DESIGN, DEVELOPMENT AND CONTROL OF BATTERY-SOLAR-WIND BASED HYBRID MICROGRID WITH SYNCHRONIZATION TO GRID

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Design, Development and Control of Battery-Solar-Wind Based Hybrid Microgrid with Synchronization to Grid

by

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Electrical Engineering Department

Submitted
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DOCTOR OF PHILOSOPHY

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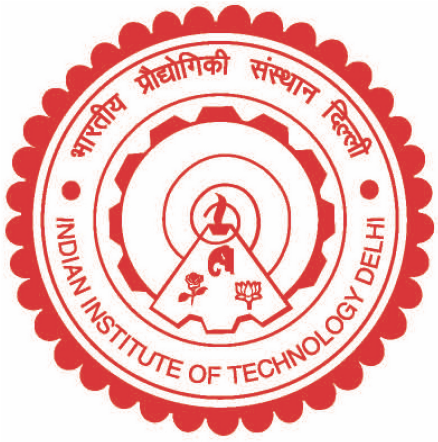

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CERTIFICATE

It is certified that the thesis entitled "**Design, Development and Control of Battery-Solar-DFIG Based Microgrid with Synchronization to Grid**," being submitted by **Mr. Sudip Bhattacharyya** 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 my 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

The rapid advancement of renewable energy has profoundly transformed the energy sector over the past decade. Microgrids, which integrate renewable energy sources with localized loads, offer a sustainable solution to meet the growing global energy demand while mitigating environmental impacts. Typically positioned near distribution networks, microgrids employ power converters to operate effectively in both off-grid and grid-connected modes. Progress in technology, supportive policies, and the adoption of custom power devices have enhanced the flexibility and reliability of microgrids, significantly boosting their performance. However, the inherent unpredictability of renewable energy sources introduces challenges, such as irregular power generation and complex integration with the main utility grid. Furthermore, the increasing deployment of microgrids within the power grid brings issues such as poor power factor, stability concerns, power quality degradation, and intricate power management requirements. To overcome these challenges, it is essential to develop advanced circuit configurations and sophisticated control algorithms that ensure the efficient and stable operation of microgrids. These innovations are crucial for enabling a sustainable and resilient energy future.

This research emphasizes the development of a variable-speed, fixed-pitch wind energy generation system (WEGS) designed with doubly fed induction generator (DFIG) for efficient energy utilization. The system features two voltage source converters (VSCs) arranged in a back-to-back configuration with a shared DC link. The rotor-side converter (RSC) is responsible for maximizing wind energy extraction, while the grid-side converter (GSC) ensures smooth integration with the utility grid, managing power flow to the grid and local loads, including auxiliary services. For solar energy generation, the system can be designed to operate in either single-stage or two-stage configurations, depending on the

specific application requirements. The primary objective is to achieve efficient energy generation from both variable-speed wind turbines and solar photovoltaic arrays. Key challenges include maintaining consistent power output despite fluctuations in wind speed and solar irradiance, as well as ensuring stable and reliable grid integration.

This study explores two distinct configurations for forming a local grid. The first configuration employs a grid-forming converter (GFC) supported by a photovoltaic (PV) array and a battery energy storage system (BESS). The second configuration utilizes a GFC exclusively powered by a BESS. In the PV-based system, maximum power extraction is achieved through the incremental conductance (INC) algorithm, while the wind-driven doubly-fed induction generator (DFIG) uses a maximum power point tracking (MPPT) algorithm to optimize wind energy capture. The stator windings of the DFIG are synchronized with the local grid to ensure seamless integration. To maintain efficient microgrid operation, a robust control algorithm is essential. This research introduces an advanced control strategy designed to ensure smooth microgrid performance under dynamic conditions, including load connection and disconnection, variations in wind speed, and changes in solar insolation. The proposed approach enhances the reliability and stability of the microgrid, even in fluctuating environmental and operational scenarios.

The microgrid architecture and control strategies are initially validated through software simulations using the MATLAB/Simulink platform. Following promising results, a physical prototype of a microgrid is constructed, incorporating a wind turbine driven doubly-fed induction generation (DFIG), a solar photovoltaic array, and a battery energy storage system (BESS). This prototype is subjected to extensive testing across various configurations, utilizing appropriate control algorithms to evaluate performance.

The simulated and experimental results are analyzed under a range of challenging conditions, including fluctuations in wind speed, solar insolation, unbalanced and balanced

loads. Notably, the system demonstrates effective maximum power point tracking (MPPT) for wind and solar energy under normal conditions. Additionally, the microgrid's performance is assessed during both off-grid and grid-interactive operations, showcasing a smooth transition between these modes. The results highlight the capability of this multi-functional microgrid to maintain reliability and efficiency under diverse operational scenarios.

नवीकरणीय ऊर्जा की तीव्र प्रगति ने पिछले दशक में ऊर्जा क्षेत्र को गहराई से बदल दिया है। माइक्रोग्रिड, जो स्थानीय भार के साथ नवीकरणीय ऊर्जा स्रोतों को एकीकृत करता है, पर्यावरणीय प्रभावों को कम करते हुए बढ़ती वैश्विक ऊर्जा मांग को पूरा करने के लिए एक स्थायी समाधान प्रदान करता है। आमतौर पर वितरण नेटवर्क के पास स्थित, माइक्रोग्रिड ऑफ-ग्रिड और ग्रिड-कनेक्टेड दोनों मोड में प्रभावी ढंग से काम करने के लिए पावर कन्वर्टर्स का उपयोग करते हैं। प्रौद्योगिकी में प्रगति, सहायक नीतियों और कस्टम बिजली उपकरणों को अपनाने से माइक्रोग्रिड के लचीलेपन और विश्वसनीयता में वृद्धि हुई है, जिससे उनके प्रदर्शन में काफी वृद्धि हुई है। हालाँकि, नवीकरणीय ऊर्जा स्रोतों की अंतर्निहित अप्रत्याशितता अनियमित बिजली उत्पादन और मुख्य उपयोगिता ग्रिड के साथ जटिल एकीकरण जैसी चुनौतियाँ पेश करती है। इसके अलावा, पावर ग्रिड के भीतर माइक्रोग्रिड की बढ़ती तैनाती खराब बिजली कारक, स्थिरता संबंधी चिंताएं, बिजली की गुणवत्ता में गिरावट और जटिल बिजली प्रबंधन आवश्यकताओं जैसे मुद्दे लाती है। इन चुनौतियों से पार पाने के लिए, उन्नत सर्किट कॉन्फ़िगरेशन और परिष्कृत नियंत्रण एल्गोरिदम विकसित करना आवश्यक है जो माइक्रोग्रिड के कुशल और स्थिर संचालन को सुनिश्चित करते हैं। टिकाऊ और लचीले ऊर्जा भविष्य को सक्षम करने के लिए ये नवाचार महत्वपूर्ण हैं।

यह शोध कुशल ऊर्जा उपयोग के लिए डिज़ाइन की गई एक चर-गति, निश्चित-पिच पवन ऊर्जा उत्पादन प्रणाली (WEGS) के विकास पर जोर देता है। सिस्टम में दो वोल्टेज स्रोत कनवर्टर (वीएससी) हैं जो एक साझा डीसी लिंक के साथ बैक-टू-बैक कॉन्फ़िगरेशन में व्यवस्थित हैं। रोटर-साइड कनवर्टर (आरएससी) पवन ऊर्जा निष्कर्षण को अधिकतम करने के लिए जिम्मेदार है, जबकि ग्रिड-साइड कनवर्टर (जीएससी) उपयोगिता ग्रिड के साथ सुचारू एकीकरण सुनिश्चित करता है, सहायक सेवाओं सहित ग्रिड और स्थानीय

भार में बिजली के प्रवाह का प्रबंधन करता है। सौर ऊर्जा उत्पादन के लिए, सिस्टम को विशिष्ट अनुप्रयोग आवश्यकताओं के आधार पर एकल-चरण या दो-चरण कॉन्फ़िगरेशन में संचालित करने के लिए डिज़ाइन किया जा सकता है। प्राथमिक उद्देश्य चर-गति पवन टर्बाइन और सौर फोटोवोल्टिक सरणियों दोनों से कुशल ऊर्जा उत्पादन प्राप्त करना है। प्रमुख चुनौतियों में हवा की गति और सौर विकिरण में उतार-चढ़ाव के बावजूद लगातार बिजली उत्पादन बनाए रखना, साथ ही स्थिर और विश्वसनीय ग्रिड एकीकरण सुनिश्चित करना शामिल है।

यह अध्ययन स्थानीय ग्रिड बनाने के लिए दो अलग-अलग कॉन्फ़िगरेशन की खोज करता है। पहला कॉन्फ़िगरेशन एक फोटोवोल्टिक (पीवी) सरणी और एक बैटरी ऊर्जा भंडारण प्रणाली (बीईएसएस) द्वारा समर्थित ग्रिड-फॉर्मिंग कनवर्टर (जीएफसी) को नियोजित करता है। दूसरा कॉन्फ़िगरेशन विशेष रूप से BESS द्वारा संचालित GFC का उपयोग करता है। पीवी-आधारित प्रणाली में, अधिकतम बिजली निष्कर्षण वृद्धिशील संचालन (आईएनसी) एल्गोरिदम के माध्यम से प्राप्त किया जाता है, जबकि पवन-चालित डबल-फेड इंडक्शन जनरेटर (डीएफआईजी) टिप-स्पीड अनुपात-आधारित अधिकतम पावर पॉइंट ट्रैकिंग (एमपीपीटी) एल्गोरिदम का उपयोग करता है। पवन ऊर्जा कैप्चर को अनुकूलित करने के लिए। निर्बाध एकीकरण सुनिश्चित करने के लिए डीएफआईजी की स्टेटर वाइंडिंग्स को स्थानीय ग्रिड के साथ सिंक्रनाइज़ किया गया है। कुशल माइक्रोग्रिड संचालन को बनाए रखने के लिए, एक मजबूत नियंत्रण एल्गोरिदम आवश्यक है। यह शोध एक उन्नत नियंत्रण रणनीति पेश करता है जो गतिशील परिस्थितियों में सुचारू माइक्रोग्रिड प्रदर्शन सुनिश्चित करने के लिए डिज़ाइन की गई है, जिसमें लोड कनेक्शन और डिस्कनेक्शन, हवा की गति में बदलाव और सौर सूर्यातप में परिवर्तन शामिल हैं। प्रस्तावित दृष्टिकोण उतार-चढ़ाव वाले पर्यावरणीय और परिचालन परिदृश्यों में भी माइक्रोग्रिड की विश्वसनीयता और स्थिरता को बढ़ाता है।

माइक्रोग्रिड आर्किटेक्चर और नियंत्रण रणनीतियों को प्रारंभ में MATLAB/Simulink प्लेटफ़ॉर्म का उपयोग करके सॉफ़्टवेयर सिमुलेशन के माध्यम से मान्य किया जाता है। आशाजनक परिणामों के बाद, एक माइक्रोग्रिड का एक भौतिक प्रोटोटाइप बनाया गया है, जिसमें एक पवन चालित डबल-फेड इंडक्शन जेनरेशन (डीएफआईजी), एक सौर फोटोवोल्टिक सरणी और एक बैटरी ऊर्जा भंडारण प्रणाली (बीईएसएस) शामिल है। प्रदर्शन का मूल्यांकन करने के लिए उपयुक्त नियंत्रण एल्गोरिदम का उपयोग करते हुए, इस प्रोटोटाइप को विभिन्न कॉन्फ़िगरेशन में व्यापक परीक्षण के अधीन किया गया है।

सिम्युलेटेड और प्रयोगात्मक परिणामों का विश्लेषण कई चुनौतीपूर्ण परिस्थितियों में किया जाता है, जिसमें हवा की गति और सौर सूर्यातप में उतार-चढ़ाव, असंतुलित और संतुलित भार शामिल हैं। विशेष रूप से, सिस्टम सामान्य परिस्थितियों में पवन और सौर ऊर्जा के लिए प्रभावी अधिकतम पावर प्वाइंट ट्रैकिंग (एमपीपीटी) प्रदर्शित करता है। इसके अतिरिक्त, ऑफ-ग्रिड और ग्रिड-इंटरैक्टिव संचालन दोनों के दौरान माइक्रोग्रिड के प्रदर्शन का मूल्यांकन किया जाता है, जो इन मोडों के बीच एक सहज संक्रमण को दर्शाता है। परिणाम विविध परिचालन परिदृश्यों के तहत विश्वसनीयता और दक्षता बनाए रखने के लिए इस बहु-कार्यात्मक माइक्रोग्रिड की क्षमता को उजागर करते हैं।

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LIST OFABBREVIATIONS

3P3W	Three-Phase Three Wire
3P4W	Three-Phase Four Wire
AC	Alternating Current
AMAF	Adaptive Moving Average Filter
ANN	Artificial Neural Networks
ASVF	Advance Space Vector Filter
BBF	Butter Worth Band Pass Filter
BESS	Battery Energy Storage System
BDC	Bidirectional DC-DC Converter
CBPF-FLL	Complex Band-Pass Filter-Based Frequency-Locked Loop
CBPF-FLL	Complex Band Pass Filter-Based FLL
CC-ROGI	Complex Coefficient Reduced Ordered Generalised Integrator
CCP	Common Coupling Point
CMS	Comb Sliding Mode
CSM	Comb Sliding Mode
DC	Direct Current
DFIG	Doubly Fed Induction Generation
DFOGI-FLL	Discrete Fourth Order Generalized Integrator-Frequency Locked Loop
DFOGI-FLL	Double Frequency Oscillator Generalized Integrator-Frequency Locked Loop
DoD	Depth Of Discharge
DSOGI	Double Second-Order Generalized Integrator
dSpace	Digital Signal Processing And Control Engineering
DSTATCOM	Distribution Static Synchronous Compensator
ESS	Energy Storage System
EV	Electric Vehicle
FLC	Fuzzy Logic Controller
FOC	Flux-Oriented Control
FOGI	Fourth Order Generalized Integrator
GFC	Grid Forming Converter
GSC	Grid-Side Converter
GW	Gigawatts
HOGI	High-Order Generalized Integral
IEEE	Institute Of Electrical and Electronics Engineers
IGBT	Insulated Gate Bipolar Transistors
ILC	Inter-Linking Converter
IMRF	Improved Multiple Reference Frame
INC	Incremental Conductance
IRPT	Instantaneous Reactive Power Theory
ITOGI	Improved Third Order Generalized Integrator
KE	Kinetic Energy
KF	Kalman Filter
LFP	Lithium Ferro Phosphate
LG	Local Grid
LMF	Least Mean Fourth
LMS	Least Mean Square

LVRT	Low Voltage Ride Through
MATLAB	Matrix Laboratory
MPC	Model Predictive Control
MPPT	Maximum Power Point Tracking
MS-TOGI	Second- And Third-Order Generalized Integrator
OC	Orthogonal Component
P&O	Perturbation And Observation
PCB	Printed Circuit Board
PCC	Point Of Coupling
PI	Proportional-Integral
PLL	Phase Locked Loop
PPA	Power Purchase Agreement
PQ	Power Quality
PSF	Power Signal Feedback
PV	Photovoltaic
PWM	Pulse Width Modulation
ROGI	Reduced Ordered Generalized Integrator
RSC	Rotor-Side Converter
SOC	State Of Charge
SOGI	Second-Order Generalized Integrator
SOSF-FLL	Second Order Sequence Filter-Frequency Locked Loop
SRF	Synchronous Reference Frame
STS	Static Transition Switch
TDSOGI-FLL-WPF	Tustin Discretized Second Order Generalized Integrator-Frequency Locked Loop
THD	Total Harmonic Distortion
TOGI	Third-Order Generalized Integrator
TSR	Tip To Speed Ratio
VOC	Voltage Oriented Control
VSC	Voltage Source Converter
WECS	Wind Energy Conversion System
WT	Wind Turbine

LIST OF SYMBOLS

θ_s	FLL stator angle
a	Overloading factor
b_1	Energy variation is considered during dynamic change
c, b, k_a, k_b	Linearized controller gain
C_{bat}	DC-link capacitor across battery based converter
C_{dc1}	Capacitor of PV-VSC
C_{dc2}	Capacitor of GSC
C_f	Capacitance of the ripple filter
C_p	Power coefficient
C_{pmax}	Maximum theoretical value of power coefficient
c_{pv}	Capacitor across PV array
D	Duty cycle
E_b	Battery voltage
e_{idr}	Error between reference and actual rotor *d*-axis current
e_{rdgr}	Error between stator and PCC terminal voltage
er_{dgr}	Error (er_{dgr}) between stator and CCP terminal voltage
er_{iqr}	Difference of reference and actual q-axis current
e_{rqs}	Difference between reference and actual reactive power Q_s
err_{dpv}, err_{qpv}	*D*-axis and *q*-axis error voltage of GFC control
er_{θ}	Error component between stator and PCC angle
$er_{\omega m}$	Error between reference and actual rotor speed
f	Line frequency
f_{ccp}	Line frequency at CCP
F_s	Stator flux of DFIG
f_s	Switching frequency
F_s	Stator flux
G_1, G_2	Adaptive gains
I_{am} ,I_{bm}, I_{cm}	Active load current component
I_{bat}	Battery current
I_{bater}	Difference between the reference current and actual battery current
I_{batre}	Reference battery current
I_{bc}	Battery charging current
I_{bd}	Battery discharging current
i_c	Sensed converter currents
i_{ca}, i_{cb} *and* i_{cc}	Three phase converter currents (PV-VSC)
i_{caf}, i_{cbf}, i_{ccf}	Three phase Reference GFC currents
I_{cdf}, I_{cqf}	*D*-axis and *Q*-axis current of GFC
i_{cer}	Error signals of GFC current
I_{cmax}	Maximum current of the VSC
$I_{cmax,\ peak}$	Maximum peak current of the VSC
i_{cref}	Reference converter current
i_d	Load current in *d*-axis
I_{dbat}, I_{qbat}	Converter reference currents
i_{dfig}	DFIG currents (combination of GSC and stator current)
I_{dr}	Actual rotor *d*-axis current
I_{dr1}	Internal *d*-axis rotor current
I_{dref}	*D*-axis rotor reference current, first part of RSC control

I_{drref}	*D*-axis reference rotor current
I_{Drt}, I_{Qrt}	*D*-axis and *Q*-axis rotor currents component
i_{err}	Error between reference and actual PCC current
i_{gabc}	Grid current
i_{gref}	Reference PCC current
i_{gsc}	GSC currents
I_{IGBT}	IGBT current
i_L	Load current
i_{La}, i_{Lb} *and* i_{Lc}	Three phase load currents
i_{Lad}	In-phase load current components
i_{Laq}	Load current components
I_{Lav}	Average load current component
I_{Line}	Line current
i_{Lma}, i_{Lmb}, i_{Lmc}	Active load component in phase-*abc*
I_{loss2}	Loss current component
I_{mppv}	Maximum MPPT current
i_p	Primary current
I_{pav}	Average current component
I_{pnet}	Net active current component
I_{pnet}	Net active component
I_{pv}	PV current
I_{qr1}	Internal *q*-axis rotor current
I_{qref}	*Q*-axis rotor reference current, first part of RSC control
I_{qref}	Reference *q*-axis RSC current
i_r	Rotor current
i_{raf}, i_{rbf}, i_{rcf}	Three phase reference rotor currents in first part of RSC control
i_{rerr}	Error between reference and actual rotor current
i_{rsc}	RSC currents
i_s	Secondary current
i_{sa}, i_{sb} *and* i_{sc}	Stator currents
i_{sabc}	Actual CCP/PCC current
I_{sca}	Short circuit current
i_{sense}	Current input to the sensor
$i_{\alpha 1}$, $i''_{\alpha 1}$, $i_{\beta 1}$ and $i''_{\beta 1}$	Internal signals of CBPF-FLL control
$i_{\alpha f1}$ and $i_{\beta f1}$	Filter load current components
k	Constant gain
k_a and k_b	Forward path gain
k_g	Accelerate or decelerate the process
k_i	Integral gain
k_p	Proportional gain
k_{p1}, k_{p2}, k_{i1}, k_{i2}	PI controller gain for GFC control
k_{pd}, k_{id}, $k_{i\theta}$	PI controller gain of RSC control before stator windings synchronization
k_{pdgi}, k_{idgi}	PI controller gain of GSC control
k_{pr1}, k_{ir1}, k_{pr2}, k_{ir2}, $k_{p\omega 1}$, $k_{i\omega 1}$, $k_{p\omega 2}$, $k_{i\omega 2}$	PI controller gain of RSC control after stator windings synchronization
L	Inductor of DC-DC converter
L_b	Inductor of DC-DC converter
L_{bat}	Interfacing inductor of battery based VSC

L_{fgsc}	Interfacing inductor of GSC
L_{fvsc}	Interfacing inductor of PV-VSC
L_m	Mutual inductance of DFIG
L_s	Stator inductance of DFIG
M	Measuring point
M_{ga}	Filtering gain of the controller
m_k	Modulation index
M_p	Maximum peak overshoot
n_{plpv}	Number of parallel PV array
n_{spv}	Number of series PV array
P_{bat}	Battery power
p_L	Load power
P_m	Mechanical power
P_{mppv}	Maximum PV power
P_{pv}	PV power
P_t	DFIG power
r	Turbine blade radius
R_1	Resistance of sensor
R_f	Resistance of the ripple filter
R_m	Measuring resistance
t_d	Delay time
TF_{DGI}	Transfer function
t_m	DC voltage recover time
T_m	Mechanical torque
t_r	Rise time
T_s	Sample time
u_{sabc}	Unit templates of PCC/CCP voltages
v_{a1}, v_{b1}, v_{c1}	Reference PCC voltages
V_{ADCm}	Maximum ADC input voltage
V_{bat}	Battery voltage
V_{batrf}	Reference battery voltage
v_{ccp}	Standalone grid voltage
v_{ccpa}, v_{ccpb}, v_{ccpc}	Sensed local grid voltages
V_{ccpd}, V_{ccpq}	DQ reference voltages
V_D, V_Q	D-axis and Q-axis voltages of FOC based RSC control
V_{dc}	DC-link voltage
V_{dc1}	DC-bus voltage across PV-VSC
V_{dc2}	Actual DC-bus voltage of GSC
V_{dcerr}	Error between reference and actual DC-link voltages
V_{dcerr}	DC-link error voltage (GSC)
V_{DCREF}	Reference DC link voltage
V_{drt}	Internal signal of d-axis rotor voltage
V_{drt} and V_{qrt}	Voltage references for RSC
V_{gdpvf}	PCC/CCP voltage magnitude
v_{gfa}, v_{gfb}, v_{gfc}	Reference PCC/CCP voltages
V_{IGBT}	IGBT voltage
V_{mppv}	Maximum MPPT voltage
V_{oc}	Open circuit voltage of single solar cell
V_{odc}	Output of the DC-DC converter voltage

v_{offset}	Offset voltage
v_{out}	Output voltage
v_{pcca}, v_{pccb}, v_{pccc}	Three phase PCC voltages
V_{pccd}, V_{pccq}	*D*-axis and *q*-axis PCC voltage
V_{ph}	Phase voltage
V_{pv}	PV voltage
V_{qrt}	Internal signal of *q*-axis rotor voltage
v_{raf}, v_{rbf}, v_{rcf}	Three phase reference voltage of FOC based RSC control
V_{ref2}	Reference DC-bus voltage of GSC
v_s	Stator voltage
v_{sa}, v_{sb}, v_{sc}	Three phase stator voltages
V_{sen}	Voltage to be sensed
V_{sensor}	Sensor voltage
V_{st}	Stator terminal voltage
V_w	Wind speed
β	Pitch angle
δ	Adaptive feed forward term
ΔI_{mppv}	Allowable current ripple
ΔV_{mppv}	Voltage ripple
ζ_f	Feedback term
θ_e, θ_m and θ_r	Electrical, mechanical and rotor angles
θ_{gf}	Reference of grid forming converter angle
θ_{grid}	Local grid angle
θ_{pcc} *and* θ_{ccp}	PCC/CCP angle
θ_s	Stator angle
θ_{slip}	Slip angle of the DFIG
λ	Tip-to-speed ratio
ρ	Air density
ω_c	Cut-off frequency
ω_m	Actual rotor speed
ω_{mref}	Reference rotor speed
ω_n	Line frequency
ω_r	Angular rotor speed
ϕ_s	Sine angle difference [$\sin(\theta_{pcc}-\theta_s)$]