

**CONTROL OF GRID INTERACTIVE MICROGRIDS
EMPLOYING SOLAR PHOTOVOLTAIC ARRAY, WIND
TURBINE DRIVEN PMSG AND BATTERY**

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AUGUST 2021

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EMPLOYING SOLAR PHOTOVOLTAIC ARRAY, WIND
TURBINE DRIVEN PMSG AND BATTERY**

by

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Submitted

In fulfilment of the requirements of the degree of Doctor of Philosophy

to the



INDIAN INSTITUTE OF TECHNOLOGY DELHI

AUGUST 2021

CERTIFICATE

It is certified that the thesis entitled “**Control of Grid Interactive Microgrids Employing Solar Photovoltaic Array, Wind Turbine Driven PMSG and Battery,**” being submitted by Mrs. Subarni Pradhan 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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ACKNOWLEDGEMENTS

I wish to express my deepest gratitude and indebtedness to **Prof. Bhim Singh and Prof. Bijaya Ketan Panigrahi** for providing me guidance and constant supervision to carry out the Ph.D. work. Working under them has been a wonderful experience, which has provided a deep insight to the world of research. Determination, dedication, innovativeness, resourcefulness, and discipline of **Prof. Bhim Singh** have been the inspiration for me to complete this work. His consistent encouragement, continuous monitoring and commitments to excellence have always motivated me to improve my work and use the best of my capabilities. Due to their blessings, I have earned various experiences other than research, which will help me throughout my life.

My sincere thanks and deep gratitude are to **Prof. Sukumar Mishra, Prof. Nilanjan Senroy, and Prof. Ashu Verma**, all SRC members for their valuable guidance and consistent support during my research work.

I wish to convey my sincere thanks to **Prof. Bhim Singh, Prof. B. K. Panigrahi, Late Dr. Mashuq un-Nabi, Dr. Shubhendu Bhasin and Dr. Anandarup Das** for their valuable inputs during my course work, which made the foundation for my research work. I am grateful to **IIT Delhi** for providing me the research facilities. I wish to express my sincere gratitude to **Prof. G. Bhuvaneswari and Prof. M. Veerachary**, Prof. in-charge, PG Machine Lab., for providing me immense facilities to carry out experimental work. Thanks to Mr. Srichand, Mr. Puran Singh, and Mr. Jitendra and Mr. Anurag, of PG Machines Lab., IIT Delhi for providing me the facilities and assistance during this work. I would like to thank my seniors, Dr. Ikhtlaq Hussain, Dr. Rajan Sonakar, Dr. Nishant Kumar, Dr. Aniket Anand, Dr. Shailendra Kumar Dwivedi, Dr. Anjanee Mishra, Dr. Sachin Devassy, Dr. Saurabh Shukla, Dr. Piyush Kant for motivating me in the starting of my research work. I would like to use this opportunity to thank Dr. Ikhtlaq

Hussain, Dr. Shahdab Murshid, Dr. Nishant Kumar, Dr. Shailendra Dwivedi, Mr. Anshul Varshney for providing me with valuable technical and non-technical support.

I would like to thank Mrs. Tabish Nazir Mir for her constant support and encouragement throughout my PhD work. I also wish to take this opportunity to thank Mr. Utkarsh Sharma, Ms. Rashmi Rai, Mrs. Yashi Singh, Mr. Vineet P Chandra, Mr. Priyank shah, Mr. Dipu Vijaya M, Mrs. Shataskshi Sharma, Mrs. Aakanksha Rajput, Mr. Vivek Narayanan, Mr. Debasish Mishra, Mr. Anjeet Verma, Mr. Gurmeet Singh, Mr. Sreejith R, Mrs. Radha Kushwaha, Mrs. Vandana Jain, Ms. Seema Kewat, Mrs. Subhra, Mrs. Nidhi Mishra, Mrs. Farheen Chishti, Mrs. Pavitra Shukl, Ms. Sunaina Singh, Mr. Sai Pranith Girimaji, Mr. Tripurari Nath for the encouragement they have provided. I would like to thank Mr. Gaurav Modi, Mr. Bilal Naqvi, Mr. K.P. Tomar, Mr. Sunil Pandey, Ms. Shalvi Tyagi, Mrs. Rohini Sharma, Ms. Chandrakala, Ms. Kousalya, Mr. Aryadip Sen, Mr. Kashif, Mr. Sharan Shastri, Ms. Hina Parveen, Mr. Yalavarthi Amarnath, Mr. VL Srinivas, Mr. Priyabrat Vats, Mr. Suri Paneeth, Mr. Jitendra Gupta, Mr. Rahul Kumar, Mr. Sayandev Ghosh, Mr. Utsav Sharma, Mr. Saran Chourasiya, Mr. Shivam Yadav, Mr. Deepak shaw, Mr. Sambasivaiah, Mr. Sudip Bhattacharya, Mr. Sandeep Sahoo, Mr. Souvik Das, Ms. Kripa, Ms. Farha Siddique, , Mr. Zarkab, Mr. Saurabh, Mr. Vipin, Mr. Rohit, Mr. Arjun, Mr. Biswajit, Mr. Sumit, Mr. Himanshu, Mr. Subir Karmakar, Mr. Girja Shankar and all PG Machines lab group for their valuable support. I would like to thank Mrs. Priya Vinayak, Mrs. Shruti Ranjan, Dr. Neelima Nath, Mrs. Sushreesmita Mishra, Mr. Subrat Kumar, Mr. Rahul Sharma, Mr. Rajat, who supported and inspired me during my stay in the campus. I would also like to thank Mr. Yatindra, Mr. Satish, Mr. Sandeep, and all other Electrical Engineering office staff for being supportive throughout. I am likewise thankful to those who have directly or indirectly helped me to finish my dissertation study.

I would like to thank my Mother, Mrs. Sushama Pradhan, Father, Mr. Sidheswar Pradhan, Brother, Sikan Kumar Pradhan for their dreams, blessings, and constant encouragement. I

would like to thank my husband, Mr. Biswanath Dehury for giving me the inner strength and wholehearted support. I would like to thank my younger sister, Ms. Bandana Pradhan and all my family members for their continuous support and encouragement. Their trust in my capabilities had been a key factor to all my achievements.

At last, I am beholden to Almighty for their blessings to help me to raise my academic level to this stage. I pray for their benediction in my future endeavours. Their blessings may be showered on me for strength, wisdom, and determination to achieve in future.

Date:

Subarni Pradhan

ABSTRACT

The accelerated growth of renewable energy has been one of the most defining features of energy sector in the last decade. The microgrid structure consisting of renewable energy sources and local loads, is the sustainable structure to deal with the ever-increasing global energy demand without causing further damage to the environment. The microgrids are generally situated near the distribution network and with the help of power converters it is feasible to operate them under off-grid as well as grid interfaced modes, effectively. Typically, upgraded policies, technology advancement and introduction of custom power devices add flexibility in constructing a resilient and reliable microgrid. However, the stochastic behavior of renewables, creates challenges for smooth energy generation and an integration to the main utility grid. The penetration of these microgrids into the power grid encounters challenging issues that involves poor power factor, stability, power management and power quality. With this view, it is indispensable to develop modern circuit arrangements and control algorithms.

Due to the advantages of variable speed fixed pitch wind energy generation system (WEGS), it is preferred in this work, which is configured with two full scale voltage source converters (VSCs) connected back-to-back sharing a common DC link. One of them serves the objective of effective wind energy generation named as converter of turbine side (CTS) whereas the other one serves the objective of grid integration named as converter of grid side (CGS). Besides, the CGS manages the power flow of the utility grid and/or load meeting the auxiliary services. Depending on the requirement, the solar energy generation system is configurable as single stage and two stage configurations. Most important issues include effective wind and solar power generation from variable speed wind turbine (VSWT) and solar photovoltaic array (SPVA), respectively.

This work presents a simple and economical mechanical sensor-less WEGS. An observer based adaptive speed control (OASC) is developed for permanent magnet synchronous generator (PMSG) speed regulation aiming effective wind energy generation with respect to stochastic wind speed. The design of OASC includes a disturbance observer loop with backstepping control. The OASC provides fast and precise speed control exhibiting robustness against parameter uncertainties and structured and unstructured disturbances. Moreover, it includes a parameter adaptation structure based on discontinuous projection law. This work also presents a soft switching adaptive sliding mode observer (SSA-SMO) for PMSG rotor speed and position estimation, which are the required signals for control implementation. The fixed gains of classical sliding mode observer are replaced with adaptive gains, depending on speed, to achieve the estimated parameters with improved precision. This approach alleviates the inevitability of mechanical sensors and thereby resulting a reliable system with reduced cost and complexity.

This research work focuses on the development of a grid interactive multifunctional WEGS, which is also operable under the grid outage. Owing to the complement profile of the

renewable sources, wind and solar, this work emphasizes on the development of a multifunctional microgrid employing VSWT driven PMSG and SPVA. Focusing on system reliability, configurations with battery energy storage (BES), integrated at DC link, are presented with and without a bidirectional converter. Moreover, functionality of the microgrid during various operating modes are discussed. A seamless transition logic in conjunction with an islanding detection technique is incorporated for transferring the mode of operation, from off grid to grid interactive and vice versa. During grid interactive mode, the system is proficient in providing power quality (PQ) solutions such as, harmonics elimination, power factor correction, reactive power compensation, and grid currents balancing. During off grid mode, the control objectives include voltage and frequency regulation at point of common coupling (PCC). The core objective of the system is to deliver uninterrupted power to the local critical loads even during grid outage.

Based on the strength of main utility grid, strong or weak, the control algorithms for CGS are developed. Concentrating on the development of control algorithms for CGS when microgrid integrated to strong utility grid, a convex combined robust cost function (CCRCF) based control structure is used. The CCRCF algorithm lacks in dealing with voltage sags, swells, distortion, unbalance, etc. Targeting the PQ improvement during the microgrid integrated to a weak grid, a higher order complex coefficient filter (HOCCF) is presented. The HOCCF is used to extract fundamental positive and negative sequence of components from distorted grid voltages and nonlinear load currents. Additionally, it eliminates the DC component from the input signals. An occurrence of unbalanced voltages is common for the system connected to a weak grid. The microgrid is supposed to respond these faults by remaining connected at PCC while supplying the local loads and main utility grid. Further, according to the IEEE Standard 1547.4, the microgrid is to supply reactive power to stabilize the PCC voltage. Considering the condition of weak grid and stringent grid codes, a ride-through technique is developed for the microgrid. Triggering of overcurrent protection is avoided by introducing a current limiting structure to it.

The microgrid structures and the control algorithms are replicated through software simulation with the help of MATLAB/Simulink toolbox. Noticing satisfactory results, a prototype of microgrid employing variable wind turbine driven PMSG, SPVA and BES is developed. Various configurations are tested with applicable control algorithms. Simulated and test results are demonstrated for various adverse conditions such as, wind speed and solar insolation variation, unbalanced load, balanced and unbalanced voltages, voltage swells and voltage distortion. Moreover, it is worth mentioning that the extracted wind and solar powers track the maximum power point after perturbation during normal condition and continue to supply active and reactive powers operating at off maximum power point mode for PCC voltage stabilization and CGS protection during voltage dips. Finally, the performance during off grid and grid interactive modes with seamless transition between them is illustrated for multifeatured microgrid.

सार

रीन्यूएबल एनर्जी का त्वरित विकाश पिछले दशक में एनर्जी क्षेत्र की सबसे परिभाषित विशेषताओं में से एक रहा है। रीन्यूएबल एनर्जी स्रोतों और स्थानीय लोड से युक्त माइक्रोग्रिड स्ट्रक्चर पर्यावरण को और नुकसान पहुंचाए बिना लगातार बढ़ती एनर्जी मांग से निपटने के लिए ससटेनेबल स्ट्रक्चर है। माइक्रोग्रिड आमतौर पर वितरण नेटवर्क के पास स्थित होते हैं और पावर कन्वर्टर्स की मदद से उन्हें ऑफ-ग्रिड के साथ-साथ ग्रिड इंटरफेस मोड के तहत प्रभावी ढंग से संचालित करना संभव है। आमतौर पर, उन्नत नीतियां, प्रौद्योगिकी उन्नति और कस्टम बिजली उपकरणों की शुरूआत एक रेजिलिएन्ट और रिलायबल माइक्रोग्रिड के निर्माण में फ्लेक्सिबिलिटी जोड़ती है। हालांकि, रीन्यूएबल एनर्जी का स्टोकेस्टिक व्यवहार सुचारू एनर्जी उत्पादन और मुख्य ग्रिड में एकीकरण के लिए चुनौतियां पैदा करता है। पावर ग्रिड में इन माइक्रोग्रिड की एकीकरण चुनौतीपूर्ण मुद्दों का सामना करती है जिसमें खराब पावर फैक्टर, स्थिरता, बिजली प्रबंधन और बिजली की गुणवत्ता शामिल है। इस दृष्टि से, आधुनिक सर्किट व्यवस्था और नियंत्रण एल्गोरिदम विकसित करना अनिवार्य है।

भेरिएबल स्पीड फिक्स्ड पिच विंड एनर्जी जेनरेशन सिस्टम के फायदों के कारण, इसे इस काम में प्राथमिकता दी जाती है, जिसे दो फुल स्केल भोल्टेज सोर्स कन्वर्टर्स कनेक्टेड बैक-टू-बैक एक कॉमन डीसी लिंक शेयरिंग के साथ कॉन्फिगर किया गया है। उनमें से एक प्रभावी विंड एनर्जी उत्पादन के उद्देश्य को पूरा करता है जिसे टर्बाइन साइड के कनवर्टर के रूप में नामित किया गया है जबकि दूसरा ग्रिड एकीकरण के उद्देश्य को ग्रिड साइड के कनवर्टर के रूप में नामित करता है। इसके अलावा, ग्रिड साइड के कनवर्टर यूटिलिटी ग्रिड के बिजली प्रवाह और/या सहायक सेवाओं को पूरा करने वाले लोड का प्रबंधन करता है। आवश्यकता के आधार पर, सोलार एनर्जी उत्पादन प्रणाली सिंगल स्टेज और दो स्टेज विन्यास के रूप में विन्यास योग्य है। सबसे महत्वपूर्ण मुद्दों में क्रमशः परिवर्तनीय गति विंड टरबाइन और सोलार फोटोवोल्टिक अरै से प्रभावी पवन और सोलार एनर्जी उत्पादन शामिल हैं।

यह कार्य एक सरल और किफायती यांत्रिक सेंसर-रहित विंड एनर्जी जेनरेशन सिस्टम प्रस्तुत करता है। स्थायी चुंबक सींक्रोनोस जनरेटर के गति विनियमन के लिए एक ऑब्जर्वर बेस्ड एडप्टीव स्पीड कंट्रोल विकसित किया गया है जिसका लक्ष्य स्टोकेस्टिक पवन गति के संबंध में प्रभावी पवन एनर्जी उत्पादन है। मुख्य ग्रिड की ताकत के आधार पर, मजबूत या कमजोर, ग्रिड साइड के कनवर्टर के लिए कंट्रोल एल्गोरिदम विकसित किए जाते हैं। ग्रिड साइड के कनवर्टर के लिए नियंत्रण एल्गोरिदम के विकास पर ध्यान केंद्रित करते हुए जब माइक्रोग्रिड को मजबूत उपयोगिता ग्रिड में एकीकृत किया जाता है, तो एक कॉनभेक्स कम्बाइन्ड रोबस्ट कॉस्ट फ़ंक्शन आधारित कंट्रोल स्ट्रक्चर का उपयोग किया जाता है।

कॉनभेक्स् कम्बाइन्ड रोबस्ट कॉस्ट फ़ंक्शन एल्गोरिथम में वोल्टेज की कमी, स्वेल, विकृति, असंतुलन आदि से निपटने में कमी होती है। कमजोर ग्रिड से एकीकृत माइक्रोग्रिड के दौरान पावर क्वालिटी सुधार को लक्षित करते हुए, एक हाइयर ऑर्डर कॉम्प्लेक्स कोफिसिएन्ट फ़िल्टर प्रस्तुत किया जाता है। हाइयर ऑर्डर कॉम्प्लेक्स कोफिसिएन्ट फ़िल्टर का उपयोग विकृत ग्रिड वोल्टेज और नॉनलिनीअर लोड धाराओं से फंडामेंटल पाज़िटिव और नेगटिव अनुक्रम को निकालने के लिए किया जाता है। इसके अतिरिक्त, यह डीसी कम्पोनन्ट को समाप्त कर देता है। कमजोर ग्रिड से जुड़े सिस्टम के लिए असंतुलित वोल्टेज की घटना आम है। माइक्रोग्रिड को स्थानीय भार और मुख्य उपयोगिता ग्रिड की आपूर्ति करते समय पॉइंट ऑफ कॉमन कप्लिंग से जुड़े रहकर इन दोषों का जवाब देना चाहिए। इसके अलावा, माइक्रोग्रिड में पॉइंट ऑफ कॉमन कप्लिंग वोल्टेज को स्थिर करने के लिए रेयकटिव पावर की आपूर्ति करना है। कमजोर ग्रिड और स्ट्रॉंग ग्रिड कोड की स्थिति को ध्यान में रखते हुए माइक्रोग्रिड के लिए एक राइड-थ्रू तकनीक विकसित की गई है। करेंट लिमिटिंग स्ट्रक्चर को उपयोग करने से ओभरकरेंट सुरक्षा को ट्रिगर करने से बचा जाता है।

माइक्रोग्रिड स्ट्रक्चरस् और कंट्रोल एल्गोरिदम को MATLAB/Simulink टूलबॉक्स की सहायता से सॉफ्टवेयर सिमुलेशन के माध्यम से दोहराया जाता है। संतोषजनक परिणामों को देखते हुए, भेरियबल स्पीड विंड टरबाइन संचालित स्थायी चुंबक सींकरोनोस् जनरेटर, सोलार फोटोवोल्टिक अरे और बैटरी एनर्जी स्टॉरिज को नियोजित करने वाले माइक्रोग्रिड का एक प्रोटोटाइप विकसित किया गया है। लागू नियंत्रण एल्गोरिदम के साथ विभिन्न विन्यासों का परीक्षण किया जाता है। विभिन्न प्रतिकूल परिस्थितियों जैसे हवा की गति और सौर सूर्यातप भिन्नता, असंतुलित लोड, संतुलित और असंतुलित वोल्टेज, वोल्टेज स्वेल और वोल्टेज विरूपण के लिए सिमुलेटेड और परीक्षण के परिणाम प्रदर्शित किए जाते हैं। इसके अलावा, यह उल्लेखनीय है कि निकाली गई विंड और सौर शक्तियां सामान्य स्थिति के दौरान गड़बड़ी के बाद अधिकतम पावर पॉइंट को ट्रैक करती हैं और वोल्टेज डिप्स के दौरान पॉइंट ऑफ कॉमन कप्लिंग वोल्टेज स्थिरीकरण और ग्रिड साइड के कनवर्टर के सुरक्षा के लिए ऑफ मेक्सिमम पावर पॉइंट मोड पर सक्रिय और प्रतिक्रियाशील शक्तियों की आपूर्ति जारी रखती हैं। अंत में, ऑफ ग्रिड और ग्रिड इंटरएक्टिव मोड के दौरान उनके बीच सीमलेस ट्रांजिसन के दौरान प्रदर्शन को बहु-विशेषीकृत माइक्रोग्रिड के लिए चित्रित किया गया है।

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LIST OF ABBREVIATIONS

AARC	Average Active Reactive Control
ADRC	Active Disturbance Rejection Control
ANN	Artificial Neural Network
ANFIS	Adaptive Network-Based Fuzzy Inference System
BDC	Bidirectional Converter
BES	Battery Energy Storage
BPF	Band Pass Filter
BPSC	Balanced Positive Sequence Control
CCRCF	Convex Combined Robust Cost Function
CGS	Converter of Grid Side
CTS	Converter of Turbine Side
DCC	Decoupled Current Control
DG	Distributed Generation
DPC	Direct Power Control
DSTATCOM	Distributed Static Compensator
EKF	Extended Kalman Filter
EMF	Electromotive Force
ESO	Extended State Observer
FLC	fuzzy logic control
FLL	Frequency Locked Loop
FOC	Field Oriented Control
FSFP	Fixed Speed Fixed Pitch
FSVP	Fixed Speed Variable Pitch
GI	Generalized Integrator
HCS	Hill Climbing Search
HFSI	High Frequency Signal Rejection
HOCCF	Higher Order Complex Coefficient Filter
IAPC	Instantaneous Active Power Control
IARC	Instantaneous Active Reactive Control
ICPS	Instantaneously Controlled Positive Sequence
IGBT	Insulated Gate Bipolar Transistor
IIR	Infinite Impulse Response

IM	Induction Motor
InC	Incremental Conductance
LCOE	Levelized Cost per Electricity
LMF	Least Mean Fourth
LMS	Least Mean Square
LVRT	Low Voltage Ride Through
MAF	Moving Average Filter
MFGI	Multilayered Fourth Order Generalized Integrator
MPP	Maximum Power Point
MPPT	Maximum Power Point Technique
MRAS	Model Reference Adaptive System
NDZ	Non-detection Zone
NNS	Neural Network Structure
OASC	Observer Based Adaptive Speed Control
ORB	Optimum Relationship-Based
PCC	Point of Common coupling
PI	Proportional Integral
PLL	Phase Locked Loop
PMSG	Permanent Magnet Synchronous Generator
PNSC	Positive Negative Sequence Compensation
P&O	Perturb and Observe
PSF	Power Signal Feedback
PQ	Power Quality
RES	Renewable Energy System
SCR	Short Circuit Ratio
SEGS	Solar Energy Generation System
SMC	Sliding Mode Control
SOC	State of Charge
SOGI	Second Order Generalized Integrator
SOGI-QSG	Second Order Generalized Integrator with Quadrature Signal Generator
SPCS	Solar Power Capturing Subsystem
SPVA	Solar Photovoltaic Array
SRF	Synchronous Reference Frame

STS	Static Transition Switch
SSA-SMO	Soft Switching Adaptive Sliding Mode Observer
TCSCC	Torque Controlling Stator Current Component
THD	Total Harmonic Distortion
TSR	Tip Speed Ratio
UNFCCC	United Nations Framework Convention on Climate Change
UPF	Unity Power Factor
VC	Vector Control
VFD	Variable Frequency Drive
VPRS	Voltage-Power Regulatory Subsystem
VSC	Voltage Source Converter
VSFP	Variable Speed Fixed Pitch
VSVP	Variable Speed Variable Pitch
VSWT	Variable Speed Wind Turbine
WEGS	Wind Energy Generation System
WPCS	Wind Power Capturing Subsystem
WT	Wind Turbine

LIST OF SYMBOLS

a	Overloading factor for calculating capacitance of DC link capacitor
α	Regularization constant
β	Rotor blade pitch angle
β_f	Mixing parameter
C_{dc}	DC link Capacitance
C_p^{opt}	Optimum power coefficient
C_p	Wind turbine power coefficient of rotor
C_f	Ripple filter capacitance
$d(\omega_m, t)$	Disturbance of the system
D_{BB}	Duty ratio of buck-boost converter
Δi	Allowable current ripple
ΔP_w	Change in wind power
ΔP_{pv}	Change in PV power
$\Delta \omega_m$	Change in speed
Δf_g	Change in grid frequency
$\Delta \theta$	Phase angle error
ε	Threshold value
e_α, e_β	Back electromotive force of PMSG in $\alpha\beta$ -reference frame
$\hat{e}_\alpha, \hat{e}_\beta$	Estimated back electromotive force of PMSG in $\alpha\beta$ -reference frame
e_{pa}, e_{pb}, e_{pc}	Error estimation functions
f_s	Switching frequency
h	Overload factor for calculating inductance of interfacing inductor
i_d, i_q	d and q axis currents of PMSG
i_α, i_β	Stator current in $\alpha\beta$ -reference frame
$\hat{i}_\alpha, \hat{i}_\beta$	Estimated stator current in $\alpha\beta$ -reference frame
$\tilde{i}_\alpha, \tilde{i}_\beta$	Current error in $\alpha\beta$ -reference frame
I_b	Battery current
I_{CGSmax}	Maximum CGS current
$I_{CGSmax,peak}$	Peak of maximum CGS current
i_{ga}, i_{gb}, i_{gc}	Grid currents
$i_{ga}^*, i_{gb}^*, i_{gc}^*$	Reference grid current
I_{IGBT}	Current rating of IGBT devices
i_{La}, i_{Lb}, i_{Lc}	Load currents

$i_{La}, i_{L\beta}$	Load current in $\alpha\beta$ -reference frame
$i_{Laf}, i_{L\beta f}$	Filtered load current in $\alpha\beta$ -reference frame
i_{pa}, i_{pb}, i_{pc}	CGS currents
i_{wa}, i_{wb}, i_{wc}	Stator currents in abc - reference frame
I_d^*, I_q^*	Reference CGS currents in dq -reference current
$i_{pa}^*, i_{pb}^*, i_{pc}^*$	Reference CGS currents
i_{pa}, i_{pb}, i_{pc}	CGS currents in abc - reference frame
J	Equivalent moment of inertia
k_f	Viscous frictional constant
k_{te}	torque constant of PMSG
k_1	Allowable voltage ripples
λ_{tsr}	Tip speed ratio
λ_{opt}	Optimum tip speed ratio
l_1, l_2	Gains of SMO
L_{BB}	Inductance of buck-boost converter
L_i	Inductance of interfacing inductor
L_d, L_q	d and q axis inductance of PMSG
m	Modulation index
n_p	Number of pole pair of PMSG
η	Adaptation function
η_1, η_2	Adaptative coefficients of SMO
ω_{est}	Estimated speed of PMSG
ω_{rm}	Wind turbine rotor speed
ω_m	Rotor mechanical speed
ω_e	Rotor electrical speed
ω_{ref}	Reference shaft speed
$\hat{\omega}$	Estimated frequency of the HOCCF
p	1 st order derivative with respect to time (d/dt)
P_b	Battery power
P_{b-ch}	Battery charging power
P_{b-dch}	Battery discharging power
P_{CGS}	Power available at the AC side of CGS
P_g	Active power of grid
P_L	Load power
P_{pv}	PV power

P_{tur}^{\max}	Maximum turbine power
P_{tur}	Aerodynamic power of wind turbine
P_{th}	Threshold active power that is allowed to be injected to the grid
P_w	Maximum available wind power
Q	Reactive power requirement
Q_g	Instantaneous reactive power of grid
ρ	Air density
$\rho(e_{pa}(k))$	M-estimate function
R	PMSG stator currents
R_b	Radius of turbine blade
R_f	Ripple filter resistance
ψ_p	Flux of permanent magnet
σ	Fixed step size of CCRCF
σ_p	Positive feedback gain
σ_1, σ_2	Gains of HOCCF
S_g	Maximum apparent power of CGS
s_{vf}	Safety factor for calculating voltage rating of IGBT devices
s_{if}	Safety factor for calculating current rating of IGBT devices
Γ	Adaptation rate matrix
θ_g	Phase angle of grid voltage
θ_p	Phase angle of PCC voltage
ϕ_e	Estimated rotor position of PMSG
t	DC voltage recovering time
T_d	Frictional torque
T_e	Electromagnetic torque of PMSG
T_s	Switching time
T_{tur}^{\max}	Maximum turbine Torque
V	Lyapunov function
V_p	Magnitude of positive sequence voltage
V_n	Magnitude of negative sequence voltage
V_{pu}	Per unit PCC voltage
V_t	PCC terminal voltage
\mathcal{g}	Parameter vector
\mathcal{g}_{dc}	DC loss component
$\mathcal{g}_{La}, \mathcal{g}_{Lb}, \mathcal{g}_{Lc}$	Load components of three phases

\mathcal{G}_L	Average Load component
\mathcal{G}_{pvf}	PV feed-forward component
\mathcal{G}_{wf}	Wind feed-forward component
\mathcal{G}_{net}	Net active power component
\mathcal{G}_q	Net reactive power component
u_{pa}, u_{pb}, u_{pc}	In-phase unit templates
u_{qa}, u_{qb}, u_{qc}	Quadrature unit templates
$v_{\alpha}^p, v_{\beta}^p$	Positive sequence voltages
$v_{\alpha}^n, v_{\beta}^n$	Negative sequence voltages
V_b	Battery voltage
V_g	Magnitude of grid voltage
v_b	Base wind velocity
v_g	Gust component of wind
v_r	Ramp component of wind
v_n	Background noises
v_d, v_q	d and q axis voltages of PMSG
V_d^*, V_q^*	Reference PCC voltages
V_{dc}	DC link voltage
V_{dc}^*	Reference DC link voltage
v_{ab}	Line-line voltage at AC side of CGS
V_{dcmin}	Minimum DC link voltage
V_{IGBT}	Voltage rating of IGBT devices
V_{min}	Minimum AC side voltage
v_w	Wind speed
x_2	Lumped disturbance
z_1	Speed tracking error
ξ	Damping factor
ζ_{pa}	Variable step size of CCRCF based filter
$\zeta(k)$	Lipschitz constant