऊर्जा, विशेष रूप से डबली फीड इंडक्शन जनरेटर (डीएफआईजी) के माध्यम से, महंगे दुर्लभ पृथ्वी चुम्बकों की अनुपस्थिति और आंशिक रूप से रेटेड पावर कन्वर्टर के साथ थोक बिजली उत्पादन की क्षमता के कारण प्रमुखता प्राप्त हुई है, जबकि सौर फोटोवोल्टिक (एसपीवी) सरणियाँ अपनी व्यापक उपलब्धता, कम लागत और घूर्णन भागों की अनुपस्थिति के कारण न्यूनतम रखरखाव आवश्यकताओं के कारण एक प्रमुख अक्षय स्रोत हैं। हालाँकि, इन स्रोतों के एकीकरण से कॉमन कपलिंग (पीसीसी) के बिंदु पर बिजली परिवर्तनशीलता और वोल्टेज चरण कोण कूद और आयाम उतार-चढ़ाव से जुड़े पीसीसी वोल्टेज मापदंडों में उतार-चढ़ाव होता है। इसके अलावा, हार्मोनिक्स, नकारात्मक अनुक्रम और प्रतिक्रियाशील धाराओं से प्रदूषित धाराओं की मांग करने वाले भार सिस्टम की बिजली की गुणवत्ता को और कम करते हैं, जिससे बिजली संचरण घाटा बढ़ता है और पवन ट्रांसफार्मर का प्रदर्शन खराब होता है। ऐसी धाराएं इन्वर्टर नियंत्रण के लिए आवश्यक मौलिक अनुमान क्षमताओं को चुनौती देती हैं। इसके अतिरिक्त, वोल्टेज की गड़बड़ी चरण और आवृत्ति लॉक लूप (पीएलएल/एफएलएल) के अंतर-युग्मित अनुमान लूप के माध्यम से फैलती है, जिससे इन्वर्टर नियंत्रण को बढ़ाने के लिए तेज और सटीक मौलिक सिग्नल अनुमान के लिए उन्नत फिल्टर के साथ परिष्कृत नियंत्रण रणनीतियों के कार्यान्वयन की आवश्यकता होती है। इन मुद्दों को संबोधित करने के लिए, विश्वसनीय संचालन, बेहतर बिजली की गुणवत्ता और सुचारू सिंक्रनाइजेशन प्रदर्शन के साथ विभिन्न ऑपरेटिंग मोड के बीच निर्बाध सिस्टम संक्रमण सुनिश्चित करने के लिए मल्टीमोड, बहुक्रियाशील नियंत्रण रणनीतियाँ आवश्यक हैं। शुरुआत में, बैटरी रहित एकल-चरण एसपीवी माइक्रोग्रिड ने मध्यवर्ती कन्वर्टर और ऊर्जा भंडारण को समाप्त करके लागत प्रभावी और सरल डिज़ाइन की पेशकश की। हालाँकि, वे डीसी लिंक उतार-चढ़ाव से जूझते थे जो ओवरमॉड्यूलेशन ज़ोन में सौर इन्वर्टर के संचालन को जन्म दे सकता है। इसके अलावा, डीसी लिंक वोल्टेज में बदलाव से इन्वर्टर के नुकसान भी बढ़ जाते हैं, जिसे एक दो चरण या दोहरे चरण विन्यास के साथ एक मध्यवर्ती डीसी-डीसी बूस्ट कनवर्टर के साथ कम किया जा सकता है जो ग्रिड वोल्टेज के साथ इष्टतम डीसी लिंक वोल्टेज विनियमन सुनिश्चित करने के लिए अनुकूली डीसी लिंक वोल्टेज सुनिश्चित करता है ताकि इन्वर्टर के भीतर इष्टतम नुकसान सुनिश्चित हो सके। इसके अलावा,

तीन-चरण तीन-तार (३पी३डब्लू) से तीन-चरण चार-तार (३पी४डब्लू) विन्यास में संक्रमण ने असंतुलित और एकल-चरण भार से संबंधित महत्वपूर्ण मुद्दों को संबोधित किया, जो ३पी३डब्लू सिस्टम में चरण अधिभार और वोल्टेज अस्थिरता का कारण बना। एक तटस्थ कंडक्टर के साथ ३पी४डब्लू एसी सिस्टम ने संवेदनशील उपकरणों के सुरक्षित संचालन को सुनिश्चित करते हुए लोड में बेहतर लोड संतुलन और वोल्टेज विनियमन प्रदान किया। हालांकि, कनेक्टेड नॉनलाइनियर लोड के दौरान न्यूट्रल कंडक्टर पर बोझ के कारण न्यूट्रल ओवरलोडिंग या ओवरहीटिंग हो सकती है और न्यूट्रल वायर के फटने की संभावना हो सकती है, जिसके लिए लोड हार्मोनिक्स, नेगेटिव सीकेंस और रिएक्टिव पावर मुआवजे के साथ-साथ सोलर इन्वर्टर के साथ न्यूट्रल करंट मुआवजे की आवश्यकता होती है। इन सुधारों के बावजूद, बैटरी रहित विन्यास में ऊर्जा भंडारण की अनुपस्थिति ने कम सौर विकिरण या ग्रिड आउटेज की अवधि के दौरान उनकी क्षमता को सीमित कर दिया। बैटरी ऊर्जा भंडारण प्रणाली (बीईएस) को एकीकृत करना, विशेष रूप से एक द्विदिश कनवर्टर (बीडीसी) के साथ, अतिरिक्त ऊर्जा को संग्रहीत करके और पीक डिमांड या रात के समय बैकअप प्रदान करके विनियमित बिजली आपूर्ति को सक्षम करता है, जिससे सिस्टम की आत्मनिर्भरता और बिजली की गुणवत्ता में वृद्धि होती है। बीडीसी ने १०० हर्ट्ज रिपल करंट को भी कम किया, जिससे बीईएस और एसपीवी सरणी दोनों पर तनाव कम हुआ। इसके अलावा, दोहरे चरण वाले एसपीवी आर्किटेक्चर में संक्रमण - एसपीवी सरणी और बीईएस के लिए समर्पित कन्वर्टर के साथ - स्वतंत्र नियंत्रण और अनुकूलित पावर प्रोसेसिंग की अनुमति देता है। ये सिस्टम ग्रिड-फॉर्मिंग (जीएफएम) और ग्रिड-फॉलोइंग (जीएफएल) मोड के बीच लचीले ढंग से स्विच कर सकते हैं, जिससे ग्रिड-टाईड और स्टैंडअलोन दोनों ऑपरेशन में हार्मोनिक्स, नेगेटिव सीकेंस करंट और लोड असंतुलन के लिए बेहतर मुआवजा मिल सकता है। बेहतर लचीलेपन और मल्टी-सोर्स इंटीग्रेशन की आवश्यकता ने एसपीवी सरणियों को डीएफआईजी -आधारित पवन ऊर्जा प्रणालियों (डब्ल्यूईसीएस) के साथ संयोजित करने वाले कॉन्फ़िगरेशन को जन्म दिया। इन प्रणालियों ने चार मोड में हाइब्रिड अक्षय संचालन को सक्षम किया- ग्रिड-कनेक्टेड या आइलैंडेड, डीएफआईजी स्टेटर कनेक्टेड या डिस्कनेक्टेड के साथ- जिससे आठ संभावित संक्रमण अवस्थाएँ संभव हो सकीं। नियंत्रण रणनीतियाँ सुनिश्चित करती हैं। डब्ल्यूईसीएस ट्रांसफॉर्मर रेटिंग और लोड हार्मोनिक्स, रिएक्टिव और न्यूट्रल करंट के बोझ को कम करने और निरंतर लोड न्यूट्रल और हार्मोनिक्स क्षतिपूर्ति सुनिश्चित करने के लिए वैकल्पिक पावर कनवर्टर (एपीसी) को शामिल करते हुए अधिक उन्नत माइक्रोग्रिड टोपोलॉजी का भी विश्लेषण किया गया है। इस थीसिस में प्रस्तुत शोध में प्रस्तावित समाधानों को खोजे गए माइक्रोग्रिड टोपोलॉजी में मान्य करने के लिए प्रयोगात्मक हार्डवेयर परिणामों और सिमुलेशन अध्ययनों दोनों का उपयोग किया गया है। व्यापक हार्डवेयर परीक्षण के माध्यम से, थीसिस बेहतर बिजली गुणवत्ता प्रदर्शन के साथ सिस्टम विश्वसनीयता में सुधार करने में प्रस्तावित नियंत्रण एल्गोरिदम की प्रभावशीलता को प्रदर्शित करती है। प्रयोगात्मक निष्कर्षों का समर्थन करने के लिए सिमुलेशन परिणाम प्रस्तुत किए गए हैं।

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LIST OF ABBREVIATIONS

APC	Alternate Power Converter
BES	Battery Energy Storage
BDC	Bidirectional Converter
C-SOGI	Cascaded Second Order Generalized Integrator
DFIG	Doubly Fed Induction Generator
DSC	Delayed Signal Cancellation
EFOGI	Enhanced Fourth Order Generalized Integrator
EPLL	Enhanced Phase Locked Loop
FLL	Frequency Locked Loop
PILC	Prefilter In-Loop Comb
LMS	Least Mean Square
MFLL	Modified FLL
MSOGI	Multiple or Multilayered Second Order Generalized Integrator
PCC	Point of Common Coupling
PES	Power Electronic Switch
PLL	Phase Locked Loop
POI	Point of Interconnection
RES	Renewable Energy Source
RSC	Rotor Side Converter.
SOGI	Second Order Generalized Integrator
SPV	Solar Photovoltaic
SPVS	Solar Photovoltaic System
SSC	Stator Side Converter
STS	Static Transfer Switch
THD	Total Harmonic Distortion
TOGI	Third Order Generalized Integrator
UPF	Unity Power Factor
UPS	Uninterruptible Power Supply
VLCCF	Variable Cost Coefficient Cost Function
VSC	Voltage Source Converter
WECSs	Wind Energy Conversion System(s).
3P3/4W	Three Phase Three/ Four Wire

LIST OF SYMBOLS

v_g, i_g, P_g	Grid voltage, current, and power.
v_L, i_L, P_L	Load voltage, current, and power.
V_t, V_g, V_{tg}	Grid phase voltage peak amplitude.
f_g, θ_g	Grid fundamental voltage component frequency and phase angle.
V_L, V_{tL}	Load phase voltage peak amplitude.
f_L, θ_L	Load fundamental voltage component frequency and phase angle.
V_{PV}, I_{PV}	SPV array voltage and current.
P_{PV}	SPV array power.
I_{PVF}	PV feedforward term.
V_B, I_B	BES voltage and current.
P_B	BES power.
I_{BF}	BES feedforward term.
I_{gdq}	Grid active and reactive current component amplitude.
I_{Ldq}	Load active and reactive current component amplitude.
$i_{L\alpha\beta l}^+$	Load fundamental filtered $\alpha\beta$ current components.
$v_{g\alpha\beta l}^+$	Grid fundamental filtered $\alpha\beta$ voltage components.
B_{AH}	BES Ampere-Hour (Ah) Capacity
C_B	Rated charge/discharge rate of BES.
v_s, i_s, P_s	DFIG stator voltage, current, and power.
i_r	Rotor current.
i_{VSC}	VSC current.
i_{gn}	Grid neutral current.
i_{Ln}	Load neutral current.
i_{VSCn}	VSC neutral current.
i_c, i_{cn}	APC currents (In topologies without APC, i_c refers to i_{ssc} , same as i_c).
i_x, i_{xn}	WECS transformer currents.
L_1, L_2	Boost and BDC inductors.
$L_{f1,2}$	Interfacing inductors for inverters.
L_x	WECS SSC interfacing inductors after the wind transformer.
R_1, C_1	Grid stator side ripple filters.
R_2, C_2	Load / APC side ripple filters.
R_3, C_3	DFIG stator ripple filters.

$V_{DC1,2}$	DC link voltages.
S_i, S_s	DFIG stator incoming moment and stator synchronization signals.
M, S_g	Grid availability moment (M or S_m) and grid synchronization signals.
S_o, S_w	Wind system incoming moment and synchronization signals.
G_{STS}	Grid Side STS.
S_{STS}	DFIG Stator STS.
W_{STS}	Wind system STS.
i_{wabc}	Wind system currents.
P_w	Wind system power.