Indian Institute of Technology Delhi

THE UNIVERSITY OF QUEENSLAND
AUSTRALIA

ENHANCING THE GRID SUPPORT CAPABILITY OF WIND FARMS

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INDIAN INSTITUTE OF TECHNOLOGY DELHI

&

THE UNIVERSITY OF QUEENSLAND

DECEMBER 2024

ENHANCING THE GRID SUPPORT CAPABILITY OF WIND FARMS

by

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Submitted

in fulfillment of the requirements for the joint degree of

DOCTOR OF PHILOSOPHY

to the

INDIAN INSTITUTE OF TECHNOLOGY DELHI

&

THE UNIVERSITY OF QUEENSLAND

DECEMBER 2024

This work is dedicated to a better tomorrow, where Knowledge fuels Progress, Innovation transforms Challenges, and the Pursuit of Excellence shapes a brighter future for all...

Supervisor Certification

This is to certify that the thesis entitled "**Enhancing the Grid Support Capability of Wind Farms**" being submitted by **Mr. Akshay Kumar Bhyri** to the Indian Institute of Technology Delhi and The University of Queensland for the award of degree of **Doctor of Philosophy** is a record of *bonafide* research work carried out by him. **Mr. Akshay Kumar Bhyri** 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 contained in this thesis are original and have not been submitted, in part or full, to any other University or Institute for the award of any other degree or diploma.

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Abstract

The present decade has seen significant growth in renewable energy sources-based generators (RESs) due to growing concerns for sustainable development. However, as clean as they are, RESs have a major drawback of variability. In addition, these generators are interfaced to the grid via power electronic converters, which have a low short circuit ratio (SCR), leading to reduced system strength and grid support participation. To this end, various solutions are being proposed, ranging from deploying energy storage systems (ESSs) to legacy system upgrades involving retrofitting and software modifications. A retrofitting or ESS deployment would incur additional costs, while a software upgrade involves resource-intensive design changes. To provide an immediate solution to maximize the grid support contribution of legacy wind RES systems, this work explores techniques involving optimized control references to unlock their full potential in grid support without design changes. The research involves a case study of a legacy GE1.5 commercial-scale Doubly-Fed Induction Generator (DFIG)–based Wind Farm (WF). DFIG-based WFs (DFWFs) are popular in onshore systems due to their low capital cost. The first part of the work identifies the support capability of a legacy DFWF by considering system and regulatory constraints. These limits are quantified, and the generator operating set points are determined under various operating conditions. The Wake Effect (inter-turbine wind interference) in the WF necessitates a Farm-Level Optimization (FLO) to ascertain these set points. Considering this, the support limits are optimized to achieve the objectives with minimal control transition effort to increase the equipment's lifetime. The proposed optimization is time-independent, offline, and a one-time procedure for a given WF geometry. Next, the support performance is tested in low and high-voltage ride-through (L/HVRT) modes to validate its efficacy, adding significant value over the prior art, where a comprehensive solution with quantified support limits was lacking. This solution package is termed the Systematic Enhanced Optimization and Grid Support (SEOGS) algorithm. Next, the research extends to tap into the full support potential of the DFWF by integrating the Grid Side Converter (GSC) into the SEOGS framework. By harnessing the reactive power headroom of the GSC, the reactive power burden on the DFIG is reduced, enabling an even higher active power ramping limit. The new package is called the Modified SEOGS (M-SEOGS) algorithm. On a larger scale, the proposed solutions are expected to enhance the support performance of legacy DFWFs without altering the system design, utilizing optimized lookup references. Overall, the thesis introduces strategies for optimizing farm-level operations by enhancing spinning reserves, minimizing blade wear, and establishing clear grid support limits while ensuring compatibility with legacy systems. The findings shall contribute to higher operational efficiency, reliability, and profits (with appropriate policies), empowering operators to enhance grid stability as RES penetration increases. Ultimately, this study promotes the effective integration/utilization of wind energy in power systems, supporting their present transition to a cleaner and sustainable future.

Abstract in Hindi

वर्तमान दशक में सतत विकास के लिए बढ़ती चिंताओं के कारण नवीकरणीय ऊर्जा स्रोतों आधारित जनरेटरों (आर.ई.एस.) का महत्वपूर्ण विकास हुआ है। किंतु इनका प्रमुख नकारात्मक पहलू उनका उतार-चढ़ाव है। इन जनरेटरों को ग्रिड से जोड़ने के लिए पावर इलेक्ट्रॉनिक कन्वर्टर्स का उपयोग किया जाता है, जिनका शॉर्ट सर्किट अनुपात (एस.सी.आर.) कम होता है, जिससे सिस्टम का बल और ग्रिड सहायता में भागीदारी कम हो जाती है। इस संदर्भ में, विभिन्न समाधान प्रस्तावित किए जा रहे हैं, जिनमें ऊर्जा भंडारण प्रणालियों (ई.एस.एस.) का उपयोग, पुराने सिस्टम का उन्नयन, रेट्रोफिटिंग और सॉफ़्टवेयर संशोधन शामिल हैं। रेट्रोफिटिंग या ई.एस.एस. तैनाती अतिरिक्त लागत को जन्म देती है, जबकि सॉफ़्टवेयर उन्नयन में संसाधन-गहन डिज़ाइन परिवर्तन शामिल होते हैं। इस कार्य का उद्देश्य मौजूदा पवन आर.ई.एस. सिस्टम्स के ग्रिड सहायता योगदान को अधिकतम करने के लिए एक तात्कालिक समाधान प्रदान करना है, जो डिज़ाइन परिवर्तन किए बिना अनुकूलित नियंत्रण संदर्भों का उपयोग करके उनकी पूर्ण क्षमता को उजागर सके। यह अनुसंधान एक मौजूदा जी.ई. १ दशमलव ५ वाणिज्यिक-स्तरीय डबल-फेड इंडक्शन जनरेटर (डी.एफ.आई.जी.)-आधारित पवन फार्म (डब्ल्यू.एफ.) का अध्ययन करता है। डी.एफ.आई.जी.-आधारित पवन फार्म भूमि-आधारित प्रणालियों में लोकप्रिय हैं क्योंकि इनका पूंजीगत खर्च कम होता है। इस कार्य के पहले भाग में, यह पहचाना गया है कि एक मौजूदा डब्ल्यू.एफ. की सहायता क्षमता को सिस्टम और नियामक प्रतिबंधों को ध्यान में रखते हुए कैसे बढ़ाया जा सकता है। इन सीमाओं को मात्रात्मक रूप से परिभाषित किया गया है और विभिन्न परिचालन स्थितियों के तहत जनरेटर संचालन सेट प्वाइंट्स निर्धारित किए गए हैं। वेक प्रभाव (इंटर-टर्बाइन पवन हस्तक्षेप) के कारण फार्म-स्तरीय अनुकूलन (एफ.एल.ओ.) आवश्यक है, ताकि इन सेट प्वाइंट्स को निर्धारित किया जा सके। इस परिप्रेक्ष्य में, सहायता सीमाओं का अनुकूलन इस प्रकार से किया गया है कि उद्देश्य पूरे किए जा सकें और नियंत्रण में न्यूनतम प्रयास हो, ताकि उपकरण की आयु बढ़ सके। प्रस्तावित अनुकूलन समय-स्वतंत्र, ऑफलाइन और एक-बार की प्रक्रिया है, जो एक विशिष्ट डब्ल्यू.एफ. ज्यामिति के लिए की जाती है। इसके बाद, सहायता प्रदर्शन को निम्न और उच्च-तनाव (एल./एच.वी.आर.टी.) मोड में परखा गया है, ताकि इसके प्रभावशीलता को सत्यापित किया जा सके। इस समाधान पैकेज को सिस्टमेटिक एन्हांस्ड ऑप्टिमाइजेशन और ग्रिड सपोर्ट (एस.ई.ओ.जी.एस.) एल्गोरिदम कहा गया है। थीसिस कार्य का दूसरा चरण मौजूदा डब्ल्यू.एफ. की पूरी सहायता क्षमता को उजागर करने के लिए एस.ई.ओ.जी.एस. ढांचे में ग्रिड साइड कन्वर्टर (जी.एस.सी.) को एकीकृत करता है, जिससे डी.एफ.आई.जी से प्रतिक्रियाशील शक्ति (रिएक्टिव पावर) का भार घटाकर सक्रिय शक्ति रैम्पिंग सीमा को बढ़ाया गया है। इस नए पैकेज को संशोधित एस.ई.ओ.जी.एस. (एम-एस.ई.ओ.जी.एस.) एल्गोरिदम कहा गया है। बड़े पैमाने पर, ये दोनों समाधान बिना सिस्टम डिज़ाइन में बदलाव किए अनुकूलित लुकअप संदर्भों का उपयोग करते हुए डब्ल्यू.एफ. की सहायता क्षमता को बढ़ाने की उम्मीद करते हैं। कुल मिलाकर, यह थीसिस मौजूदा प्रणालियों के साथ संगतता सुनिश्चित करते हुए स्पिनिंग रिजर्व्स को बढ़ाने, फार्म-स्तरीय संचालन को अनुकूलित करने, ब्लेड की घिसाई को न्यूनतम करने और स्पष्ट ग्रिड सहायता सीमाओं को स्थापित करने के लिए रणनीतियाँ प्रस्तुत करती है। ये निष्कर्ष उच्च परिचालन क्षमता, विश्वसनीयता और धन लाभ में योगदान करेंगे (उचित नीतियों के साथ), जो ऑपरेटरों को उच्च आर.ई.एस. समावेश के समय अधिक ऊर्जा ग्रिड स्थिरता बढ़ाने के लिए सक्षम बनाएंगे। अंततः, यह अध्ययन पवन ऊर्जा के प्रभावी एकीकरण/उपयोग को बढ़ावा देता है, जो पावर सिस्टम्स के वर्तमान को एक स्वच्छ और सतत भविष्य की ओर बढ़ाने का समर्थन करता है।

Declaration by author

This thesis is composed of my original work, and contains no material previously published or written by another person except where due reference has been made in the text. I have clearly stated the contribution by others to jointly-authored works that I have included in my thesis.

I have clearly stated the contribution of others to my thesis as a whole, including statistical assistance, survey design, data analysis, significant technical procedures, professional editorial advice, financial support and any other original research work used or reported in my thesis. The content of my thesis is the result of work I have carried out since the commencement of my higher degree by research candidature and does not include a substantial part of work that has been submitted to qualify for the award of any other degree or diploma in any university or other tertiary institution. I have clearly stated which parts of my thesis, if any, have been submitted to qualify for another award.

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Akshay Kumar Bhyri

Publications included in this thesis

1. **A.K. Bhyri**, N. Senroy, and T.K. Saha, ”Enhancing the Grid Support From DFIG-Based Wind Farms During Voltage Events,” in *IEEE Transactions on Power Systems*, vol. 39, no. 1, pp. 733-744, Jan. 2024, doi: 10.1109/TPWRS.2023.3239503.

2. **A.K. Bhyri**, N. Senroy, and T.K. Saha, ”Optimizing the Grid Support Limits in DFIG-based Wind Farms using Grid-Side Converter Participation for Increased Support during Voltage Dip Events,” in *2024 IEEE 4th International Conference on Sustainable Energy and Future Electric Transportation (SEFET)*, Hyderabad, India, 2024, pp. 1-8, doi: 10.1109/SEFET61574.2024.10718040.

Submitted manuscripts included in this thesis

No active submissions.

Other publications during candidature

No other publications.

Contributions by others to the thesis

All chapters

Editorial suggestions were provided by the candidate’s supervisors, Prof. Nilanjan Senroy and Prof. Tapan Kumar Saha, and PhD committee, Prof. Sukumar Mishra, Dr. Richard Yan, and Prof. Bijaya Ketan Panigrahi.

Statement of parts of the thesis submitted to qualify for the award of another degree

No works submitted towards another degree have been included in this thesis.

Research involving human or animal subjects

No animal or human subjects were involved in this research.

Acknowledgements

This dissertation is dedicated to all the people who believed in me and came forward to support my work. I express my sincere gratitude to my research advisors, Prof. Nilanjan Senroy and Prof. Tapan Kumar Saha, who taught me the fundamentals of my field, ethical research practice, and writing research articles, helped me correct my flaws, channeled my unhinged energies to bring the best and transformed me into a competent researcher from a mere academic novitiate who just had the will to push through the glass ceiling. Inspiring me to show courage and take a leap of faith in the face of adversity and imbibing the principles of patience, hard work, determination, and discipline into my work ethic, it is their constant guidance and support that made this journey absolutely wonderful and made every moment worth cherishing. Transitioning from industry to research was challenging, and their constructive criticism and motivation were invaluable in producing quality work. Collaborating with them has been a remarkable journey of growth that fundamentally changed my perspective. I would also like to thank the entire UQIDAR team for recognizing my potential as a researcher and believing in our successful collaboration with IIT Delhi and The University of Queensland, Australia.

I want to thank my research committee experts, Prof. Sukumar Mishra, for enabling me to showcase my research and spark insightful discussions that greatly helped with my research; A/Prof. Richard Yan for being a friendly and inquisitive mentor and guiding me through my research complexities, without whom my research might never have grown into an acceptable work; and chairperson Prof. Bijaya Ketan Panigrahi for supporting me at my lowest points and providing invaluable feedback that greatly improved the quality of my research. I am grateful to Prof. Abhijit Abhyankar for his support during the comprehensive exams and the important lessons he imparted throughout this journey. A special thanks to Prof. Bhim Singh for reminding me that sheer will combined with hard work makes success, which seems impossible from afar, become a reality. I would also like to express my gratitude to Prof. Mithulan Nadarajah for a delightful workplace experience in Australia. I also thank the wonderful people of Australia for welcoming me and making my stay comfortable, providing me with a home away from home.

I am deeply thankful to my senior Ph.D. colleagues, peers, and friends at IIT Delhi and UQ for their continuous support and motivation throughout this journey. I also extend my gratitude to everyone who worked tirelessly to maintain our society during the challenging times of COVID-19, providing a safe haven for all while putting their lives on the line.

Finally, I want to express my appreciation to my family for their love, care, guidance, and encouragement, without which this journey would not have been possible.

In this work, I aimed to address the key requirements of the power system to achieve the goal of clean energy for sustainability. I am profoundly grateful to all the researchers, reviewers, examiners, and peers who made this thesis a reality. Lastly, I thank the readers for their vested interest and support in research, as this endeavour could not have been realized without them.

Akshay Kumar Bhyri

Financial support

This research was supported by an Indian Institute of Technology Delhi Research Scholarship and a Research grant from the UQ-IITD Academy of Research (UQIDAR).
This work was funded partly by Renew Power through research grant RP03457.

Keywords

Doubly fed induction generators, Frequency response, Grid code, Grid support, Mathematical programming, Optimization, Reactive power, Renewable energy sources, Voltage ride through, Wind energy conversion, Wind farms.

Australian and New Zealand Standard Research Classifications (ANZSRC)

ANZSRC code: 400805, Electrical energy transmission, networks and systems, 50%
ANZSRC code: 400899, Electrical engineering not elsewhere classified, 50%

Fields of Research (FoR) Classification

FoR code: 4008, Electrical Engineering, 100%

Contents

Supervisor Certification . . . i
Abstract . . . ii
Abstract in Hindi . . . iii
Declaration by author . . . iv
Publications included in this thesis . . . v
Submitted manuscripts included in this thesis . . . v
Other publications during candidature . . . v
Statement of parts of the thesis submitted to qualify for the award of another degree . v
Acknowledgements . . . vi
Financial support . . . vii
Keywords . . . vii
Australian and New Zealand Standard Research Classifications (ANZSRC) . . . vii
Fields of Research (FoR) Classification . . . vii

Contents **viii**

List of Figures **xii**

List of Tables **xiv**

List of Abbreviations and Symbols **xv**

1 Introduction **1**
1.1 Background . . . 1
1.2 Motivation and Problem Statement . . . 2
1.3 Research Questions . . . 4
1.4 Aims and Research Objectives . . . 5
1.5 Novel Contribution and Outcomes . . . 6
1.6 Organization of the Thesis . . . 7
1.7 Summary . . . 9

2 Literature Review on Wind Farm Control and Grid Support 11
2.1 Introduction 11
2.2 De-loading in Wind Farms 11
2.3 De-Loading based solutions for Active Power Control and Primary Frequency Response from Wind Farms 12
2.4 Recent Works in Wind Farm Optimization 13
2.5 Enhancing Reactive Power Support in Wind Farms 14
2.6 Advances in Grid Support from Wind Farms 15
2.7 Challenges in Grid Support and GSC Participation 17
2.8 Summary and Specific Research Objectives 19

3 System Modelling and Description 21
3.1 System Modelling and Description 21
3.2 Conventional Wind Turbine Generator (WTG) Control 21
3.2.1 Mechanical Power Control (MPC) 21
3.2.2 Electrical Power Control (EPC) 22
3.2.3 Overview of the GE1.5 WECS 25
3.3 Multi-WTG Wind Farm Modelling 28
3.3.1 The Wake Effect: Jensen's Model 28
3.3.2 The Grid Model: Synchronous Generators 28
3.3.3 De-loading Control using PAC and CSC 29
3.3.4 Chronology of Control Action 29
3.3.5 Assessment Studies 31
3.3.6 Reactive Power Capability Curves 36
3.4 Inferences and Summary 36

4 Allocating the Power Generation in Wind Farms: The SEOGS Algorithm (Part 1) 39
4.1 Introduction 39
4.1.1 Research Gaps in Steady-State Optimization 40
4.2 System Description and Modeling 40
4.2.1 Wind Turbine Generator (WTG) Model 40
4.2.2 WTG Control Model 41
4.2.3 The Grid Code Model 43
4.2.4 The Wake Effect Model 44
4.2.5 Power-Point Tracking - Greedy vs. Farm-level 45
4.2.6 Proposed Solution: The SEOGS Algorithm 45
4.3 Wind Farm: Optimizing steady-state setpoints with SEOGS Algorithm 46
4.3.1 Wind Farm - Optimizing WTG power set-points 46

4.4 Results and Discussion 49
4.4.1 The Test Model 49
4.4.2 Testing the Wake Effect Model 50
4.4.3 Testing the FLO efficacy of the proposed SEOGS algorithm 50
4.4.4 Testing the set-point trackability in real-time 52
4.4.5 Discussion 55
4.4.6 Sample Lookup Tables 58
4.5 Summary 58

5 Enhancing the Grid Support from Wind Farms: The SEOGS Algorithm (Part 2) 59
5.1 Introduction 59
5.1.1 Research Gaps in Grid-Support during L/HVRT Events 60
5.1.2 The Grid Code Model 60
5.1.3 Wind Farm: Assigning Grid Support Limits with SEOGS Algorithm . . 61
5.2 Results and Discussion 64
5.2.1 The Test Model 65
5.2.2 Testing grid-support with the proposed SEOGS algorithm 65
5.2.3 Impact of Grid Strength (SCR) and X/R-ratio 69
5.2.4 Sample Lookup Tables 70
5.2.5 Discussion 73
5.3 Summary 74

6 Additional Grid Support in Onshore Wind Farms: The M-SEOGS Algorithm 75
6.1 Introduction 75
6.1.1 The Need for Optimization with GSCs 76
6.1.2 Related Works 76
6.1.3 Proposed Solution: The M-SEOGS Algorithm 78
6.2 WTG Control Model 78
6.2.1 The Grid Code Model 78
6.3 Proposed Strategy 78
6.4 Results and Discussion 83
6.4.1 Testing grid support with proposed M-SEOGS Algorithm 84
6.4.2 Sample Lookup Table 86
6.4.3 Discussion 86
6.5 Summary 88

7 Conclusion 89
7.1 Summary of the Dissertation 89
7.2 Novelty and Contribution of the Thesis 91

7.3 Recommendations for Future Work 93

Bibliography **95**

Bio-Sketch **106**

List of Figures

1.1 Projected Growth of Worldwide Wind Installation (in GW) 2

3.1 GE1.5 DFIG - Rotor Side Converter Control 23
3.2 GE1.5 DFIG - Grid Side Converter Control 24
3.3 Modified GE 1.5 Pitch Angle Control 27
3.4 An example of Pitch Angle and Converter Set-Point Controls 30
3.5 Power Speed Characteristics 31
3.6 Grid Code for Danish Grid 33
3.7 Impact of Control Policies for Wind Farms (Active and Reactive Power) 33
3.8 Impact of Control Policies for Wind Farms (Voltage and Frequency) 34
3.9 PFR from a single WTG 35
3.10 Capability Curves of DFIG 36

4.1 Schematic of the IEC Type-3 WECS Topology. 41
4.2 Power Curves and Capability Curves of a Single Wind Turbine 42
4.3 L/HVRT support requirement of the Indian national grid for the connectivity of RESs (CEA IEGC 2019 Amendment). 43
4.4 Control schematic of WTG local controller based on GE-1.5 model (Top-half represents the PAC loop and bottom-half represents the CSC loop). 44
4.5 Handshaking between the WF Central and WTG Local Controllers. 49
4.6 Test model used for simulation studies. 50
4.7 Wind speeds at different WTG locations as a function of free-wind speed for different farm-loading scenarios. Turbine 1 is the 1^{st} WTG in the free wind direction followed by WTGs 2 & 3 in a back-to-back arrangement. 51
4.8 Cp-λ curves depicting loci of operating points as functions of wind speeds for a single-WTG system. 52
4.9 Cp-λ curves depicting loci of operating points as functions of wind speeds for a multi-WTG system placed back-to-back along the wind direction. 53

4.10 Comparison of the Q-capabilities I) Scenario-A (WTGs placed Back-to-Back in the direction of the wind, undergoing Wake effect) II) Scenario-B (WTGs placed Side-by-Side in the direction of the wind, without Wake Effect). 54
4.11 Response of the wind farm to changing wind speed conditions. 55
4.12 Response of the wind farm to changing de-loading conditions. 56
4.13 Sample Lookup Table of References for SEOGS Algorithm (Part-1) 57

5.1 L/HVRT support requirement of the Indian national grid for the connectivity of RESs (CEA 2019 Amendment). 61
5.2 Curves depicting the set of Grid Support Limits (GS-L) for a single WTG for PFR during L/HVRT events as a function of WTG Terminal Voltage. 63
5.3 Final Process Flow Chart for the proposed Systematic Enhanced Optimal power control and Grid support Strategy (SEOGS) algorithm. 64
5.4 Handshaking between the WF Central and WTG Local Controllers. 65
5.5 Test model used for simulation studies. 66
5.6 Response of the wind farm during LVRT event. 67
5.7 Response of the wind farm during HVRT event. 69
5.8 Impact of SCR and X/R ratio on response during LVRT event. 70
5.9 Impact of SCR and X/R ratio on response during HVRT event. 71
5.10 Sample Lookup Table of References for SEOGS Algorithm (Part-2) 72

6.1 L/HVRT support requirement of the Indian national grid for the connectivity of RESs (CEA 2019 Amendment). 79
6.2 Control schematic of WTG controller based on GE-1.5 model with control reference assignment using the proposed M-SEOGS algorithm. 79
6.3 Comparision of Reactive Power Capability of a Single WTG with and without GSC Participation at rated bus voltage (1 pu). 80
6.4 Test model used for simulation studies. 84
6.5 Response of the wind farm during LVRT event 85
6.6 Sample Lookup Table of References for M-SEOGS Algorithm 87

List of Tables

3.1 Ratings of GE1.5 WECS 26
3.2 Two-Mass Model parameters of GE1.5 WECS 26
3.3 Power Extraction Coefficients for GE1.5 WECS 26
3.4 Control Limits for GE1.5 WECS 26
3.5 Parameters for GE1.5 Pitch Angle Controller 27

List of Abbreviations and Symbols

Abbreviations	
BESS	Battery Energy Storage System
CAPCS	Coordinated Active Power Control Strategy
CSC	Converter Set-point Control
DFIG	Doubly-Fed Induction Generator
EPC	Electrical Power Control
ESS	Energy Storage System
FLO	Farm-Level Optimization
FRT	Fault-Ride-Through
GC	Grid Code
GSC	Grid Side Converter
HVRT	High-Voltage-Ride-Through
IEGC	Indian Electricity Grid Code
IGA	Individual Greedy Optimization
IRC	Inertial Response Control
KE	Kinetic Energy
KESS	Kinetic Energy Storage System
LVRT	Low-Voltage-Ride-Through
MFLC	Multiple Fair Load-sharing Control
MPC	Mechanical Power Control
MPP	Maximum Power Point
MPPT	MPP Tracking
M-SEOGS	Modified - Systematic Enhanced Optimal power control and Grid Support
P	Active Power
PAC	Pitch Angle Control
PCC	Point of Common Coupling
PFR	Primary Frequency Response
PMSG	Permanent Magnet Synchronous Generator

Q	Reactive Power
RES	Renewable Energy Source
ROC	Rotor Over-speeding Control
RSC	Rotor Side Converter
SCR	Short Circuit Ratio
SEOGS	Systematic Enhanced Optimal power control and Grid Support
SQP	Sequential Quadratic Programming
TSR	Tip Speed Ratio
VG	Variable Generation
VRT	Voltage-Ride-Through
VVVF	Variable Voltage and Variable Frequency
WECS	Wind Energy Conversion System
WF	Wind Farm
WS	Wind Speed
WT	Wind Turbine
WTG	Wind Turbine Generator

Symbols	
C_p	Power Coefficient of the WT
C_t	Thrust coefficient of the WT
N_{WTG}	Number of participating WTGs
$[\cdot]_{base}$	Rated quantity
$[\cdot]_i$	Quantity for ith WT
$[\cdot]_{max}$	Maximum quantity
$[\cdot]_{min}$	Minimum quantity
$[\cdot]_{opt}$	Optimal quantity
$[\cdot]_{ref}$	Reference quantity
α	Axial flow induction factor of the WT
β	Pitch angle of the WT (in degrees)
λ	Tip Speed Ratio of the WT
ρ_{ar}	Represents the product of 1/2 * Air Density Factor * Area of WT
v_{wind}	Speed of incident wind on a WT (in m/s)
V_{PCC}	PCC Voltage (pu)