STABILITY ASSESSMENT OF INVERTER-BASED RESOURCES INTEGRATED POWER GRIDS

DIPTAK PAL

DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI
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STABILITY ASSESSMENT OF INVERTER-BASED RESOURCES INTEGRATED POWER GRIDS

by

DIPTAK PAL

Department of Electrical Engineering

Submitted

in fulfilment of the requirements of the degree of Doctor of Philosophy

to the

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Dedicated to My Parents

CERTIFICATE

This is to certify that the thesis entitled **‘STABILITY ASSESSMENT OF INVERTER-BASED RESOURCES INTEGRATED POWER GRIDS’**, being submitted by **Mr. Diptak Pal** 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.

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Diptak Pal

— Diptak Pal

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Abstract

The interconnection standards have made it mandatory for the utility-scale inverter-based resources (IBRs) to comply with the low-voltage ride-through (LVRT) requirement. Additionally, the IBRs have been instructed to provide dynamic reactive power support and enable active power curtailment provision during low-voltage and over-frequency events, respectively. However, the instability issues associated with the IBRs integrated power grids arising due to unintentional islanding and grid-induced voltage sag events are mostly overlooked. To address these issues, the work in this thesis presents a comprehensive assessment of the stability issues associated with IBRs integrated power grids. First, the conflicting interaction between the P(f) and Q(V) regulations of IBRs leading to oscillatory instability in power islands has been investigated analytically using the small-signal stability analysis technique. This is a significant contribution to the prior art where the analysis has only been carried out with the help of non-detection zones of IBRs. Following this, the small-signal stability analysis of a full-order model of IBR interconnected to weak grids has been performed under varying set-points of real and reactive power as well as under reduced grid voltage. A supplementary stabilizing controller has been designed for the IBRs to enhance their small-signal stability margin under weak grids and reduced grid voltage scenario. Next, the large-signal/transient stability of grid-tied inverters has been assessed extensively. An equivalent-circuit model of a three-phase grid-tied inverter has been developed and leveraged to assess the large-signal stability considering its full-order averaged dynamics. Following this, reduced-order models have been developed and innovative approaches have been applied for assessing the large-signal stability of multiple grid-following (GFL) inverters having the same and different points of synchronization. Finally, the conflicting requirement between the stringent LVRT standards and transient stability boundary of GFL and grid-forming (GFM) inverters has also been investigated by leveraging Lyapunovs direct method. The work in this thesis may provide some reference for the revision of interconnection standards/grid codes in the future where the small-signal, as well as large-signal stability issues will be taken into account.

The major highlights of the work are summarized as follows:
(1) The cause for sustained oscillations arising in active distribution networks following unintentional islanding has been investigated using eigenvalue analysis and non-detection zones.
(2) Small-signal stability analysis of weak grid-tied IBRs has been performed and auxiliary stabilizing controller has been designed for enhancing the stability margin.
(3) Large-signal stability assessment of IBRs integrated power grids has been performed leveraging Lyapunov's direct method.

Key Words: Inverter-based Resources, Lyapunov's Method, Small-signal Stability, Transient Synchronization Stability, Weak Grids.

सारांश

इंटरकनेक्शन मानकों ने यूटिलिटी-स्केल इन्वर्टर-आधारित संसाधनों (आईबीआर) के लिए लो-वोल्टेज राइड-थ्रू (एलवीआरटी) आवश्यकता का अनुपालन करना अनिवार्य बना दिया गया है। इसके अतिरिक्त, आईबीआर को क्रमशः कम वोल्टेज और अधिक आवृत्ति की घटनाओं के दौरान गतिशील प्रतिक्रियाशील शक्ति समर्थन प्रदान करने और सक्रिय बिजली कटौती प्रावधान को सक्षम करने का निर्देश दिया गया है। हालांकि, अनजाने में आईलैंडिंग और ग्रिड-प्रेरित वोल्टेज शिथिलता की घटनाओं के कारण उत्पन्न होने वाले आईबीआर एकीकृत पावर ग्रिड से जुड़े अस्थिरता के मुद्दों को ज्यादातर नजरअंदाज कर दिया जाता है। इन मुद्दों को हल करने के लिए, इस प्रबंध में आईबीआर एकीकृत पावर ग्रिड से जुड़े स्थिरता मुद्दों का व्यापक मूल्यांकन प्रस्तुत किया जा रहा है। सबसे पहले, आईबीआर के पी (एफ) और क्यू (वी) नियमों के बीच परस्पर विरोधी क्रिया से बिजली द्वीपों में दोलन अस्थिरता पैदा होती है, जिसकी विश्लेषणात्मक रूप से छोटे-संकेत स्थिरता विश्लेषण तकनीक का उपयोग करके जांच की गई है।यह इस क्षेत्र में एक महत्वपूर्ण योगदान है, जहां विश्लेषण केवल आईबीआर के गैर-पहचान क्षेत्रों की सहायता से किया गया है। इसके बाद, कमजोर ग्रिड से जुड़े आईबीआर के एक सम्पूर्ण विस्तृत मॉडल का लघु-संकेत स्थिरता विश्लेषण वास्तविक और प्रतिक्रियाशील शक्ति के साथ-साथ कम ग्रिड वोल्टेज के अलग-अलग सेट-पॉइंट के तहत किया गया है। कमजोर ग्रिड और कम ग्रिड वोल्टेज परिदृश्य के तहत अपने छोटे-सिग्नल स्थिरता मार्जिन को बढ़ाने के लिए आईबीआर के लिए एक पूरक स्थिरीकरण नियंत्रक तैयार किया गया है। इसके बाद, ग्रिड-बंधे इनवर्टर के बड़े-सिग्नल/क्षणिक स्थिरता का बड़े पैमाने पर मूल्यांकन किया गया है। तीन-फेज ग्रिड-बंधे इन्वर्टर का एक समकक्ष-सर्किट मॉडल विकसित किया गया है और इसकी विस्तृत औसत गतिशीलता को देखते हुए बड़े-सिग्नल स्थिरता का आकलन करने के लिए उपयोग किया गया है। इसके बाद, कम-क्रम वाले मॉडल विकसित किए गए हैं और तादात्म्य के समान और विभिन्न बिंदुओं वाले असंख्य ग्रिड-फॉलोइंग (जीएफएल) इनवर्टर के बड़े-सिग्नल स्थिरता का आकलन करने के लिए नए दृष्टिकोण लागू किए गए हैं। अंत में, कड़े लो-वोल्टेज राइड-थ्रू मानकों और ग्रिड-अनुसरित और ग्रिड बनाने वाले इनवर्टर की क्षणिक स्थिरता सीमा के बीच परस्पर विरोधी आवश्यकता की भी ल्यापुनोव की प्रत्यक्ष विधि का लाभ उठाकर जांच की गई है। यह प्रबंध कार्य भविष्य में इंटरकनेक्शन मानकों/ग्रिड कोड के संशोधन के लिए कुछ संदर्भ प्रदान कर सकता है जहां छोटे सिग्नल, साथ ही साथ बड़े सिग्नल स्थिरता मुद्दों को ध्यान में रखा जाएगा।

कार्य के प्रमुख अंश संक्षेप में इस प्रकार हैं:

(१) अनजाने में आईलैंडिंग के बाद सक्रिय वितरण नेटवर्क में उत्पन्न होने वाले निरंतर दोलनों के कारणों की जांच आइजेनवेल्यू विश्लेषण और गैर-पहचान क्षेत्रों का उपयोग करके की गई है।

(२) कमजोर ग्रिड-बंधे आईबीआर का लघु-संकेत स्थिरता विश्लेषण किया गया है और स्थिरता मार्जिन को बढ़ाने के लिए सहायक स्थिरीकरण नियंत्रक को डिजाइन किया गया है।

(३) इनवर्टर-आधारित संसाधनों के एकीकृत पावर ग्रिड के बड़े-सिग्नल स्थिरता मूल्यांकन को ल्यापुनोव की प्रत्यक्ष विधि का लाभ उठाते हुए किया गया है।

मुख्य शब्द: इन्वर्टर-आधारित संसाधन, ल्यापुनोव की विधि, लघु-संकेत स्थिरता, क्षणिक तुल्यकालन स्थिरता, कमजोर ग्रिड।

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Nomenclature

Acronyms/Abbreviations

AVC	AC-bus Voltage Control
CC	Current Control
CCT	Critical Clearing Time
CHIL	Controller-hardware-in-the Loop
CIL	Constant Impedance Load
d-q	direct-quadrature
DAE	Differential-algebraic Equation
DVC	DC-bus Voltage Control
GFL	Grid-following
GFM	Grid-forming
HIL	Hardware-in-the-loop
IBRs	Inverter-based Resources
IEEE	Institute of Electrical and Electronics Engineers

LOS	Loss of Synchronism
LVRT	Low Voltage Ride-through
MATLAB	MATrix LABoratory
NASC	Nonlinear Adaptive Stabilizing Control
NDZ	Non-detection zone
PC	Power controller
PCC	Point of Common Coupling
PI	Proportional-integral
PLL	Phase-locked Loop
POS	Point of Synchronization
PSCAD	Power Systems Computer Aided Design
RMS	Root Mean Square
ROM	Reduced-order Model
SCR	Short Circuit Ratio
SRF	Synchronous Reference Frame
VC	Voltage Control
VSC	Voltage Source Converter

List of Suffixes/Superscripts

$(\cdot)_i$	Denotes variable for i^{th} IBR

$(\cdot)_{DQ}$	Variables in global frame of reference
$(\cdot)_{dq}$	Variables in local frame of reference

List of Symbols

Δf	Frequency deviation from 50.2 Hz ($f - 50.2$).
ΔP	Active power mismatch at the PCC
ΔQ	Reactive power mismatch at the PCC
δ	Angle between the global and local frame of reference
δ^s	Post-fault stable equilibrium point
δ^u	Post-fault unstable equilibrium point
γ_1	Learning rate
γ_2	Learning rate
γ_{avc}	State of AVC
γ_{dq}	States of the current controller in d-q frame of reference
γ_{dvc}	State of DVC
γ_{pll}	State of PLL
ω	Angular frequency estimated by PLL (rad/s)
ω_c	Cut-off frequency of the low-pass filter of PLL
ω_g	Angular frequency of the grid (rad/s)
ω_n	Nominal angular frequency (rad/s)

ω_p	Cut-off frequency of the low pass filters present in the active power control loop
ω_q	Cut-off frequency of the low pass filters present in the reactive power control loop
ϕ	Intermediate state of the PLL
Ψ	Power factor angle
σ_1	Damping co-efficient
σ_2	Damping co-efficient
τ	Time constant of the power controller
τ_{dc}	Time constant of the dc-bus capacitor
$\mathbf{A}$	State matrix
$\mathbf{B}$	Input matrix
θ	Phase angle estimated by PLL/PC
θ_g	Phase angle of the grid
ζ	Damping ration of the PLL
BW_{Hz}	Bandwidth of the PLL
C	Capacitance of the local load
C_{dc}	DC-bus capacitance
E	Terminal voltage of the GFM inverter
E_{ref}	Reference terminal voltage of the GFM inverter
f_{op}	Operating frequency of the system

f_{res}	Resonating frequency of the parallel RLC load
$G_{pll}(s)$	Transfer function of PLL
G_{PQ}	Gain of the power controller
$i^{\star}_{dc}$	Input current to the dc-bus capacitor
$i^{\star}_{dq}$	Reference set-points to the current controller from outer control loops
I_d	Steady-state value of the d-axis output current
I_m	Short term current carrying capability of the IBR
I_q	Steady-state value of the q-axis output current
i_{dc}	Output current from the dc-bus capacitor
i_{dqg}	Grid-side current d-q frame of reference
I_{dqref}	Constant current reference set-points to the current controller
i_{dq}	Output current of the IBR in d-q frame of reference
k^i_{avc}	Integral gain of the ac-bus voltage controller
k^i_{cc}	Integral gain of the current controller
k^i_{dvc}	Integral gain of the dc-bus voltage controller
k^i_{pll}	Integral gain of the PLL
k^p_{avc}	Proportional gain of the ac-bus voltage controller
k^p_{cc}	Proportional gain of the current controller
k^p_{dvc}	Proportional gain of the dc-bus voltage controller

k_{pll}^{p}	Proportional gain of the PLL
K_1	Feedback stabilizing gain
K_2	Feedback stabilizing gain
K_3	Feedback stabilizing gain
k_p	Active power droop gain
k_q	Reactive power droop gain
L	Inductance of the local load
L_f	Filter inductance
L_g	Reactance of the grid
P	Instantaneous active power output of IBR
$P(f)$	Real power regulation as a function of frequency
$P_{dc}^{\star}$	Input power to the dc-bus capacitor
P_G	Active power generation
P_L	Active power consumed by the load
P_n	Nominal base Power
P_{dc}	Output power from the dc-bus capacitor
P_{IBR}	Rated power of the IBR
P_{ref}	Active power reference to the IBR
P_{sat}	Active power output when saturation is activated for GFM IBR

Q	Instantaneous reactive power output of IBR
$Q(V)$	Reactive power regulation with change in voltage
Q_f	Quality factor of the parallel RLC load
Q_G	Reactive power generation
Q_L	Reactive power consumed by the load
Q_{ref}	Reactive power reference to the IBR
Q_{sat}	Reactive power output when saturation is activated for GFM IBR
R	Resistance of the local load
R_f	Filter resistance
R_g	Resistance of the grid
$T(\delta)$	Frame transformation matrix
t_s	Settling time of PLL
T_{cl}	Fault clearing time
T_{cr}	Critical clearing time
V	Operating RMS PCC voltage
$v_{dc}^{\star}$	Reference set-point of DVC
v^{pos}	Point of synchronization voltage
v_g	Instantaneous grid voltage
V_n	Nominal RMS PCC voltage

v_{ac}	PCC voltage
v_{dc}	DC-bus voltage
v_{dqg}	Voltage of the grid in d-q frame of reference
v_{dqt}	Terminal voltage of the IBR in d-q frame of reference
v_{dq}	PCC voltage in d-q frame of reference
P(θ)	Park's transformation matrix