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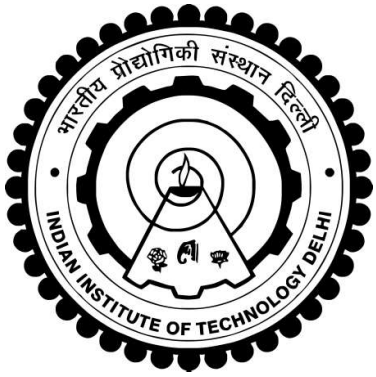

DEPARTMENT OF ELECTRICAL ENGINEERING

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CONTROL OF AC/DC MICROGRIDS WITH DFIG BASED WIND ENERGY CONVERSION AND SOLAR PV GENERATION

By

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Submitted

In fulfillment of the requirements of the degree of doctor of philosophy

to the

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CERTIFICATE

This is to certify that the thesis entitled **"Control of AC/DC Microgrids with DFIG based Wind Energy Conversion and Solar PV Generation,"** being submitted by Mr. **Souvik Das** for the award of the degree of **Doctor of Philosophy** in the Department of Electrical Engineering of Indian Institute of Technology Delhi is a record of a bonafide research work carried out by him under my supervision and guidance. The matter embodied in this thesis has not been submitted for award of any other degree or diploma.

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Souvik Das

ABSTRACT

The decentralization of electricity generation has initiated a paradigm shift in the power sector. Decentralized generation, in the form of solar photovoltaics (SPVs), wind energy conversion systems (WECSs), etc., when aggregated with local loads, forms a self-sufficient entity, commonly termed a microgrid. Hybrid AC/DC microgrids are rapidly evolving into the preferred microgrid architecture due their minimized power converter redundancy when interfacing the DC-based generation sources or loads. The doubly-fed induction generator (DFIG) shares a large portion of current market share among various variable speed WECSs. This is primarily due to its permanent magnet-free constructional benefits and reduced rating generator-side power converter. When integrated along with the SPV array-based solar energy conversion system (SECS), it provides an effective means of meeting the load power requirement. The DFIG-SPV based AC/DC microgrids may either operate as a grid-integrated entity that enables the import or export of the net power with the utility grid or operate as a standalone system, wherein, the deficit/excess generated power is exchanged with an energy storage system.

This work initially deals with the operation and control of DFIG-SPV based standalone AC/DC microgrid. The preliminary requirement of the standalone system is the effective amplitude and frequency regulations. Moreover, power quality aspects of the standalone voltages and currents amidst the presence of unbalanced and nonlinear AC loads cannot be undermined. This becomes increasingly prominent in case of DFIG-SPV based AC/DC microgrids due to the direct inter-connection of DFIG stator terminals with these abnormal AC loads. Any unregulated operation in such circumstances results in unsymmetrical and harmonics currents in the DFIG. Another major concern in the standalone DFIG-SPV based microgrids pertains to the availability and connection status of the DFIG-based WECS. The disconnection/reconnections instants of the DFIG is required to be smooth, while, the standalone AC as well as DC loads are required to be fed uninterruptedly.

In case of grid-integrated DFIG-SPV based AC/DC microgrids, three major issues are dealt in this thesis. The first issue relates to the uncertainty in the grid, especially in AC/DC microgrids located in rural and remote areas. Although many of the rural areas are declared electrified, the grid continuity in such regions is still a major concern. The need for ensuring a seamless transition between grid-integrated and system islanding operating modes is quite apparent. Furthermore, the

uninterrupted operation of the system during these transitions is also a necessity. The second issue relates to the vulnerability of the grid to sudden power changes in the system. The large ramp-rate power changes in the system may impact the grid voltage amplitude and frequency, especially in the remote and secluded regions, where, the grid-interconnection is through long and weak distribution feeders. Grid-assistive power smoothening approaches need to be supplemented within the microgrid control to minimize the risk of grid instability. The third issue that is addressed, relates to the operation of the DFIG-SPV system amidst the presence of unbalance and distortions in the grid voltages. The non-idealities in the voltages culminate into oscillations in the DFIG torque, DFIG stator power, and injected grid power. Meanwhile, it degrades the power quality of DFIG rotor currents, DFIG stator currents, and injected grid currents. Both control-related and topology-related approaches are required to ensure enhanced operation of the system with the non-ideal grid voltage scenario.

After effectively mitigating the three major issues in the grid-integrated operation of the DFIG-SPV system, this thesis deals with the self-sustainability aspect of the microgrid during prolonged grid outage scenarios. Normally, the energy storage integrated to the microgrid provides sufficient back-up during islanding conditions. However, the energy storage cannot be designed to sustain prolonged periods of grid-outage. Therefore, to maintain the self-sufficiency of the system, the framework for operation of a dispatchable diesel generator system working alongside the WECS and SECS is required. The uninterrupted operation and seamless mode transition are also inculcated in this thesis through the control scheme of diesel generator (DG)-equipped microgrid.

Upon devising the methodology for control and operation of DFIG-SPV-DG based AC/DC microgrid, the focus of the research work shift towards devising generalized methodologies with uninterrupted feature and seamless mode transition for systems with multiple DFIGs and multiple SPV arrays integrated within a well-structured AC/DC microgrid architecture with separate AC and DC subgrids. Initially, control and operation of standalone multiple-source AC/DC microgrids are investigated, which are followed by implementation of grid-integrated multiple-source AC/DC microgrids.

The performance of all the microgrids are examined through simulation and experimental analyses. The obtained results showcase satisfactory control performance for all the features in the AC/DC microgrids comprising of DFIG-based wind energy conversion and solar photovoltaic generation.

सार

बिजली उत्पादन के विकेंद्रीकरण ने बिजली क्षेत्र में एक आदर्श बदलाव की शुरुआत की है। सौर फोटोवोल्टाइक्स (एसपीवी), पवन ऊर्जा रूपांतरण प्रणाली (डब्ल्यूईसीएस) आदि के रूप में विकेंद्रीकृत उत्पादन, जब स्थानीय भार के साथ जोड़ा जाता है, एक आत्मनिर्भर इकाई बनाता है, जिसे आमतौर पर माइक्रोग्रिड कहा जाता है। हाइब्रिड एसी/डीसी माइक्रोग्रिड तेजी से पसंदीदा माइक्रोग्रिड आर्किटेक्चर में विकसित हो रहे हैं क्योंकि डीसी-आधारित पीढ़ी के स्रोतों या भारों को इंटरफेस करते समय उनके न्यूनतम पावर कन्वर्टर अतिरेक होते हैं। डबल-फेड इंडक्शन जनरेटर (डीएफआईजी) विभिन्न चर गति डब्ल्यूईसीएस के बीच वर्तमान बाजार हिस्सेदारी का एक बड़ा हिस्सा साझा करता है। यह मुख्य रूप से इसके स्थायी चुंबक-मुक्त निर्माण लाभों और घटी हुई रेटिंग जनरेटर-साइड पावर कन्वर्टर के कारण है। जब एसपीवी सरणी-आधारित सौर ऊर्जा रूपांतरण प्रणाली (एसईसीएस) के साथ एकीकृत किया जाता है, तो यह भार शक्ति की आवश्यकता को पूरा करने का एक प्रभावी साधन प्रदान करता है। डीएफआईजी-एसपीवी आधारित एसी/डीसी माइक्रोग्रिड या तो एक ग्रिड-एकीकृत इकाई के रूप में काम कर सकते हैं जो यूटिलिटी ग्रिड के साथ शुद्ध बिजली के आयात या निर्यात को सक्षम बनाता है या एक स्टैंडअलोन सिस्टम के रूप में काम करता है, जिसमें घाटे/अधिक उत्पन्न बिजली का आदान-प्रदान किया जाता है। एक ऊर्जा भंडारण प्रणाली।

यह काम शुरू में डीएफआईजी-एसपीवी आधारित स्टैंडअलोन एसी/डीसी माइक्रोग्रिड के संचालन और नियंत्रण से संबंधित है। स्टैंडअलोन सिस्टम की प्रारंभिक आवश्यकता प्रभावी आयाम और आवृत्ति नियम है। इसके अलावा, असंतुलित और गैर-रैखिक एसी लोड की उपस्थिति के बीच स्टैंडअलोन वोल्टेज और धाराओं की बिजली गुणवत्ता पहलुओं को कम नहीं किया जा सकता है। डीएफआईजी-एसपीवी आधारित एसी/डीसी माइक्रोग्रिड्स के मामले में डीएफआईजी स्टेटर टर्मिनलों के इन असामान्य एसी लोड के साथ सीधे इंटर-कनेक्शन के कारण यह तेजी से प्रमुख हो जाता है। ऐसी परिस्थितियों में किसी भी अनियमित संचालन का परिणाम डीएफआईजी में असममित और हार्मोनिक्स धाराओं में होता है। स्टैंडअलोन डीएफआईजी-एसपीवी आधारित माइक्रोग्रिड्स में एक अन्य प्रमुख चिंता डीएफआईजी-आधारित डब्ल्यूईसीएस की उपलब्धता और कनेक्शन स्थिति से संबंधित है। डीएफआईजी के डिस्कनेक्शन/रीकनेक्शन इंस्टेंट सुचारू होने की आवश्यकता है, जबकि स्टैंडअलोन एसी के साथ-साथ डीसी लोड को निर्बाध रूप से फीड करने की आवश्यकता है।

ग्रिड-एकीकृत डीएफआईजी-एसपीवी आधारित एसी/डीसी माइक्रोग्रिड्स के मामले में, इस थीसिस में तीन प्रमुख मुद्दों को निपटाया गया है। पहला मुद्दा ग्रिड में अनिश्चितता से संबंधित है, विशेष रूप से ग्रामीण और दूरस्थ क्षेत्रों में स्थित एसी/डीसी माइक्रोग्रिड में। हालांकि कई ग्रामीण क्षेत्रों को विद्युतीकृत घोषित कर दिया गया है, ऐसे क्षेत्रों में

ग्रिड निरंतरता अभी भी एक प्रमुख चिंता का विषय है। ग्रिड-एकीकृत और सिस्टम आइलैंडिंग ऑपरेटिंग मोड के बीच एक निर्बाध संक्रमण सुनिश्चित करने की आवश्यकता काफी स्पष्ट है। इसके अलावा, इन संक्रमणों के दौरान सिस्टम का निर्बाध संचालन भी एक आवश्यकता है। दूसरा मुद्दा सिस्टम में अचानक बिजली परिवर्तन के लिए ग्रिड की भेद्यता से संबंधित है। सिस्टम में बड़े रैंप-दर बिजली परिवर्तन ग्रिड वोल्टेज आयाम और आवृत्ति को प्रभावित कर सकते हैं, विशेष रूप से दूरस्थ और एकांत क्षेत्रों में, जहां ग्रिड-इंटरकनेक्शन लंबे और कमजोर वितरण फीडरों के माध्यम से होता है। ग्रिड अस्थिरता के जोखिम को कम करने के लिए ग्रिड-सहायक पावर स्मूथनिंग दृष्टिकोणों को माइक्रोग्रिड नियंत्रण के भीतर पूरक करने की आवश्यकता है। तीसरा मुद्दा जिसका समाधान किया गया है, ग्रिड वोल्टेज में असंतुलन और विकृतियों की उपस्थिति के बीच डीएफआईजी-एसपीवी प्रणाली के संचालन से संबंधित है। वोल्टेज में गैर-आदर्शता डीएफआईजी टोक़, डीएफआईजी स्टेटर पावर, और इंजेक्शन ग्रिड पावर में दोलनों में समाप्त होती है। इस बीच, यह डीएफआईजी रोटर धाराओं, डीएफआईजी स्टेटर धाराओं, और इंजेक्शन ग्रिड धाराओं की बिजली की गुणवत्ता को कम करता है। गैर-आदर्श ग्रिड वोल्टेज परिदृश्य के साथ सिस्टम के संवर्धित संचालन को सुनिश्चित करने के लिए नियंत्रण-संबंधित और टोपोलॉजी-संबंधित दोनों दृष्टिकोणों की आवश्यकता होती है।

डीएफआईजी-एसपीवी सिस्टम के ग्रिड-एकीकृत संचालन में तीन प्रमुख मुद्दों को प्रभावी ढंग से कम करने के बाद, यह थीसिस लंबे समय तक ग्रिड आउटेज परिदृश्यों के दौरान माइक्रोग्रिड के स्व-स्थिरता पहलू से संबंधित है। आम तौर पर, माइक्रोग्रिड में एकीकृत ऊर्जा भंडारण द्वीपीय स्थितियों के दौरान पर्याप्त बैक-अप प्रदान करता है। हालाँकि, ग्रिड-आउटेज की लंबी अवधि को बनाए रखने के लिए ऊर्जा भंडारण को डिज़ाइन नहीं किया जा सकता है। इसलिए, सिस्टम की आत्मनिर्भरता बनाए रखने के लिए, डब्ल्यूईसीएस और एसईसीएस के साथ काम करने वाले डिस्पैचेबल डीजल जनरेटर सिस्टम के संचालन के लिए रूपरेखा की आवश्यकता है। डीजल जनरेटर (डीजी) से लैस माइक्रोग्रिड की नियंत्रण योजना के माध्यम से इस थीसिस में निर्बाध संचालन और निर्बाध मोड संक्रमण भी शामिल है।

डीएफआईजी-एसपीवी-डीजी आधारित एसी/डीसी माइक्रोग्रिड के नियंत्रण और संचालन के लिए कार्यप्रणाली तैयार करने पर, अनुसंधान कार्य का ध्यान अबाधित विशेषता के साथ सामान्यीकृत कार्यप्रणालियों को तैयार करने और कई डीएफआईजी और कई एसपीवी सरणियों के साथ सिस्टम के लिए सीमलेस मोड ट्रांज़िशन के साथ एकीकृत करने की ओर जाता है। अलग-अलग एसी और डीसी सबग्रिड के साथ अच्छी तरह से संरचित एसी/डीसी माइक्रोग्रिड आर्किटेक्चर। प्रारंभ में, स्टैंडअलोन बहु-स्रोत एसी/डीसी माइक्रोग्रिड के नियंत्रण और संचालन की जांच की जाती है, जिसके बाद ग्रिड-एकीकृत बहु-स्रोत एसी/डीसी माइक्रोग्रिड का कार्यान्वयन किया जाता है।

सिमुलेशन और प्रयोगात्मक विश्लेषण के माध्यम से सभी माइक्रोग्रिड्स के प्रदर्शन की जांच की जाती है। प्राप्त परिणाम डीएफआईजी-आधारित पवन ऊर्जा रूपांतरण और सौर फोटोवोल्टिक उत्पादन वाले एसी/डीसी माइक्रोग्रिड्स में सभी सुविधाओं के लिए संतोषजनक नियंत्रण प्रदर्शन दिखाते हैं।

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LIST OF ABBRREVIATIONS

AC	Alternating Current
APSA	Affine Projection Sign Algorithm
Arc-NLMS	Arctangent Normalized Least Mean Square
ATLMLS	Arctangent Least Mean Logarithmic Square
AVR	Automatic Voltage Regulator
BDC	DC–DC Bidirectional Converter
BES	Battery Energy Storage
BEVC	DC–DC Bidirectional Converter for Electric Vehicle Charging
BKC	DC–DC Buck Converter
BSC	Battery-side Converter
BTC	DC–DC Boost Converter
C*ext*SOGI-HSS	Cross-feedback Extended Second Order Generalized Integrator based Harmonics Sequence Separator
DBR	Diode Bridge Rectifier
DC	Direct Current
DFIG	Doubly-fed Induction Generator
DG	Diesel Generator
DSO	Digital Signal Oscilloscope
D_{SSTS}	DG-side Solid State Transition Switch
DT	DFIG-side Control Target for Multi-target Control at Non-ideal Grid
ES	Energy Storage
EV	Electric Vehicle
*ext*SOGI	Extended Second Order Generalized Integrator
GMBZ-AF	Generic Modified Blake-Zisserman Adaptive Filter
GSC	Grid-side Converter
G_{SSTS}	Grid-side Solid State Transition Switch
GT	Grid-side Control Target for Multi-target Control at Non-ideal Grid
HGI	Higher-order Generalized Integrator
HPRE	High Power Ramp Event
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated Gate Bipolar Transistor
ILC	Interlinking Converter
InC	Incremental Conductance
LVDC	Low Voltage Direct Current
LVUF	Line Voltage Unbalance Factor
MPP	Maximum Power Point

MPPT	Maximum Power Point Tracking
MRAS	Model Reference Adaptive Scheme
MRHGI-HE	Multi-resonant Higher-order Generalized Integrator based Harmonic Estimator
MVDC	Medium Voltage Direct Current
NLMAT	Normalized Least Mean Absolute Third
NMCC	Normalized Maximum Correntropy Criterion
OFU	Optimal Fuel Utilization
OTSR	Optimal Tip Speed Ratio
OTT	Optimal Turbine Torque
PCI	Point of Common Interconnection
PI	Proportional Integral
PLL	Phase Locked Loop
PMS	Power Management Scheme
PMSG	Permanent Magnet Synchronous Generator
P&O	Perturb and Observe
PQ	Power Quality
PQA	Power Quality Analyzer
PR	Proportional Resonant
PRR	Power Ramp Rate
PSF	Power Signal Feedback
PWM	Pulse Width Modulation
RES	Renewable Energy Source
RLMAT	Robust Least Mean Absolute Third
RMS	Root Mean Square
RRL	Ramp Rate Limit
RSC	Rotor-side Converter
SCIG	Squirrel Cage Induction Generator
SCIM	Squirrel Cage Induction Motor
SCR	Silicon Controlled Rectifier
SECS	Solar Energy Conversion System
SG	Synchronous Generator
SSC	Stator-side Converter
SPV	Solar Photovoltaic
S_{SSTS}	Stator-side Solid State Transition Switch
THD	Total Harmonic Distortion
ToUEP	Time of Use Electricity Price
TP	Transition Phase
UPF	Unity Power Factor

VSC	Voltage Source Converter
VZA-LMS	Versoria Zero-Attraction Least Mean Square
WECS	Wind Energy Conversion System
WRIG	Wound Rotor Induction Generator
WRSG	Wound Rotor Synchronous Generator
WT	Wind Turbine

LIST OF SYMBOLS

β	Pitch angle of wind turbine blade (rad.)
χ	Air density
B_r	Blade radius of wind turbine (m)
C_{bkc}	BKC capacitor (F)
C_{dc}	DC-link capacitor (F)
C_f	Ripple filter capacitor (F)
C_p	Coefficient of power from wind turbine
C_{pmax}	Maximum coefficient of power from wind turbine
C_{pv}	Capacitor connected across SPV array (F)
C_t	Coefficient of torque from wind turbine
δ	Percentage of Voltage Ripple across Two DC Link Capacitors (V)
D_{bkc}	Diode of BKC
D_{btc}	Diode of BTC
D_{pv}	Protection diode of SPV array
D_{sgnl}	DG-side signal to determine necessity for connection of DG-set
D_0, D_1	Disconnected and connected state of D_{SSTS}
Δi_{rpBDC}	Ripple content in inductor current of BDC (A)
Δi_{rpBKC}	Ripple content in inductor current of BKC (A)
Δi_{rpBTC}	Ripple content in inductor current of BTC (A)
Δi_{rpSSC}	Ripple content in inductor current of SSC (A)
ΔI_{pv}	Change in SPV array current after one sample instant (A)
ΔV_{pv}	Change in SPV array voltage after one sample instant (V)
ΔV	Fixed step increment/decrement in SPV array voltage for MPPT algorithm (V)
e	Error signal for adaptive filtering techniques
ε_{dc}	Error between reference and sensed DC-link voltages (V)
ε_{ω}	Error between reference and sensed DFIG rotor speeds (rad./s)
ε_{ψ}	Error between stator fluxes for MRAS algorithm (Wb)
ε_{vdc}	Error between reference and sensed LVDC voltages (V)
ε_{vs}	Error between reference and sensed DFIG stator voltages (V)
f	Rated frequency of system (Hz)
f_d	Frequency of DG-set voltage (Hz)
f_g	Frequency of grid voltage (Hz)
f_l	Frequency of PCI-1 voltage (Hz)
f_L	Frequency of PCI-2 voltage (Hz)
f_s	Frequency of DFIG stator voltage (Hz)

f_{th}	Frequency error tolerance in voltage as per IEEE 1547 (Hz)
f_{swBDC}	Switching frequency of BDC (Hz)
f_{swBKC}	Switching frequency of BKC (Hz)
f_{swBTC}	Switching frequency of BTC (Hz)
f_{swSSC}	Switching frequency of SSC (Hz)
G_r	Gearbox ratio of wind turbine
G_{sgnl}	Grid-side signal to determine availability of utility grid
G_0, G_1	Disconnected and connected state of G_{SSTS}
G_{pv}	Solar irradiation incident at SPV array (W/m^2)
h_{dc}	Overload factor for DC-link capacitance
h_{SSC}	Overload factor for L_{iS} design
L_{iB}	Interfacing inductance for BSC (H)
L_{iG}	Interfacing inductance for GSC (H)
L_{iI}	Interfacing inductance for ILC (H)
L_{iS}	Interfacing inductance for SSC (H)
L_{bdc}	Inductance for BDC (H)
L_{bevc}	Inductance for BEVC (H)
L_{bkc}	Inductance for BKC (H)
L_{btc}	Inductance for BTC (H)
Q_g	Grid reactive power (VAR)
Q_l	PCI-1 side AC load reactive power (VAR)
Q_L	PCI-2 side AC load reactive power (VAR)
Q_r	DFIG rotor reactive power (VAR)
Q_s	DFIG stator reactive power (VAR)
I_b	BES current (A)
i_{bsc}	BSC current (A)
i_c	PCI-1 side shunt current (A)
i_C	PCI-2 side shunt current (A)
i_d	DG-set current (A)
I_{ev}	EV load current (A)
i_g	Grid current (A)
i_{ilc}	Interlinking converter current (A)
i_l	PCI-1 side AC load current (A)
i_L	PCI-2 side AC load current (A)
I_{mp_array}	MPP current of SPV array at standard test conditions (A)
I_{mp_panel}	MPP current of SPV panel at standard test conditions (A)
I_{olv}	LVDC load current (A)

I_{omv}	MVDC load current (A)
I_{pv}	SPV array current (A)
i_r	DFIG rotor current (A)
i_s	DFIG stator current (A)
I_{sc_array}	Short circuit current rating of SPV array at standard test conditions (A)
I_{sc_panel}	Short circuit current rating of SPV panel at standard test conditions (A)
I_{swRSC}	Current rating of IGBT switches in RSC (A)
I_{swSSC}	Current rating of IGBT switches in SSC (A)
i_w	Current injected by each WECS in multiple-source AC/DC microgrid
k	Represents signal at the present sample instant
k_{dc}	Measure of energy variation in DC-link capacitor during dynamics
k_i	Integral gain for PI regulator
k_p	Proportional gain for PI/PR regulator
k_r	Resonant gain for PR regulator
kVA_{RSC}	kVA rating of RSC
kVA_{SSC}	kVA rating of SSC
L_{bdc}	BDC inductor (H)
L_{bkc}	BKC inductor (H)
L_{btc}	BTC inductor (H)
L_{iG}	GSC interfacing inductor (H)
L_{iS}	SSC interfacing inductor (H)
L_m	DFIG magnetizing inductance (H)
L_r	DFIG rotor inductance (H)
L_s	DFIG stator inductance (H)
$L_{\sigma r}$	DFIG rotor leakage inductance (H)
$L_{\sigma s}$	DFIG stator leakage inductance (H)
λ	Tip speed ratio of wind turbine
λ_i	Intermediate tip speed signal in wind turbine modelling
λ_o	Optimal tip speed ratio of wind turbine
m	Amplitude modulation index of VSC
$\mu, \sigma, \gamma, \rho$	Constants used in adaptive filtering techniques
$n_{parallel}$	Number of parallel connected SPV strings in an SPV array
$N_{rt/st}$	DFIG rotor to stator turns ratio
n_{series}	Number of series connected SPV panels in an SPV string
Ω_t	Rotational speed of wind turbine (rad./s)
Ω_m	Rotational speed of DFIG mech. (rad./s)
Ω_{mmax}	Maximum rotational speed of DFIG mech. (rad./s)

Ω_s	Synchronous speed of DFIG mech. (rad./s)
ω_e	Reference angular seed corresponding to rated frequency (rad./s)
ω_m	Rotational speed of DFIG elec. (rad./s)
ω_{PR}	Bandwidth for PR regulator (rad./s)
p	DFIG pole pairs
P_b	BES power (W)
P_g	Grid active power (W)
P_l	PCI-1 side AC load active power (W)
P_L	PCI-2 side AC load active power (W)
P_m	Power from wind turbine (W)
P_{mmax}	Rated power from wind turbine (W)
P_{pv}	SPV array power (W)
P_r	DFIG rotor active power (W)
P_s	DFIG stator active power (W)
P_{SSC}	SSC active power (W)
P_w	Power injected by each WECS in multiple-source AC/DC microgrid
R_f	Ripple filter resistor (Ω)
R_r	DFIG rotor resistance (Ω)
R_s	DFIG stator resistance (Ω)
s	Laplace operator
S_0, S_1	Disconnected and connected state of S_{SSTS}
S_{bkc}	IGBT switch of BKC
S_{btc}	IGBT switch of BTC
S_{bk}, S_{bt}	IGBT switches of BDC
ψ_s	Stator flux (Wb)
s_l	DFIG operating slip
S_{sgnl}	DFIG stator-side signal to determine generation possibility from WECS
$S_{w1} - S_{w6}$	IGBT switches of RSC
$S_{w7} - S_{w12}$	IGBT switches of SSC
$S_{w13} - S_{w18}$	IGBT switches of GSC
t_{dc}	Recovery time for DC-link capacitor to regain steady-state (s)
T_m	Torque from wind turbine (Nm)
T_{PR}	Transfer function for PR regulator
T_{pv}	Temperature incident at SPV array (^{0}C)
θ_d	Phase angle of DG-set voltage (rad.)
θ_e	Reference phase angle corresponding to rated frequency (rad.)
θ_{ed}	Error in phase angles of PCI-2 voltages and DG-set voltages (rad.)

θ_{eg}	Error in phase angles of PCI-1/2 voltages and grid voltages (rad.)
θ_{es}	Error in phase angles of PCI-1 voltages and DFIG stator voltages (rad.)
θ_g	Phase angle of grid voltage (rad.)
θ_l	Phase angle of PCI-1 voltage (rad.)
θ_m	DFIG rotor position electrical (rad.)
θ_{m_mech}	DFIG rotor position mechanical (rad.)
θ_r	DFIG slip angle (rad.)
θ_s	Phase angle of DFIG stator flux (rad.)
θ_{st}	Phase angle of DFIG stator voltage (rad.)
θ_{th}	Phase angle error tolerance in voltage as per IEEE 1547 (rad.)
u	Unit sinusoid
V_b	BES voltage (V)
v_d	DG-set voltage (V)
V_{dc}	DC-link voltage (V)
V_{dcB}	DC-link voltage across BSC (V)
V_{dcq}	DC-link voltage across q^{th}-DFIG in multiple-source AC/DC microgrid (V)
V_{dpk}	Amplitude of DG-set voltage (V)
V_{ed}	Error in amplitudes of PCI-2 voltages and DG-set voltages (V)
V_{eg}	Error in amplitudes of PCI-1/2 voltages and grid voltages (V)
V_{es}	Error in amplitudes of PCI-1 voltages and DFIG stator voltages (V)
v_g	Grid voltage (V)
V_{gpk}	Amplitude of grid voltage (V)
v_l	PCI-1 voltage (V)
v_L	PCI-2 voltage (V)
V_{lpk}	Amplitude of PCI-1 voltage (V)
V_{Lpk}	Amplitude of PCI-2 voltage (V)
V_{mp_array}	MPP voltage of SPV array at standard test conditions (V)
V_{mp_panel}	MPP voltage of SPV panel at standard test conditions (V)
V_{oc_array}	Open circuit voltage rating of SPV array at standard test conditions (V)
V_{oc_panel}	Open circuit voltage rating of SPV panel at standard test conditions (V)
V_{olv}	LVDC bus voltage (V)
V_{pk}	Amplitude of AC voltage (V)
V_{pv}	SPV array voltage (V)
V_{ref}	SPV array reference voltage for MPPT (V)
v_s	DFIG stator voltage (V)
V_{spk}	Amplitude of DFIG stator voltage (V)
V_{swRSC}	Voltage rating of IGBT switches in RSC (V)

V_{swSSC}	Voltage rating of IGBT switches in SSC (V)
V_{th}	Amplitude error tolerance in voltage as per IEEE 1547 (V)
v_w	Sensed voltages across WECSs in multiple-source AC/DC microgrids (V)
V_w	Wind speed (m/s)
V_{wmax}	Rated wind speed (m/s)
VF_{dc}	Variation factor in DC-link capacitor
ξ	Weight component (A)
X_m	DFIG magnetizing reactance (Ω)

Subscripts

abc	Three phase entities
αβ	Stationary reference frame coordinates
dq	Synchronous reference frame coordinates
DQ	Rotor reference frame coordinates
1, 2, 3…q	Different units of DFIGs in multiple-source AC/DC microgrids
1, 2, 3…t	Different units of SPV arrays in multiple-source AC/DC microgrids
1+, 5–...	Positive sequence fundamental frequency component, negative sequence fifth harmonic frequency component, etc.

Superscripts

*	Reference entities
1+, 5–...	Signal referred to reference frame rotating with $+\omega_{syn}$ speed, $-5\ \omega_{syn}$ speed, etc.