SYNCHRONIZATION OF SOLAR-PHOTOVOLTAIC AND DOUBLY FED INDUCTION GENERATOR WIND ENERGY CONVERSION BASED MICROGRIDS

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by

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Submitted

In fulfilment of the requirement of the degree of

DOCTOR OF PHILOSOPHY

to the

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Dedicated
To The
Almighty
And
My Family

CERTIFICATE

This is to certify that the thesis entitled **“Synchronization of Solar-Photovoltaic and Doubly Fed Induction Generator Wind Energy Conversion Based Microgrids,”** being submitted by Mr. **Suvom Roy** for the award of the degree of **Doctor of Philosophy** is a record of a bonafide research work carried out by him in the Department of Electrical Engineering of Indian Institute of Technology Delhi.

Mr. **Suvom Roy** has worked under my guidance and supervision and has fulfilled the requirements for the submission of this thesis, which to my knowledge has reached the requisite standard. The results obtained herein have not been submitted to any other University or Institute for the award of any degree.

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ABSTRACT

This thesis investigates challenges associated with the integration, control, and synchronization of solar photovoltaic (SPV) and wind-driven doubly fed induction generator (DFIG) based three-phase microgrids with battery energy storage (BES) support. Various configurations, including single-stage and double-stage SPV-based microgrids, wind-driven DFIG-based microgrids, and hybrid SPV-DFIG microgrid architectures, are analysed to improve system stability, power quality (PQ), and seamless operational transitions between grid-connected and islanded modes. Major challenge in these microgrid configurations is managing the inherent intermittency and variability of SPV and wind energy sources. Traditional set-point regulators fail to provide adequate stability and responsiveness in these dynamic environments, necessitating the development of advanced adaptive control strategies capable of autonomously adjusting to real-time system variations. This thesis also contributes to adaptive control methodologies by proposing a range of intelligent algorithms that enhance microgrid performance at variable renewable energy conditions. Adaptive filtering techniques are developed to improve PQ by ensuring accurate and real-time fundamental current extraction. The generalized robust logarithmic family-least mean square (GRLF-LMS) and proportionate robust diffusion recursive least exponential hyperbolic cosine (PR-DRLEHC) adaptive algorithms provide superior convergence rates and resilience against system disturbances, ensuring high-fidelity grid current injection. These algorithms dynamically adjust control parameters based on system state, allowing the microgrid to adapt to fluctuations in solar insolation, wind speed, and nonlinear load conditions. Unlike conventional proportional-integral (PI) controllers, which require manual tuning and struggle under stochastic operating conditions, proposed adaptive controllers exhibit self-learning capabilities, reduced a need for extensive recalibration and improving system robustness. The thesis further introduces adaptive synchronization techniques for reliable grid integration, ensuring smooth transitions between operational modes. Phase-locked loop (PLL) and frequency-locked loop (FLL) schemes are enhanced with novel adaptive filtering methodologies. A double-loop inertia PLL (DLI-PLL) improves phase-tracking accuracy by mitigating disturbances and noise in grid voltage signals. The complex band-pass filter-enabled second-order generalized integrator FLL (CBF-SOGI-FLL) enhances frequency estimation under unbalanced and distorted grid conditions, while the half-tangent PLL (HT-PLL) achieves faster synchronization, reducing transient disruptions. Additionally, an IEEE-1547-based islanding monitoring scheme (IMS) is integrated into control framework, dynamically adjusting synchronization thresholds based on real-time grid parameters. This intelligent islanding detection mechanism ensures reliable mode transitions without compromising microgrid stability. In addition to adaptive control algorithms for power quality and synchronization, the thesis introduces an optimized energy management strategy by integrating an extremum power extraction converter (EPEC) and a bidirectional DC/DC converter (BDC). These components dynamically regulate SPV and BES power contributions to microgrid, enhancing voltage stability and ensuring continuous power supply to local loads during grid outages. BDC’s adaptive bidirectional control ensures that BES operates efficiently, prolonging its lifespan by mitigating deep charge-discharge cycles. The adaptive nature of proposed control methodologies allows microgrid to maintain optimal performance at fluctuating renewable energy conditions, improving overall system efficiency and reliability. To validate proposed control strategies, extensive MATLAB-based simulations and experimental tests on the laboratory prototypes are conducted. Microgrid performance is evaluated under diverse dynamic conditions, including variations in wind speed, solar irradiance, load transients, and grid faults. Obtained results demonstrate that adaptive control methodologies significantly improve microgrid stability, grid synchronization, and PQ compared to conventional control approaches. GRLF-LMS and DPI-PLL schemes outperform traditional techniques in terms of convergence speed, disturbance rejection, and power quality enhancement, ensuring compliance with IEEE-519 and IEEE-1547 standards. The findings of this research contribute to advancement of intelligent, adaptive control methodologies for renewable energy-based microgrids. By integrating self-tuning algorithms, real-time synchronization enhancements, and optimized energy management techniques, this thesis lays foundation for development of resilient and efficient microgrids. Proposed solutions offer practical and scalable approaches for deployment of decentralized renewable energy systems, supporting global transition toward sustainable and intelligent power networks.

सार

यह शोध प्रबंध बैटरी ऊर्जा भंडारण (बीईएस) समर्थन के साथ सौर फोटोवोल्टिक (एसपीवी) और पवन-चालित डबली फीड इंडक्शन जनरेटर (डीएफआईजी) आधारित तीन-चरण माइक्रोग्रिड के एकीकरण, नियंत्रण और समन्वय से जुड़ी चुनौतियों की जांच करता है। सिस्टम स्थिरता, बिजली की गुणवत्ता (पीक्यू), और ग्रिड-कनेक्टेड और आइलैंडेड मोड के बीच निर्बाध परिचालन संक्रमण को बेहतर बनाने के लिए सिंगल-स्टेज और डबल-स्टेज एसपीवी-आधारित माइक्रोग्रिड, पवन-चालित डीएफआईजी-आधारित माइक्रोग्रिड और हाइब्रिड एसपीवी-डीएफआईजी माइक्रोग्रिड आर्किटेक्चर सहित विभिन्न विन्यासों का विश्लेषण किया जाता है। इन माइक्रोग्रिड विन्यासों में प्रमुख चुनौती एसपीवी और पवन ऊर्जा स्रोतों की अंतर्निहित आंतरायिकता और परिवर्तनशीलता का प्रबंधन करना है। पारंपरिक सेट-पॉइंट नियामक इन गतिशील वातावरणों में पर्याप्त स्थिरता और जवाबदेही प्रदान करने में विफल रहते हैं, जिससे वास्तविक समय प्रणाली विविधताओं को स्वायत्त रूप से समायोजित करने में सक्षम उन्नत अनुकूली नियंत्रण रणनीतियों के विकास की आवश्यकता होती है। यह थीसिस कई बुद्धिमान एल्गोरिदम का प्रस्ताव करके अनुकूली नियंत्रण पद्धतियों में भी योगदान देती है जो परिवर्तनशील अक्षय ऊर्जा स्थितियों में माइक्रोग्रिड के प्रदर्शन को बढ़ाती हैं। सटीक और वास्तविक समय के मौलिक वर्तमान निष्कर्षण को सुनिश्चित करके PQ को बेहतर बनाने के लिए अनुकूली फ़िल्टरिंग तकनीक विकसित की गई है। सामान्यीकृत मजबूत लघुगणक परिवार-न्यूनतम माध्य वर्ग (GRLF-LMS) और आनुपातिक मजबूत प्रसार पुनरावर्ती कम से कम घातीय हाइपरबोलिक कोसाइन (PR-DRLEHC) अनुकूली एल्गोरिदम उच्च-निष्ठा ग्रिड वर्तमान इंजेक्शन सुनिश्चित करते हुए सिस्टम की गड़बड़ी के खिलाफ बेहतर अभिसरण दर और लचीलापन प्रदान करते हैं। ये एल्गोरिदम सिस्टम स्थिति के आधार पर नियंत्रण मापदंडों को गतिशील रूप से समायोजित करते हैं, जिससे माइक्रोग्रिड को सौर विकिरण, हवा की गति और गैर-रेखीय भार स्थितियों में उतार-चढ़ाव के अनुकूल होने की अनुमति मिलती है। पारंपरिक आनुपातिक-अभिन्न (PI) नियंत्रकों के विपरीत, जिन्हें मैन्युअल ट्यूनिंग की आवश्यकता होती है और स्टोकेस्टिक ऑपरेटिंग स्थितियों के तहत संघर्ष करना पड़ता है, प्रस्तावित अनुकूली नियंत्रक स्व-शिक्षण क्षमताओं का प्रदर्शन करते हैं, व्यापक पुनर्मूल्यांकन की आवश्यकता को कम करते हैं और सिस्टम की मजबूती में सुधार करते हैं। थीसिस विश्वसनीय ग्रिड एकीकरण के लिए अनुकूली तुल्यकालन तकनीकों का परिचय देती है, जो परिचालन मोड के बीच सहज संक्रमण सुनिश्चित करती है। चरण-बंद लूप (पीएलएल) और आवृत्ति-बंद लूप (एफएलएल) योजनाओं को नए अनुकूली फ़िल्टरिंग तरीकों से बढ़ाया जाता है। एक डबल-लूप जड़ता पीएलएल (डीएलआई-पीएलएल) ग्रिड वोल्टेज संकेतों में गड़बड़ी और शोर को कम करके चरण-ट्रैकिंग सटीकता में सुधार करता है। जटिल बैंड-पास फ़िल्टर-सक्षम द्वितीय-क्रम सामान्यीकृत इंटीग्रेटर एफएलएल

(सीबीएफ-एसओजीआई-एफएलएल) असंतुलित और विकृत ग्रिड स्थितियों के तहत आवृत्ति अनुमान को बढ़ाता है, जबकि आधा-स्पर्शरेखा पीएलएल (एचटी-पीएलएल) क्षणिक व्यवधानों को कम करते हुए तेज़ तुल्यकालन प्राप्त करता है। इसके अतिरिक्त, एक IEEE-1547-आधारित आइलैंडिंग मॉनिटरिंग स्कीम (IMS) को नियंत्रण ढांचे में एकीकृत किया गया है, जो वास्तविक समय ग्रिड मापदंडों के आधार पर सिंक्रनाइज़ेशन थ्रेसहोल्ड को गतिशील रूप से समायोजित करता है। यह बुद्धिमान आइलैंडिंग डिटेक्शन तंत्र माइक्रोग्रिड स्थिरता से समझौता किए बिना विश्वसनीय मोड संक्रमण सुनिश्चित करता है। बिजली की गुणवत्ता और तुल्यकालन के लिए अनुकूली नियंत्रण एल्गोरिदम के अलावा, थीसिस एक चरम शक्ति निष्कर्षण कनवर्टर (EPEC) और एक द्विदिशात्मक DC/DC कनवर्टर (BDC) को एकीकृत करके एक अनुकूलित ऊर्जा प्रबंधन रणनीति पेश करती है। ये घटक माइक्रोग्रिड में SPV और BES पावर योगदान को गतिशील रूप से नियंत्रित करते हैं, वोल्टेज स्थिरता को बढ़ाते हैं और ग्रिड आउटेज के दौरान स्थानीय लोड को निरंतर बिजली आपूर्ति सुनिश्चित करते हैं। BDC का अनुकूली द्विदिशात्मक नियंत्रण सुनिश्चित करता है कि BES कुशलतापूर्वक संचालित हो, गहरे चार्ज-डिस्चार्ज चक्रों को कम करके इसके जीवनकाल को लम्बा करे। प्रस्तावित नियंत्रण पद्धतियों की अनुकूली प्रकृति माइक्रोग्रिड को उतार-चढ़ाव वाली अक्षय ऊर्जा स्थितियों में इष्टतम प्रदर्शन बनाए रखने की अनुमति देती है, जिससे समग्र प्रणाली दक्षता और विश्वसनीयता में सुधार होता है। प्रस्तावित नियंत्रण रणनीतियों को मान्य करने के लिए, प्रयोगशाला प्रोटोटाइप पर व्यापक MATLAB-आधारित सिमुलेशन और प्रयोगात्मक परीक्षण किए जाते हैं। माइक्रोग्रिड के प्रदर्शन का मूल्यांकन विभिन्न गतिशील स्थितियों के तहत किया जाता है, जिसमें हवा की गति, सौर विकिरण, लोड ट्रांजिएंट और ग्रिड दोषों में भिन्नताएं शामिल हैं। प्राप्त परिणामों से पता चलता है कि अनुकूली नियंत्रण पद्धतियां पारंपरिक नियंत्रण दृष्टिकोणों की तुलना में माइक्रोग्रिड स्थिरता, ग्रिड सिंक्रनाइज़ेशन और PQ में महत्वपूर्ण रूप से सुधार करती हैं। GRLF-LMS और DPI-PLL योजनाएं अभिसरण गति, गड़बड़ी अस्वीकृति और बिजली की गुणवत्ता वृद्धि के मामले में पारंपरिक तकनीकों से बेहतर प्रदर्शन करती हैं, जो IEEE-519 और IEEE-1547 मानकों के अनुपालन को सुनिश्चित करती हैं। इस शोध के निष्कर्ष अक्षय ऊर्जा-आधारित माइक्रोग्रिड के लिए बुद्धिमान, अनुकूली नियंत्रण पद्धतियों की उन्नति में योगदान करते हैं। स्व-ट्यूनिंग एल्गोरिदम, वास्तविक समय सिंक्रनाइज़ेशन संवर्द्धन और अनुकूलित ऊर्जा प्रबंधन तकनीकों को एकीकृत करके, यह थीसिस लचीले और कुशल माइक्रोग्रिड के विकास की नींव रखती है। प्रस्तावित समाधान विकेंद्रीकृत अक्षय ऊर्जा प्रणालियों की तैनाती के लिए व्यावहारिक और मापनीय दृष्टिकोण प्रदान करते हैं, जो वैश्विक पारगमन का समर्थन करते हैं।

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LIST OF ABBRREVIATIONS

AALMS	Amari-Alpha Least Mean Square
AC	Alternating Current
ADALINE	Adaptive Linear Neuron
ADC	Analog to Digital Converter
AGMVC	Adaptive Generalized Maximum Versoria Criterion
BES	Battery Energy Storage
BDC	Bidirectional Converter
CBF-SOGI-FLL	Complex Band-Pass Filter-SOGI-FLL
CCP	Common Connection Point
CIPNLMS-MFX	Combined Improved Proportionate-Normalized Least Mean Squares with Modified Filtered-X
CMPI	Control Mode Change Indicator
CPI	Common Point of Interconnection
CPI	Common Point of Interface
CST	Control Transfer State
DAC	Digital to Analog Converters
DBR	Diode Bridge Rectifier
DC	Direct Current
DFIG	Doubly-Fed Induction Generator
DG	Diesel Generator / Distributed Generation
DIAF	Distributed Incremental Adaptive Filter
DPI-PLL	Double-Loop Inertia PLL
DSTATCOM	Distributed Static Compensator
DSP	Dspace
DS1202	dSPACE 1202 Microlab-Box Controller
ECCF	Enhanced Single-Phase Complex-Coefficient Filters
EPE	Extremum Power Extraction
EPEC	Extremum Power Extraction Converter
EPLL	Enhanced Phase-Locked Loop
FCT2PLL	Forward Compensated Type-2 PLL
FFE	Feed-Forward Enabled

FFT	Fast Fourier Transform
FLL	Frequency-Locked Loop
FOGD-TLMP	Fractional Order Gradient-Descent Total Least Mean p-norm
GDTLS	Gradient Descent Total Least Squares
GIS	Grid Interfacing Switches
GMS	Grid Monitoring Signal
GNLMP	Gaussian Normalized Least Mean p^{th}
GRC	Grid Restoration Command
GRLF-LMS	Generalized Robust Logarithmic Family- Least Mean Square
GSC	Grid-Side Converter
H_{bC}, HBC, HyBC	Hysteresis Band Controller
HC	Hysteresis Controller
HLC	Hysteresis Loop Controller
HT-PLL	Half-Tangent PLL
IDL	Islanding Detection Logic
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insular Gate Bipolar Transistor
IMS	Islanding Monitoring Scheme
IMSC	Induction Motor of Squirrel Cage Type
INC	Incremental Conductance
IPLL	Inertial PLL
IRENA	International Renewable Energy Agency
ISS	Interfacing Semiconductor Switch
ITOAI-QSG	Improved Third Order Adaptive Integrator-Quadrature Signal Generator
LDMS	Leaky Delayed Least Mean Square
LMS	Least Mean Squares
LMF	Least Mean Fourth
LPF	Low Pass Filter
LP-PNLMS	ℓp-norm Proportionate-Normalized Least-Mean-Square
Ms-EPLL	More Stable EPLL
MAF	Moving Average Filter

MDSC	Multiple Delayed Signal Cancellation
MG	Microgrid
MNRE	Ministry of New and Renewable Energy
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
MRES	Multi-Renewable Energy Sourced
MROGI	Modified Reduced-Order Generalized Integrator
MSE	Mean Square Error
MRHGI-HE	Multi-Resonant Higher Order Generalized Integrator for Harmonic Estimation
NLMF	Normalized Least Mean Fourth
NPVSS	Nonparametric Variable Step-Size
OMTL	Operational Mode Transition Logic
OP-AMP	Operational Amplifier
OTSR	Optimal Tip Speed Ratio
P&O	Perturb and Observe
PAC	Phase Angle Controller
PACR	Phase Angle Correction Regulator
PAR	Phase Angle Regulator
PCC	Point of Common Coupling
PCI	Phase Change Initiation
PD	Phase Detector
PhCr	Phase Angle Controlled Regulator
PID	Proportional-Integral-Derivative
PLL	Phase-Locked Loop
PMHG	Permanent Magnet Hydro-Generator
PMSG	Permanent Magnet Synchronous Generator
POC	Point of Coupling
PQ	Power Quality
PR-DRLEHC	Proportionate Robust Diffusion Recursive Least Exponential Hyperbolic Cosine
PWM	Pulse Width Modulated
RDTLMMS	Robust Diffusion Total Least Mean M-estimate Square

RES	Renewable Energy Source
ROGI	Recursive Order Generalized Integrator
RPMLMMS	Robust Proportionate Normalized Least Mean M-estimate Square
RSC	Rotor Side Converter
SCIM	Squirrel Cage Induction Motor
SCP-NLMF	Sparse-Constrained-Proportionate Normalized Least-Mean-Fourth
SFT-PLL	Sliding Fourier Transform-Based PLL
SG	Synchronous Generator
SGi	Semiconductor Grid Interface
SIDC	Synchronization And Islanding Detection Logic
SIL	Synchronization Initiation Logic
SL	Switching Logic
SMU	Signal by Monitoring Utility
SOGI	Second-Order Generalized Integrator
SP / SPV	Solar Photovoltaic
SRF	Synchronous Reference Frame
SSC	Stator Side Converter
SSS	Stator Semiconductor Switches
STL	Switch Transition Logic
THD	Total Harmonic Distortion
UAPF	Universal Active Power Filter
UFS	Utility Feeding Switches
UML	Utility Monitoring Logic
UPQC	Unified Power Quality Conditioner
URC	Utility Restoration Command
USI	Utility Semiconductor Interface
VCO	Voltage-Controlled Oscillator
VFD	Variable Frequency Drive
VLLMS	Variable Leaky Least Mean Square
VLS	Variant of Least Squares
VSC	Voltage Source Converter
VSS	Variable Step-Size

VSS-GDTLS	VSS-Gradient Descent Total Least Squares
VSS-RLMLS	VSS-Robust Least Mean Logarithmic Square
VSWT	Variable Speed Wind Turbine
WECS	Wind Energy Conversion System
WT	Wind Turbine

LIST OF SYMBOLS

V_{dc}	DC-link voltage (V)
V_{pv}	SPV array voltage (V)
V_{dcSPV}	DC-link voltage of the SPV array connected to VSC (V)
V_{BES}, V_{bat}	BES voltage (V)
V_{line}	AC-line voltage (V)
v_{grab}, v_{gab}	Grid line voltage between 'a'-phase and 'b'-phase (V)
v_{grbc}, v_{gbc}	Grid line voltage between 'b'-phase and 'c'-phase (V)
v_{sabc},	Stator Voltages (V)
V_{max}, V_{min}	Voltage limits of islanding scheme (p.u.)
V_{mpp_SPV}	Maximum power point voltage for SPV panel (V)
V_{gabc}, V_{grabc}, v_{gabc}, v_{grabc},	Grid-side voltages (V)
V_{dir}	Direct axis voltage component (V)
V_{quad}	Quadrature axis voltage component (V)
dV_{pv}	Change in SPV array voltage (V)
n_{series}	Number of series connected SPV panels
$n_{parallel}$	Number of parallel connected SPV panels
P_{SPVmax}	Maximum power for SPV array (W)
P_{ISS}	Total power catered by ISS switches (W)
P_{bat}, P_{BES}	BES power (W)
P_g	Grid-injected power (W)
P_w	Wind generated power (W)
P_l	Total loads catered by BES (W)
P_{dc}	Power handled by the DC-link capacitor (W)
P_{SPV}, P_{pv}, P_{pvt}	Power from the SPV panels (W)
P_s	Stator power of DFIG (W)
P_r	Rotor power of DFIG (W)
P_m	Mechanical power of DFIG (W)
V_{mpp_SPV}	Maximum power point voltage (V)
dP_{pv}	Change in SPV array power (W)
I_{mpp_SPV}	Maximum power point current (A)
I_{ISSsw}	Current handled by ISS (A)

I_{pvt}	SPV array's current (A)
i_{grabc}^*, i_{gabc}^*, I_{grabc}^*, I_{gabc}^*	Grid current references (A)
i_{grabc}, i_{gabc}, I_{grabc}, I_{gabc}	Grid-side currents (A)
i_{labc}^*, i_{Labc}^*	Load current references (A)
i_{labc}, i_{Labc}	Load currents (A)
i_{sabc}^*	Stator reference currents (A)
i_{sabc}	Stator currents (A)
I_{dabc}^*,i_{dabc}^*	Direct-axis current references (A)
I_{qabc}^*,i_{qabc}^*	Quadrature-axis current references (A)
I_{rd}	Direct-axis rotor current component (A)
I_{rq}	Quadrature axis rotor current component (A)
i_{rabc}^*	Generated rotor current references (A)
i_{rabc}	Rotor currents (A)
ΔV_{dc}	Ripple voltage sustained by the DC-link capacitor (V)
f_{swEPE}	Switching frequency of EPE converter (Hz)
f_{swBDC}	Switching frequency of BDC converter (Hz)
f_g	Grid-side frequency (Hz)
f_l	Load-side frequency (Hz)
f_{VSCsw}	Switching frequency of VSC (Hz)
f_{max}, f_{min}	Frequency limits of islanding scheme (Hz)
Δi_{rEPE}	Inductor ripple current of EPE converter (A)
Δi_{rpBDC}	Inductor ripple current of BDC converter (A)
Δi_{rpVSC}	Ripple current of interfacing inductor of VSC (A)
L_{EPE}	Inductor of EPE converter (H)
L_{BDC}	Inductor of BDC converter (H)
L_{inVSC}, L_{inVSC}	Grid interfacing inductor of VSC (H)
L_{inter}, L_{itrfcg}	GSC filter inductor (H)
L_m	Magnetizing inductance of DFIG (H)
L_s	Stator inductance of DFIG (H)
t	Time (hours)
C_{dc}	DC-link capacitance (F)
ω_{fund}	Fundamental component of frequency (rad./s)

ω_n	Natural Frequency (Hz)
ω_{in}	Input signal frequency (rad./s)
ω_{co}	Cut-off frequency (rad./s)
ω_L	Load-end angular frequency (rad./s)
ω_{rm}	Rotational speed of the wind turbine (rad./s)
ω_m^*	Generated reference rotor speed (rad./s)
ω_m	Actual rotor speed (rad./s)
ω_{mer}, $\Delta\omega$	Change in angular frequency (rad./s)
kVA_{VSC}	kVA rating of the VSC (kVA)
kVA_{GSC}	kVA rating of the GSC (kVA)
I_{VSCsw}	Maximum current carried by VSC switches (A)
I_{GSCsw}	Maximum current carried by GSC switches (A)
I_b, I_{bat}	BES current (A)
h_{olVSC}	Overload factor
R_{fil}, R_f	Filter resistance (Ω)
C_{fil}, C_f	Filter capacitance (F)
T_s	Switching period (s)
T_{LPF}	Time constant of low pass filter in FCT2PLL
v_{Labc}^*	Load voltage references (V)
K_v	Forward path voltage gain of Ms-EPLL
k, k_{qrp}, k_{rp}, $k_{\omega rp}$, Kt_p, k_{qp}, K_{pvl}, K_{pPAC}, $K_{p\omega}$, $k_{\omega rp}$, k_{vp}, $k_{\omega p}$, g_{rqp}, g_{rdvp}, g_{rqp}, g_{rdp}, K_p	Proportional gains
k_{qri}, k_{ri}, $k_{\omega ri}$, Kt_i, k_{qi}, K_{ivl}, g_{rdvi}, g_{rqi}, g_{rdi}, K_i, K_{iPAC}, $k_{\omega i}$, $K_{i\omega}$	Integral gains
θ_g, θ_{gr}, θ_{grid}	Grid-side voltage phase angle (radians)
θ_l, θ_{ld}, θ_{load}	Load-side voltage phase angle (radians)
θ_{dif}, θ_{error}	Error between phase angles (radians)
θ_{est}	Estimated phase angle (radians)
$\Delta\theta$	Phase angle limits of islanding scheme (radians)
ff_g	Feedforward term

K_{ph}	Forward path gain of FFESOGI-FLL
R	Radius of the wind turbine blades (m)
μ	Adaptation constant/ Acceleration parameter
$G_{insolation}$	SPV array insolation (W/.m^2)
G_r	Gearbox ratio
ξ	Air density (kg/m^3)
Ω	Parameter of auto-correlation
φ	Acceleration parameter
δ	Rate of leaky-learning
λ_s, γ_s	Adaptive-step constants
V_{wind}, V_w	Wind speed (m/s)
C_p	Power coefficient
T_m	Mechanical torque of wind turbine (N-m)
λ_t	Tip-speed ratio of wind turbine
β	Pitch-angle of wind turbine (radians) / VSS-GDTLS constant
τ_l	Weight updating constant
α	Amari-Alpha constant / VSS-GDTLS constant
nz	Small positive number to eliminate possibility of division by zero
λ	CBF-SOGI-FLL constant / forgetting factor
γ	Constant of normalization
η	Adaptive-step constant /Scaling factor / Versoria constant parameter
ρ	Adaptive-step constant / Parameter of shaping
gi	Adaptive gain factor
k, λ_{MDSC}	MDSC-FLL constants
a_i, b_i, a_o, b_o	DPI-PLL constants
dq	Rotating frame of reference
abc	Synchronous frame of reference
$\alpha\beta$	Stationary frame of reference