

**INVESTIGATIONS ON UTILITY SYNCHRONIZED
MICROGRIDS WITH SOLAR-WIND-HYDRO
GENERATION**

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INDIAN INSTITUTE OF TECHNOLOGY DELHI
MAY 2022**

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MICROGRIDS WITH SOLAR-WIND-HYDRO
GENERATION**

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

MAY 2022

CERTIFICATE

It is certified that the thesis entitled “**Investigations on Utility Synchronized Microgrids with Solar-Wind-Hydro Generation,**” being submitted by **Ms. Rohini Sharma** 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 him under my supervision and guidance. The matter embodied in this thesis has not been submitted for award of any other degree or diploma.

Dated: May 11, 2022

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ACKNOWLEDGEMENTS

I wish to express my deepest gratitude and indebtedness to **Prof. Bhim Singh** for providing me guidance and constant supervision to carry out the Ph.D. work. Working under him 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 his blessing I have earned various experiences, other than research, which will help me throughout my life. My sincere thanks and deep gratitude are to **Prof. G. Bhuvaneswari, Dr. Ramkrishan Maheshwari, Dr. Ashu Verma, Dr. Anandarup Das** and all SRC members for their valuable guidance and consistent support during my research work. I wish to convey my sincere thanks to **Prof. B. P. Singh, Prof. M. L. Kothari, Prof. Sukumar Mishra, and Dr. Mashuq-un-Nabif** for their valuable inputs during my course work, which has made the foundation for my research work. I am grateful to IIT Delhi for providing me the research facilities. I would wish to express my sincere gratitude to **Prof. Bhim Singh and Prof. M. Veeracharyas** Prof. in-charge of PG Machine Lab, for providing me immense facilities to carry out experimental work. Thanks are due to Sh. Srichand, Sh. Puran Singh, Sh. Jagbir Singh, Sh. Amit Kumar, and Sh. Jitendra of PG Machines Lab, UG Machines Lab and Power Electronics Lab., IIT Delhi for providing me the facilities and assistance during this work. I would like to thank all my seniors, Dr. Ikhtlaq Hussain, Dr. Rajan Sonkar, Dr. Aniket Anand, Dr. Nishant Kumar, Mr. Anshul Varshney, Dr. Saurabh Shukla, Dr. Nidhi Mishra, Dr. Geeta Pathak, Dr. Shailendra Kumar Dwivedi and Dr. Anjaneet Kumar Mishra, Dr. Sreejith R, Mr. Debashish, Dr. Radha Khushwaha, Dr. Piyush Kant, Ms. Shatakshi Jha, Dr. Priyank Shah, Dr. V. Srinivas, Dr. Deepu Vijay M, Dr. Shadab Marshid and Dr. Tripurari Nath, to motivate me in the starting of my research work. I would like to use this opportunity to thank Dr. Seema Kewat and Dr. Anjeet Verma who have constantly helped me on all technical issues and kept me on right scent by providing insight during my research work. I would like to thank, Ms. Sanjenbam Chandrakala Devi, Ms. Shalvi Tyagi, Ms. Hina Parveen, Dr. Shubhra, Ms. Pavitra Shukl, Mr. P. Sambasivaiah, Mr. Munesh Kumar Singh, Ms. Vandana Jain and all other colleague for their valuable aid and cooperation. My heartfelt thanks to Ms. Kripa and Ms. Farheen Chisti for their help and informal support in pursuing this research work. Moreover, I would like to thank Dr. Radha Khushwaha, Dr. Tabish Mir, Dr. Utkarsh Sharma, Dr. Vineet P. Chandaran, Mr. Gurmeet Singh, Mr. Yalavarthi Amarnath, Ms. Yashi Singh, Mr. Sudip

Bhattacharyya, Ms. Nupur, Mr. Arayadip Sen, Mr. Bilal Naqvi, Mr. Gaurav Modi, Mr. Jitendra Gupta, Mr. Utsav Sharma, Ms. Rashmi Rai, Mr. Sandeep Kumar Sahoo, Mr. Souvik Das, Mr. Kashif, and all PG Machines lab group for their valuable support. I would like to thank, Ms. Shikha Srivastava, Ms. Kushboo, Ms. Ramya, Ms. Manishika Rawat and Ms. Twinkle, who supported and inspired me during my stay in 'Himadri' house and shared my joy, my sorrow and happiness always. I would also like to thank Mr. Yatindra Tripathi, Mr. Satish, Mrs. Sunita Verma, Ms. Moni and all other Electrical Engineering Department office staff for being supportive throughout. I am likewise thankful to those who have directly or indirectly helped me to finish my dissertation study.

Moreover, I would like to thank Department of Science and Technology (DST), Govt. of India for funding this research work under the fund for improvement of S&T infrastructure in higher educational institutions (FIST), UKICER (RP03391), UI-ASSIST (RP03443), SERI-II, J C Bose Fellowship (RP03128) and SERB NSC Fellowship.

My deepest love, appreciation and indebtedness go to my father, **Mr. Romesh Chander Sharma** for his dreams, sacrifices and wholeheartedly endorses. His trust in my capabilities have always motivated me to reach higher academic degrees. I would like to convey my unbounded love to my mother **Mrs. Sudha Sharma** for her ever-lasting support. From my mother I learned patience, and from my father I learned persistence. A great deal of effort, endurance, encouragement and blessings from my in-laws specially **Mr. Joginder Lal Sharma, Mr. Vinay Kumar Sharma and Mrs. Vanita Sharma**. Moreover, I would like to thank my brother **Dr. Rahul Vasudeva** and sister-in-law **Dr. Namrata Paul**, other family members **Late Mrs Savitri Sehgal, Dr. T.S Kler, Dr. Neelam Kler and Mr. Sidharth Kler** and loving friends for giving me the inner strength and wholeheartedly support. Their trust in my capabilities had been a key factor to all my achievements. I take this opportunity to thank the great asset of my life, my husband **Mr. Shagun Sharma** who has paid sincere and serious attention at my academic voyage. His patience helped me keep my sanity during the challenging times of this dissertation. During my times of self-doubt, he was encouraging, caring, and attentive. 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 endeavors. Their blessings may be showered on me for strength, wisdom and determination to achieve in future.

Date: May 11, 2022

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ABSTRACT

Resilience and reliability of the microgrids are a vital issue, as it not only decreases the power outage, but it allows high penetration of various distributed energy resources such as renewables (solar, wind, hydro) and battery energy storage. Microgrid (MG) is a small-scale power network that functions either in the grid-connected (GC) mode or an islanding (IS) mode. In both these modes of operation and transition from an IS mode to the GC mode and vice-versa, the distributed energy resources (DER) in microgrid (MG) are controlled by using various control techniques. Therefore, this thesis deals with the design, control and implementation of various configurations integrating solar PV, pico-hydro generation, wind energy conversion system, battery storage, grid/DG set and local loads. These configurations are segregated on the basis number of energy sources (one or multiple), the configuration of each source (single stage or double stage) and types of loads (single-phase, three-phase, dynamic loads). The solar and wind generations are intermittent and thus used in conjunction with pico-hydro generation to guarantee that the baseload is supplied at all times. This MG operates in multiple modes like islanded mode, grid-connected mode and DG set connected mode to facilitate uninterrupted power to local loads. Moreover, few configurations have DG set, irrespective of the fact that the DG set utilizes diesel, which is not clean. Diesel power provides reliability that supports critical loads (hospitals) when renewable energy and battery power are insufficient. However, the DG set operates in the fuel-efficient zone under load unbalance conditions as it is supported through a battery storage. The core objective of the system is to deliver power to critical loads even at the grid outage.

A prime research feature for a microgrid is its appropriate control, which assures uniform power as well as current allocation between distributed generation units while operating in different operating conditions. A single voltage source converter achieves significant roles like frequency and voltage regulation (in islanded and DG set connected mode), energy management between generating units and loads, compensating the harmonics current demand of local nonlinear load and dynamic reactive power demand of dynamic loads (Induction Motor). Therefore, the VSC control is the eminent part of the MG and for the satisfactory operation, it should be fast and robust. In this thesis, various control algorithms are implemented and these controls provide reduced steady-state error, enhanced convergence rate, DC offset rejection capability to achieve accurate extraction of the fundamental component of nonlinear load currents.

The satisfactory performance of these microgrids and their control algorithms are replicated through simulated results, which are modelled in MATLAB/Simulink platform using Simpower toolbox and test results on the developed hardware prototype. Simulated and test results are presented for adverse conditions like solar intensity change, wind speed change and unbalanced load conditions.

सार

माइक्रोसिड का लक्ष्यीकरण और निष्क्रीयीकरण एक महत्वपूर्ण मुद्दा है, क्योंकि यह न केवल विफलता की कमी को कम करता है, बल्कि यह विभिन्न विफलताओं के संभावित कारणों जैसे नवीकरणीय (सीर, फन, हाइड्रो) और बैटरी ऊर्जा संचयन के उच्च प्रयोग की अनुमति देता है। माइक्रोसिड (एनबी) एक छोटे पैमाने का विफलता डेटाबेस है जो वातावरण-बेनेफिट मोड का एक आइडेंटिफिकेशन मोड में कार्य करता है। आइडेंटिफिकेशन मोड से सिड-बेनेफिट मोड में संभालन और संक्रमण के इन दोनों तरीकों में और इसके विफलता, माइक्रोसिड (एनबी) में विफलताओं संभावना (डीजल) को विभिन्न निष्पत्ति लक्ष्यीकरणों का उपयोग करके निर्धारित किया जाता है। इसलिए, यह सीमित सीर पीसी, निम्न-हाइड्रो उत्पादन, फन ऊर्जा संचयन प्रणाली, बैटरी संचयन, सिड / डीसी सेट और लोबल लोड को एकीकृत करने वाले विभिन्न निष्पत्ति के डिजाइन, निष्पत्ति और कार्यप्रणाली से संबंधित है। इन निष्पत्तियों को ऊर्जा छोड़ों की संख्या (एक वा एनबी), प्रत्येक छोड़ के निष्पत्ति (एकल चरण वा छोड़े चरण) और चार के प्रकार (एकल-चरण, सीर-चरण, गतिशील चरण) के आधार पर अलग किया जाता है। सीर और फन पीसी एक-एक कर लेती है और इस प्रकार निम्न-हाइड्रो पीसी के साथ संबंधन में उपयोग की जाती है। तब यह सुनिश्चित हो सके कि हर समय बेसलाइन की आइडेंटिफिकेशन की जाती है। यह MG बर्न मोड में काम करता है जैसे कि आइडेंटिफिकेशन मोड, सिड-बेनेफिट मोड और DG सेट बेनेफिट मोड, तबकि लोबल लोड को निर्धारित विफलता मिल सके। इसके अलावा, कुछ सीमितप्रणाली में डीसी सेट होता है, इस समय के कारण कि डीसी सेट लोबल का उपयोग करता है, जो साथ नहीं है। लोबल निष्क्रीयीकरण चक्रांतर करती है जो नवीकरणीय ऊर्जा और बैटरी चक्रांतर होने पर महत्वपूर्ण लोड (अन्यथा) का समर्थन करती है। हालांकि, डीसी सेट डीसी-चक्रांतर सेट में लोड अनिश्चितता निष्पत्तियों के लक्ष्य संभालित होता है क्योंकि यह बैटरी स्टोरेज के माध्यम से समर्थित होता है। सिस्टम का मुख्य उद्देश्य सिड आउटपुट पर भी महत्वपूर्ण लोड को विफलता पहुंचाना है।

एक माइक्रोसिड के लिए एक प्रमुख अनुबंधन निष्पत्ति इसका उपयोग निष्पत्ति है, जो विभिन्न परिचालन निष्पत्तियों में काम करते हुए विफलता उत्पादन इकाइयों के बीच समय तबकि के साथ-साथ कार्यप्रणाली आउटपुट का आश्वासन देता है। एक एकल पोर्टेबल सेट कन्वर्टर आवृत्ति और पोर्टेबल निष्पत्ति (आइडेंटिफिकेशन मोड और डीसी सेट बेनेफिट मोड में), उत्पादन इकाइयों और लोड के बीच ऊर्जा प्रबंधन, नवीकरणीय निष्पत्ति लोड की हार्मोनिक कार्यप्रणाली और गतिशील चरण की गतिशील प्रतिक्रियाशील विफलता की मात्रा की आधार की नीति महत्वपूर्ण भूमिकाएं प्राप्त करता है। इसलिए, पीसीसी निष्पत्ति एनबी का प्रमुख हिस्सा है और संतोषजनक संभालन के लिए, यह लेब और प्रयोगों द्वारा चलाया। इस सीमित में, विभिन्न निष्पत्ति एनबीएन लान्ड किंग नए हैं और वे निष्पत्ति कम डिजिट-राम सुट्टी, बड़ी हुई अधिसूचना पर, डीसी और प्रयोग अमूर्तता क्षमता प्राप्त करते हैं तबकि निष्पत्ति लोड चक्रांतरों के सीमित चरण के सटीक निष्पत्ति को प्राप्त किया जा सके।

इन माइक्रोसिड और उनके निष्पत्ति एनबीएन के संतोषजनक उत्पादन को डिजिटल प्रणालियों के माध्यम से संचालित किने जाने हैं, जो कि डिजिटल टूलबीक का उपयोग करके MATLAB/Simulink पोर्टेबल में तैयार किंग जाते हैं और विफलता हाइब्रिड प्रोटेक्शन पर पोर्टेबल के पोर्टेबल है। सीर लोबल परिचालन, एक की नीति परिचालन और अनिश्चितता चरण निष्पत्तियों की प्रतिक्रिया प्रतिक्रियाओं के लिए परिचालन के परिचालन प्रकृत किंग नए है।

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Table 9.1	Benefits and Limitations of Architecture of Microgrids

LIST OF ABBREVIATIONS

AAF-FLL	Advanced Adaptive FilterFrequency Locked Loop
3IMPL	Three Phase Improved Magnitude Phase Locked Loop
3MPLL	Three-Phase Modified Phase-Locked Loop
ADC	Analog Digital Converter
AGI-FLL	Advanced Generalized Integrator Frequency Locked Loop
AMLMS	Approximate Multiplier Least Mean Square
ANF	Adaptive Notch Filter
BDC	Bidirectional DC-DC Converter
BES	Battery Energy Storage
BLDCGs	Brushless DC Generators
CLO	Circular Limit Cycle Oscillator
CLO-FLL-WPF	Circular Limited Cycle Oscillator-Frequency Locked Loop-with Prefilter
D-EPLL	Damped Enhanced Phase-Locked Loop
DERs	Distributed Energy Resources
DFIGs	Doubly Fed Induction Generators
DG	Diesel Generator
DOD	Depth of Charge
EPLL	Enhanced Phase Locked Loop
ESOGI-FLL-WIF	Enhanced Second-Order Generalized Integrator with an in-Loop Filter
ESOGI-MFLL	Enhanced Second-Order Generalized Integrator with Modified Frequency Locked Loop
ESOGI-OLCFLL	Enhanced Second-Order Generalized Integrator Out-Loop Compensation Frequency Locked Loop
Ext-SOGI-FLL	Extended Second Order Generalized Integrator Frequency Locked Loop
FZA-APNCA	Flexible Zero Attracting Affine Projection Normalized Correlation Algorithm
GC	Grid Connected
HCC	Hysteresis Current Controllers
IAF-FLL	Improved Adaptive Filter Frequency Locked Loop
IGI-FLL	Improved Generalized Integrator Frequency Locked Loop
ILMS	Improved Least Mean Square
IMs	Induction Motors
INC	Incremental Conductance
ITOF- FLL	Improved Third-Order Filter Frequency Locked Loop
LF	Loss Factor
LMS	Least Mean Square
MDSOGI-FLL	Modified Damped Second-Order Generalized Frequency Locked Loop

MEPLL	Modified Enhanced Phase-Locked Loop
MFLL	Modified Frequency Locked Loop
MG	Microgrid
MMSOGI-FLL	Modified Multi Second-Order Generalized Frequency Locked Loop
MPPT	Maximum Power Point Tracking
MVSS INC	Modified Variable Step Size Incremental Conductance
PCC	Point of Common Coupling
PI	Proportional Integral
PID	Proportional Integral Derivative
PLL	Phase Locked Loop
PMSGs	Permanent Magnet Synchronous Generators
PQ	Power Quality
PR	Proportional Resonant
PV	Photovoltaic
PWM	Pulse Width Modulation
RES	Renewable Energy Sources
S&H	Sample and Hold
SEIG	Self-Excited Induction Generator
SOGI	Second-Order Generalized Integrator
SRF	Synchronous Reference Frame
SSS	Solid-State-Switch
SyRG	Synchronous Reluctance Generator
UC	Utility Connected
VCO	Voltage Controlled Oscillator
VSC	Voltage Source Converter
WECS	Wind Energy Conversion System
WTGS	Wind Turbine Generation System
ZCD	Zero Crossing Detector

LIST OF SYMBOLS

α	Overloading Factor
A_g	Battery Aging Factor
C_{dc}	DC link Capacitor
C_f	Capacitance Ripple Filter
C_{min}	Minimum Capacitance
D	Duty Cycle
D_{dc}	Duty Cycle of BDC
dI_r	Change in Wind Current
dV_r	Change in Wind Voltage
$\mathcal{E}_e$	Error Between Sums of Fundamental Component Extracted and the Input Load Current Fundamental Component
$\mathcal{E}_f$	Frequency Observe Error
f	Frequency
f_{sw}	Switching Frequency
r	Gain of the FLL
h	Overload Factor
I_b	Sensed Battery Current
I_b^*	Reference Battery Current
$I_{b_{err}}$	Error of Reference Battery Current
$i_{di}^*, i_{db}^*, i_{dn}^*$	Reference DG Currents
i_{di}, i_{db}, i_{dn}	Sensed DG Current Values
$i_{di_{err}}, i_{db_{err}}, i_{dn_{err}}$	DG Current Error Signals
I_{dL}	Net Active DG Current
$I_{d_{avg}}$	Average Fundamental DG Active Current Component
i_{dn}	DG Sensed Neutral Current
i_{dn}^*	DG Reference Neutral Current
i_{d0}	Fundamental Load Current Component
i_{d0a}	Three Phase In-Phase Fundamental Load Current Component
I_p	Frequency Based Loss Component
I_L^*	Total Load Current Fundamental Component
$i_{gi}^*, i_{gb}^*, i_{gn}^*$	Grid Reference Currents
i_{gi}, i_{gb}, i_{gn}	Grid Current Sensed Values

$i_{gna}, i_{gbs}, i_{gcs}$	Grid Current Error Signals
i_{gn}	Grid Sensed Neutral Current
i_{gn}^*	Reference Grid Neutral Current
$i_{La}^*, i_{Lb}^*, i_{Lc}^*$	Reference VSC Currents
$i_{La}, i_{Lb}, \text{ and } i_{Lc}$	Sensed VSC Currents
$i_{Lao}, i_{Lbo}, i_{Lco}$	Sense the Load Currents
$i_{Lfo}, i_{Lfb}, i_{Lfc}$	Active Components (Grid mode)
i_{Lpo}	Active Power Component of Phase a
i_{Lpavg}	Fundamental Active Load Current Component Average Output
i_{Lpb}	Active Power Component of Phase b
i_{Lpc}	Active Power Component of Phase c
i_{Lqo}	Reactive Power Component of Phase a
i_{Lqavg}	Average Value of Fundamental Reactive Load Current
i_{Lqb}	Reactive Power Component of Phase b
i_{Lqc}	Reactive Power Component of Phase c
I_m	Magnitude of the Fundamental Current Estimated
I_{mpp}	MPP Current of PV
I_{pnet}	Net Fundamental Component of Active Current
I_{pf}	PI controller based Frequency Regulator Output
I_{pv}	PV Current
I_{pff}	PV Power Feed-Forward Term
I_{qnet}	Net Fundamental Reactive Current
I_{qt}	PI controller based voltage regulator output
I_r	Wind Current
$i_{sa}^*, i_{sb}^*, i_{sc}^*$	Reference Value of Currents
i_{sa}, i_{sb}, i_{sc}	Sensed Value of Currents
$i_{sao}, i_{sbo}, i_{sco}$	Current Error Signals
i_{scps}	Short Circuit Current of PV
i_{sn}	Sensed Source Neutral Current
i_{sn}^*	Reference Source Neutral Current
$i_{spa}^*, i_{spb}^*, i_{spc}^*$	In Phase Reference Source Currents
$i_{sqpa}^*, i_{sqpb}^*, i_{sqpc}^*$	Quadrature Reference Source Currents
$I_{maxpeak}$	Peak Maximum VSC Current
I_{vq}	Output of Voltage PID Controller

I_{vic}	VSC Current Rating
I_{wf}	Wind Power Feed-Forward Term
k_l	Voltage Ripple
L_b	PV Boost Inductor
L_d	Direct Axis Inductance
L_{dc}	Inductor in BDC
L_f	Value of the Interfacing Inductor
L_w	Wind inductor value
L_q	Quadrature Axis Inductance
m	Modulation Index
P	Load on the Battery
P_{DGmax}, P_{DGmin}	Maximum and Minimum Diesel Generator Power Limits
P_i	Instantaneous Power
P_{mpp}	MPP Power of PV
P_w	Wind Power Generated
q_{labc}	Three Phase Quadrature Fundamental Load Current Component
R_f	Resistance of Ripple Filter
T_c	Temperature Correction Factor
t_r	Time of Recovery
T_s	Switching Time
$u_{qph}, u_{qpd}, u_{qpd}$	In-Phase Unit Templates in DG Connected Mode
$u_{qpg}, u_{qps}, u_{qps}$	In-Phase Unit Templates in Grid Connected Mode
$u_{qpi}, u_{qpi}, u_{qpi}$	In-Phase Unit Templates in Islanded Mode
$u_{qpi}, u_{qpi}, u_{qpi}$	Quadrature Unit Templates in Islanded Mode
VA_{VSC}	VA Rating of the VSC
V_b	Battery Voltage
v_{dabc}, v_{dabc}	Sense DG Voltages
V_{dc}	DC link Voltage
V_{dcmin}	Minimum DC link Voltage
V_{dcref}	DC link Reference PV Voltage
v_{ua}, v_{ub}, v_{uc}	Error Signals
v_g	Rating of AC side voltage (line)
$v_{gah}, v_{gib}, v_{gic}$	Sense Grid Voltages
$v_{La}^*, v_{Lb}^*, v_{Lc}^*$	Reference Three-Phase Voltage

V_{Laa}, V_{Lb}, V_{Lc}	Sensed Three Phase Voltage
V_{Lab}, V_{Lbc}	Sense Load Voltage
V_{min}	Minimum AC Side Voltage
V_{mpp}	MPP Volatge of PV
V_{ocpv}	Open Circuit Voltage of PV
V_{pv}	PV Volatge
V_r	Wind Voltage
V_{in}	AC Supply Voltages
V_{in}^*	Reference Voltage
V_{mg}	Terminal Voltage of the Grid
V_{vsc}	Voltage Rating of the device (IGBT switch)
$w(k), w(k-1), \Delta w$	New, Old and Change in DC-link Reference PV Voltages
X_d	Direct Axis Reactance
ΔI_L	Ripple Current in BDC
ΔI_o	Current Ripple at Rated Wind Speed
ΔI_{lim}	Allowable Current Ripple
$\Delta \theta$	Synchronization PI Controller Output
$\Delta \omega_o$	Change in Frequency
η	Efficiency of the Battery
θ_e	Phase Angle Difference Between Grid Voltage and Load Volatge
θ_g	Phase Angle of Grid Voltage
θ_L	Phase Angle of Load Voltage
θ_{mw}	Modified Phase Angle
λ	Multiplication Factor
ω_e	Frequency Updated
ω_e	Frequency Error
ω_f^*	Updated Reference Frequency
ω_f	Additional Frequency
ω_i	Sensed Frequency
ω_i^*	Reference Frequency
ω_o	Fundamental Frequency
ω_{new}	New Frequency Deviation Component
ω_{ref}	Reference Frequency