MODELLING, STABILITY ANALYSIS, AND DECENTRALIZED CONTROL DESIGN OF INVERTER INTERFACES

PANKAJ DILIP ACHLERKAR

DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI

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by

PANKAJ DILIP ACHLERKAR

DEPARTMENT OF ELECTRICAL ENGINEERING

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ॐ वाङ्मे मनसि प्रतिष्ठिता मनो मे वाचि प्रतिष्ठितमाविरावि‌र्म एधि वेदस्य म आणीस्थः श्रुतं मे मा प्रहासीः अनेनाधी-तेनाहोरात्रान्सन्दधामि । ऋतं वदिष्यामि सत्यं वदिष्यामि तन्मामवतु तद्वक्तारमवतु अवतु मामवतु वक्तारमवतु वक्तारम् ।।

ॐ शान्तिः शान्तिः शान्तिः ।।

--- ऐतरेय उपनिषद, ऋग्वेद

Meaning :

May my speech and mind work in complete coordination with the manifested knowledge of reality, and may I work days and nights to retain whatever knowledge that is perceived. May my studies reveal whatever is governing reality, may the propounders and receivers of this knowledge be upgraded and protected by the supreme reality. May there be peace in all dimensions of life. Om, Peace ! Peace !! Peace !!

--- Aitareya Upnishad, Rigveda

CERTIFICATE

This is to certify that the thesis entitled **'MODELLING, STABILITY ANALYSIS AND DECENTRALIZED CONTROL DESIGN OF INVERTER BASED MICROGRID'**, being submitted by **Pankaj Dilip Achlerkar** to **Indian Institute of Technology Delhi** is a record of bonafide research work carried out under my supervision and I consider it worthy for consideration of the award of the degree **Doctor of Philosophy** in Electrical Engineering. The results obtained here have not been submitted to any other University or Institute for the award of any degree or diploma.

Prof. Bijaya Ketan Panigrahi
Department of Electrical Engineering,
Indian Insittute of Technology Delhi,
New Delhi - 110016, India.

Date: 13/10/2022 .

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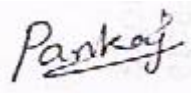

— Pankaj Dilip Achlerkar

Abstract

Undesired loss of synchronization during faults, tripping due to incorrect estimation of phase and frequency, unwanted control interactions, resonances, poorer transient responses, undesired power sharing etc. are some of the pressing issues for large-scale integration of inverter interfaces. Existing practices lack the correct mathematical models to analyze the power system phenomena of new era. This work firstly develops the linear time-periodic (LTP) models for inverter to grid synchronization. The new modeling principles are capable to demonstrate much wider issues of stability and performance than conventional positive-sequence time-invariant (LTI) dynamic models. Accordingly, the Floquet theory-based stability analysis is carried out for these models, in time- and frequency-domains. The decentralized control solutions are proposed for better synchronization, better transient response, and better interaction with weak and unbalanced grid, particularly during fault ride-through. All propositions are validated from theory, by offline and real-time simulation case-studies as well as on the laboratory-scale experimental setup. This work would be crucial asset for original equipment manufacturers (OEMs), for renewable integration planning committees, and inverter response standardization efforts.

The major highlights of the work are summarized as follows:

(1) Unbalanced grid synchronization is thoroughly analyzed. A new recursive least squares based solution is also proposed for the same.

(2) Dynamic LTP models for grid forming and grid feeding inverters, and the same for a master-slave controlled microgrid are formulated.

(3) A stabilizing output feedback control is proposed using generalized Nyquist criterion for weak and unbalanced grid interconnection of the inverter.

(4) Robust backstepping based output voltage control is proposed for improved transient response.

Key Words: Grid Synchronization, Linear Time-Periodic System, Weak Grid, Voltage Source Converter, Decentralized Control.

सारांश

विद्युत पारेषण तारों के दोषयुक्त स्थिति के दौरान तादात्म्य का अवांछनीय छूटना, कोणीय स्थान एवं वारंवारता के गलत अनुमान की वजह से विद्युतपरिपथ विच्छेदन, नियंत्रण प्रणाली में अवांछित परस्परक्रिया, सस्पंदन, ख़राब अस्थाई प्रतिसाद, अवांछित शक्ति बटवारा इत्यादि मुख्य समस्याएं बड़े पैमाने पर इन्वर्टर के एकीकरण में विद्यमान है। उपलब्ध साहित्य में ऐसे नए शक्ति प्रणाली में होनेवाली घटनाओं का वर्णन करने हेतु सुयोग्य गणितीय प्रतिरूपों का अभाव दिखाई पड़ता है। प्रथमतः, इस कार्य में इन्वर्टर का ग्रिड के साथ एकीकरण की तादात्म्य प्रक्रिया का रैखिक समयावधिक प्रतिरूप विकसित किया गया है। यह नए गणितीय प्रतिरूपों के सिद्धांत, पारम्पारिक गतिशील सकारात्मक क्रम वाले रैखिक समय-अपरिवर्तनीय प्रतिरूपों की तुलना में, प्रणाली के अनेक स्थिरता एवं प्रदर्शन सम्बन्धी मुद्दों को दर्शाने में सक्षम हैं। उन्ही प्रतिरूपों के अनुसार, फ्लोक्वे सिद्धांत के अनुरूप समय एवं वारंवारता के अधिक्षेत्रों में स्थिरता का विश्लेषण किया गया है। सर्वोत्तम तादात्म्य, सुयोग्य अस्थाई प्रतिसाद, कमजोर एवं असंतुलित ग्रिड के साथ सुलभ एकीकरण (विशेषतः दोषयुक्त परिपथ की स्थिति के दौरान), इत्यादि सुधारों के लिए विकेन्द्रीकृत नियंत्रण के उपाय सुझाये है। इस कार्य में प्रस्तुत सारे सुझाओं का परिक्षण करने हेतु विविध ऑफलाइन तथा ऑनलाइन सिम्युलेशन्स एवं प्रायोगिक स्तर के हार्डवेयर उपकरण व्यवस्था का परिचालन प्रस्तुत हैं। प्रस्तुत यह कार्य मुख्यतः मुलभूत उपकरण उत्पादकों, नवीकरणीय ऊर्जा एकीकरण योजना समितियों एवं इन्वर्टर प्रतिक्रिया मानकीकरण कार्यों की दृष्टि से अत्यंत लाभदाई साबित हो सकता है।

इस कार्यान्तर्गत प्रमुख सुझाव निम्नलिखित प्रकार से हैं :

(१) असंतुलित ग्रिड तादात्म्य का सुचारु रूप से विश्लेषण किया गया है। पुनरावर्ती न्यूनतम वर्ग नामक साधन का उपयोग करते हुए एक नया तादात्म्य का तरीका विवृत है।

(२) ग्रिड बनानेवाले एवं ग्रिड को अनुसरित करनेवाले इन्वेर्टर्स के गतिमान रैखिक समयावधिक प्रतिरूप संरचित किये है। तथा, मास्टर-स्लेव नियंत्रण व्यवस्था द्वारा चलित माइक्रोग्रिड के भी प्रतिरूप बनाये है।

(३) इन्वर्टर के कमजोर और असंतुलित ग्रिड के साथ एकीकरण करने हेतु सामान्यीकृत नीक्वीस्ट मानदंड का उपयोग करके एक स्थिरीकरणीय उत्पादन प्रतिपुष्टि नियंत्रण का प्रस्ताव है।

(४) बेहतर क्षणिक प्रतिक्रिया के लिए मजबूत बैकस्टेपिंग पर आधारित उत्पादित विभवांतर के नियंत्रण का प्रस्ताव प्रतिपादित है।

मुख्य शब्दः ग्रिड तादात्म्य, रैखिक समयावधिक प्रणाली, कमजोर एवं असंतुलित ग्रिड्स, वोल्टेज सोर्स कन्वर्टर्स, विकेन्द्रीकृत नियंत्रण।

Contents

Certificate i

Acknowledgments ii

Abstract iii

Contents v

List of Figures ix

List of Tables xv

Nomenclature xvi

1 Introduction 1

1.1 Motivation 1

1.2 Existing Works and Research Gaps 2

1.2.1 Synchronization issues due to PLL 4

1.2.2 Issues with unbalanced loading 5

1.2.3 Instability due to weak and unbalanced grid interconnection 6

1.2.4 Major Research Gaps Summarized 7

1.3 Objectives of the Thesis 8

1.4 Scopes and Common Assumptions in the Thesis 8

1.5 Brief Overview of the Contributions 9
1.6 Outline of the Thesis 11

2 Small-signal Stability Analysis of Inverter to Grid Synchronization 12
2.1 Introduction 12
2.1.1 Motivation 12
2.1.2 Existing Works and Research Gaps 14
2.1.3 Key Contributions 18
2.2 Small-Signal Instability of SRF-PLL 20
2.3 Explanation of Instability in SRF-PLL for Unbalanced Voltage Input 26
2.3.1 Improved Small-Signal Model of SRF-PLL 26
2.3.2 Brief Overview of Floquet Theory 27
2.3.3 Floquet Theory Based Stability Assessment of SRF-PLL for Unbalanced Inputs 29
2.4 DDSRF-PLL: Small Signal Model 31
2.5 Modes and Stability Boundaries of DDSRF-PLL 37
2.5.1 Determination of Precise Stability Boundaries 37
2.5.2 Modes in DDSRF-PLL 43
2.5.3 On the amplitude normalization scheme 47
2.6 Modeling Input Signal Distortions for DDSRF-PLL 47
2.6.1 Modeling DC Offset 49
2.6.2 Modeling Harmonics 50
2.7 Comparison of Floquet Theory Approach with Harmonic Domain Methods 53
2.8 Conclusion 55

3 An Adaptive Frame Transformation and Synchronization Scheme Using Recursive Least Squares 56
3.1 Introduction 56

3.2 Proposed Signal Transformation and Grid Synchronization Scheme 59
3.2.1 Preliminaries of Recursive Least Squares 59
3.2.2 Transformation of sinusoidal signal to direct (d) and quadrature (q) axes components 61
3.2.3 Achieving optimal trade-off between transient response and steady-state disturbance rejection 63
3.2.4 Estimation of fundamental frequency and phase angle for synchronization purpose 66
3.2.5 Scheme for three phase unbalanced signal transformation to positive and negative sequence dq axes 67
3.3 Stability Analysis and Design Guidelines 69
3.3.1 Large signal model and stability of parameter estimator 69
3.3.2 Small signal model of closed loop system 70
3.3.3 Design Criteria 71
3.4 Simulation Results 73
3.5 Real-time Implementation and Results 78
3.5.1 Discrete-time Realization of Proposed Signal Transformation and Synchronization Scheme 78
3.5.2 Experimental results 79
3.6 Conclusion 84

4 Modeling and Analysis of Unbalanced Inverter Interfaces 85
4.1 Introduction 85
4.2 Isolated Mode of Operation 87
4.2.1 Performance of Single Inverter Serving Unbalanced Loads 87
4.2.2 Small-Signal Model and Stability Assessment 93
4.2.3 Issue of Unbalanced Load Sharing Among Multiple Parallel Inverters . . . 97
4.3 Grid-tied Mode of Operation 104

4.3.1 Reference Frames, Transformations and Phase Locking 104
4.3.2 Grid Interfaced Inverter with L Filter 107
4.3.3 Grid Interfaced Inverter with LC Filter 109
4.4 A Microgrid with Master-Slave Control Architecture 111
4.5 Conclusion 113

5 Stabilizing Control Design for Weak and Unbalanced Grid Interfaced Inverters 114
5.1 Introduction 114
5.1.1 Motivation 114
5.1.2 Existing Literature and Research Gap 115
5.1.3 Key Aspects of Proposed Approach 119
5.2 Analysis of Small-Signal Models in Dynamic Harmonic Domain 120
5.3 Small-Signal Stability Augmentation 124
5.3.1 Motivation and Basic Idea 124
5.3.2 Design Philosophy 126
5.4 Simulation and Real Time Validation Results 132
5.5 Conclusion and Future Directions 136

6 Robust Backstepping Controller for Improved Transient Response of Inverters 138
6.1 Introduction 138
6.2 Proposed Control Strategy 140
6.2.1 Dynamic Model of Standalone/Islanded VSC System 140
6.2.2 Overview of Backstepping Control 141
6.2.3 Synthesis of Control Law Using Backstepping 142
6.2.4 Robustness Against Parameter Variations 146
6.2.5 Modification in proposed controller for unbalanced loads 147
6.2.6 Backstepping control design in natural reference frame 148
6.3 Simulation Studies and Discussions 149

6.3.1 Improvement Over Wind-up Phenomenon 151
6.3.2 Robustness Analysis 153
6.3.3 Transient and Steady-state Response 156
6.3.4 Harmonic and Unbalanced Load Scenarios 159
6.3.5 Voltage Set-point Variation 160
6.4 Experimental Validation 163
6.5 Conclusion 167

7 Conclusion and Future Scope **168**
7.1 Summary of the Thesis 168
7.2 Future Scope 168

List of Publications **179**

Biodata **180**

List of Figures

1.1 Hierarchical control of inverter interfaces 3

2.1 Natural abc, Stationary $\alpha\beta$ and rotating dq reference frames 20
2.2 Conventional SRF-PLL's response to unbalanced input 21
2.3 Small-signal model of conventional SRF-PLL considering balanced voltage inputs 23
2.4 Single Synchronous Reference Frame PLL: dq output measurements are passed through notch-filter 24
2.5 Single Synchronous Reference Frame PLL: Embedded in-loop notch filter 25
2.6 Stability analysis of LTP system 30
2.7 Stability assessment of LTP model of SRF-PLL 32
2.8 $\Phi(t, 0)$ matrices for stable versus unstable case 32
2.9 Decoupled double synchronous reference frame conversion of abc-domain signal, and synchronization by PLL 33
2.10 Stability behaviors of DDSRF-PLL and its linearized small-signal model 40
2.11 Regions of Stability of DDSRF-PLL 41
2.12 Experimental verification of stability behaviors 43
2.13 Small-signal instability or loss of synchronism in DDSRF-PLL due to input voltage's fundamental frequency variations 44
2.14 Modal analysis of DDSRF-PLL 46
2.15 Amplitude normalization scheme for DDSRF-PLL and its implications 48

2.16 Impact of harmonic distortion in input signal to DDSRF-PLL 52
2.17 Eigenvalues derived from HTF, compared with the Floquet exponents 54

3.1 Proposed structure of 1-ph PLL using recursive least squares and covariance resetting based adaptive estimation 61
3.2 Proposed structure of 3-ph PLL using recursive least squares and covariance resetting based adaptive estimation 69
3.3 Approximate small signal model of RLS-PLL 71
3.4 Frequency domain response of approximate small signal model of proposed PLL . 73
3.5 Extraction of v_d and v_q by proposed method from signal contaminated with third and fifth harmonic and noise 74
3.6 Impact of $\mathbf{\Gamma}$ on the performance of estimation 74
3.7 Trade-off in noise+harmonic tolerance vs. speed of response in existing PLL structures 76
3.8 Significance of Resetting $\mathbf{\Gamma}$ based on $t > t_r$ condition 76
3.9 Performance comparison of modification in proposed method with SOGI-PLL, when signal contains DC offset 76
3.10 Extraction of positive and negative sequence dq axes components from distorted unbalanced 3-ph signal 77
3.11 Experimental setup for real-time performance validation of proposed method . . . 77
3.12 Discrete time realization concept of recursive least square estimation 78
3.13 Recursive half-cycle RMS computation 79
3.14 Discrete time realization of proposed signal transformation and grid synchronization schemes 80
3.15 Steady-state and transient estimation of amplitude and phase angle by proposed RLS-PLL and conventinal SOGI-PLL 82
3.16 Steady-state amplitude estimation of harmonic distorted signal, by RLS-PLL and SOGI-PLL 82

3.17 Tracking step change in amplitude of harmonic distorted signal, by proposed RLS-PLL and SOGI-PLL 82
3.18 Phase jump test of proposed RLS-PLL, comparison with SOGI-PLL 82
3.19 Fundamental frequency ramp test of RLS-PLL, comparison with SOGI-PLL 83
3.20 Performance of proposed RLS-PLL compared with SOGI-PLL for flicker event . . 83
3.21 Phase bump for signal with disturbances 84
3.22 Frequency bump for signal with disturbances 84

4.1 Standalone inverter feeding distribution loads with conventional control structure . 88
4.2 Impact of unbalanced loading of an inverter with conventional PI control in single synchronous reference frame 90
4.3 DDSRF control scheme 91
4.4 Performance of DDSRF controlled DG 92
4.5 DDSRF components of output voltages and currents of the DDSRF controlled DG 92
4.6 Performance comparison of inverter's control in single vs. decoupled double synchronous reference frame 94
4.7 A generic isolated inverter interface 95
4.8 Proposed small-signal LTP model schematic 95
4.9 Overall LTP state-space of isolated, DDSRF controlled inverter serving unbalanced load(s) 95
4.10 Impact of bandwidth of filter used in DDSRF transformation on the stability of islanded inverter: validation by simulation 98
4.11 Impact of bandwidth of filter used in DDSRF transformation on the stability of islanded inverter: experimental validation 98
4.12 Two inverters sharing an unbalanced load 99
4.13 Issue with sharing of unbalanced loads by parallel inverters in presence of output impedance mismatch $\left(\frac{Z_1}{Z_2} = 1.5\right)$ 102

4.14 Impact on voltage unbalance factors of two DGs due to undesired sharing of unbalanced load . . . 102
4.15 Impact on per phase real power sharing with increase in load current unbalance factor for various Z_1/Z_2 ratios . . . 103
4.16 Voltage quality and power sharing performance of DDSRF controlled DGs ($Z_1/Z_2 = 1.5$) . . . 104
4.17 Decoupled double synchronous reference frame conversion of abc-domain signal, and synchronization by PLL . . . 105
4.18 Time-domain linearized state-space models of unbalanced grid interfaced inverter . 110
4.19 A generic Master-Slave controlled inverter interfaced microgrid . . . 112
4.20 Small-signal LTP model of Master-Slave controlled inverter interfaced microgrid . 112

5.1 Stability assessment of DDSRF-PLL . . . 124
5.2 Small-signal stability boundaries depend on grid impedance, the voltage level and voltage unbalance factor . . . 125
5.3 Basic Idea of Stability Augmentation . . . 127
5.4 Eigenvalue and Nyquist plots of open-loop plant $\mathcal{H}(s)$ . . . 129
5.5 Stability augmentation of otherwise unstable $\mathcal{H}(s)$ . . . 131
5.6 Robustness of proposed augmentation scheme in terms of Up/Down-ward Gain Margins (GM) (in dB) and Phase Margin (PM) (in degree) . . . 131
5.7 Enhancement of small-signal stability boundaries by proposed method . . . 131
5.8 System used for simulation . . . 132
5.9 Simulation case 1: Sustained B-C fault at F_2 . . . 133
5.10 Simulation case 2: Balanced 3-ph fault at F_1 and parallel line outage . . . 133
5.11 Simulation case 3: Weak and unbalanced grid operation . . . 134
5.12 Weak grid stabilization by proposed augmentation . . . 135
5.13 Enhancement of real-power injection capability with proposed stability augmentation in place . . . 135

5.14 Dynamic performance improvement with proposed method, for step change in real power injection . . . 135
5.15 Ride-through operation of inverter (without reactive power support) for sustained unbalanced (B-C) fault . . . 136

6.1 Voltage Sourced Converter Feeding Unknown Load Dynamics . . . 140
6.2 Simulation Results of VSC Response with Proposed Control Law for Load Variation and Set-point Change . . . 151
6.3 Poorer transient response with use of anti-windup in integrator of conventional PI regulator based current-limiting control of inverter . . . 152
6.4 Mitigating wind-up phenomenon with backstepping control design . . . 153
6.5 Eigenvalue analysis of closed-loop VSC system . . . 155
6.6 Loci of eigenvalues for different loading scenarios . . . 155
6.7 Robustness of proposed controller w.r.t. the variation of filter parameters . . . 156
6.8 Comparison of set-point $v^*_{od,q}$ tracking by proposed controller with PI based controller 157
6.9 Trajectory of eigenvalues for different α gains . . . 158
6.10 Output voltage and current waveforms for unbalanced and harmonic loads . . . 160
6.11 Hierarchically controlled microgrid consisting of two VSC based DGs serving common load . . . 161
6.12 Load dependent voltage set-point variation and its regulation by proposed voltage controller . . . 162
6.13 Experimental set-up for evaluating proposed control scheme (Rapid Control Prototyping Framework) . . . 164
6.14 Three phase output voltages of VSC in presence of load variations . . . 165
6.15 Robustness towards change in filter inductance and load variations . . . 166
6.16 Voltage Set-point change . . . 166
6.17 Robustness of proposed controller for DC voltage variation . . . 167

6.18 Performance of proposed controller under non-linear loading scenario: (a) A-ph voltage waveform (b) THD and magnitude spectrum of voltage (c) A-ph current waveform (d) THD and magnitude spectrum of current 167

List of Tables

2.1 Parameter ranges considered for obtaining 3-D surface plots of stability boundaries of DDSRF-PLL 39
2.2 Periodic modes in a stable DDSRF-PLL 45
2.3 Comparison of Floquet Theory based LTP System Analysis Method with Harmonic Domain Methods 54

3.1 Comparison of computational burden of proposed method with existing PLL schemes 77
3.2 Parameters of RLS-PLL designed for experimental validation 81

4.1 Steady-state operating point of system of two inverters in parallel sharing unbalanced load 102

5.1 Participation factors of unstable eigenvalues 129

6.1 Parameters for simulation and experimental tests 150

Nomenclature

Acronyms/Abbreviations

AC Alternating Current

BIBO Bounded Input, Bounded Output

BW Bandwidth

DC Direct Current

DDSRF Decoupled Double Synchronous Reference Frame

EPLL Enhanced Phase Locked-Loop

FFT Fast Fourier Transform

GUUB Globally Uniformly Ultimately Bounded

HIL Hardware-in-Loop

HSS Harmonic State-Space

HTF Harmonic Transfer Function

IGBT Insulated Gate Bipolar Transistor

LPF Low-Pass Filter

LTI Linear Time-Invariant

LTP Linear Time-Periodic

LVRT Low Voltage Ride-Through

MATLAB *MATrix LABoratory*

NF Notch Filter

OSG Orthogonal Signal Generator

P.D. Positive Definite

PI Proportional and Integral

PLL Phase Locked-Loop

PM Phase Margin

PR Proportional and Resonant

RLS Recursive Least Squares

RMS Root Mean Square

SOGI Second Order Generalized Integrator

SRF Synchronous Reference Frame

THD Total Harmonic Distortion

VCO Voltage-controlled Oscillator

VSC Voltage Sourced Converter

VUF Voltage Unbalance Factor

List of Suffixes/Superscripts

$(\cdot)^{+}$ Positive sequence quantity/vector

$(\cdot)^{-}$ Negative sequence quantity/vector

$(\cdot)^{\star}$ Reference value of a quantity/vector

$(\cdot)_{\text{max}}$ Maximum value

$(\cdot)_{\text{min}}$ Minimum value

$(\cdot)_{\text{ref}}$ Reference value of a quantity/vector

$(\cdot)_{\text{RMS}}$ Root mean square value

$(\cdot)_{\alpha\beta}$ Signal in stationary $\alpha\beta$ reference frame

$(\cdot)_{\text{ss}}$ Steady-state value

$(\cdot)_{abc}$ Signal in natural abc reference frame

$(\cdot)_{dq}$ Signal in rotating dq reference frame

List of Symbols

$0_{m\times n}$ Null matrix of size $m \times n$

$\mathbb{C}$ Set of complex numbers

$\mathbb{R}$ Set of real numbers

$\mathbb{Z}$ Set of integers

ω_n Nominal angular frequency (rad/s)

I_n Identity matrix of size $n \times n$

K_i Integral gain

K_p Proportional gain