

# STABILITY ANALYSIS AND CONTROL OF INVERTER BASED DISTRIBUTED GENERATION IN STANDALONE POWER NETWORK

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DEPARTMENT OF ELECTRICAL ENGINEERING  
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# STABILITY ANALYSIS AND CONTROL OF INVERTER BASED DISTRIBUTED GENERATION IN STANDALONE POWER NETWORK

by

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DEPARTMENT OF ELECTRICAL ENGINEERING

Submitted

in fulfillment of the requirements of the degree of Doctor of Philosophy  
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Dedicated to

*My Ammi, Daddy & Saquib*

# Certificate

This is to certify that the dissertation entitled “**STABILITY ANALYSIS AND CONTROL OF INVERTER BASED DISTRIBUTED GENERATION IN STANDALONE POWER NETWORK**” being submitted by **Ayesha Firdaus** to the Department of Electrical Engineering, Indian Institute of Technology Delhi for the award of the degree of **Doctor of Philosophy** is the record of the bonafide research work carried out by her under my supervision. In my opinion, the thesis has reached the standards fulfilling the requirements of the regulations relating to the degree. The results contained in this thesis have not been submitted either in part or in full to any other university or institute for the award of any degree or diploma.

.....

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# Abstract

The focus of the thesis is on control of frequency and active power sharing in converter dominated standalone power systems. This thesis aims to present stability analysis of inverter based microgrids, development of control schemes that can achieve better stability, active power sharing and other benefits like ease of analysis and implementation.

For inverter dominated microgrids, there are different levels of hierarchical control for achieving desired operation. One of the key requirement of microgrid operation is the accurate power sharing among the various sources which is implemented using primary level of control based on droop philosophy. Droop control suffers from lower stability margins specially in inverter dominated system. This thesis presents stability analysis and control design for microgrids operating in droop control mode with focus on the low frequency oscillations (LFOs) arising due to the droop control.

The work starts with designing a power system stabilizer (PSS) for stability improvement of a droop-controlled inverter-based autonomous microgrid. The stabilizer is designed as a lead compensator to nullify the lag associated with the droop controller of grid forming inverters. The proposed stabilizer provides sufficient damping to the LFO even at higher value of droop gains which are usually unstable otherwise. The PSS designed in this thesis is a generalized one and a step-by-step method to select the PSS parameters is also presented in this thesis.

This thesis then proposes a modified decentralised droop controller for inverter-based autonomous photovoltaics (PV) microgrids which offers three key benefits, i.e. improves active power sharing, enhances system stability, and performs the secondary control action by nullifying the frequency deviation by using only one auxiliary signal in the control loop. The proposed controller modifies the conventional droop mechanism

in transient as well as in steady state by adding an auxiliary control signal in the power control loop of the inverters. With the proposed modification, frequency is restored within 1.8 sec from the instant of load change and 75% increase in damping ratio in LFO is achieved.

This thesis also proposes a new modelling approach for studying LFOs in a droop controlled autonomous microgrid. A transfer function based closed loop small signal model of inverter-based autonomous microgrid is developed to study power sharing among the various inverters. This model uses the concept of dynamic power flow through network to find the power output of each source following load perturbations in a system. The proposed approach helps to reduce computation time and complexity with acceptable accuracy. The computation time reduces to 7 seconds from 9 minutes with the proposed modelling approach.

Following this, an application of impedance based modelling approach to identify suitable locations for design and expansion of an inverter-based autonomous AC microgrid is presented. The objective is to find out ideal location for placement of additional components which can include new inverter-based sources, microgrid damping controller, etc., ensuring sufficient stability margins. These objectives are achieved by first identifying the weakest and the strongest nodes in the system with respect to the system stability and then observing the effects of choosing various nodes for design and expansion on overall system stability. With the given approach, stability of the system can be enhanced in terms of damping ratios with the placement of new stabilizer, new grid forming inverter and new grid following inverter, from 0.47% to 29.26%, 10.3% to 29.3% and 1.1% to 9.9% respectively.

Finally, in order to improve the performance of microgrid which consists of both static and rotating sources, this thesis presents a performance comparison of different droop schemes in AC microgrids where both rotating machine-based source (diesel engine generator) and static inverter-based sources are present. Choice of appropriate scheme for droop control by evaluating transient performance is suggested keeping the system stability in view so that a sustainable operation of the microgrid is obtained without losing its stability.

## सार

इस शोध प्रबंध का ध्यान कनवर्टर आधारित पृथक विद्युत प्रणाली में आवृत्ति और सक्रिय शक्ति साझाकरण के नियंत्रण पर है। इस थीसिस का उद्देश्य इन्वर्टर आधारित माइक्रोग्रिड्स की स्थिरता विश्लेषण प्रस्तुत करना, नियंत्रण योजनाओं का विकास है जो बेहतर स्थिरता और सक्रिय शक्ति साझाकरण प्राप्त कर सकती है और विश्लेषण और कार्यान्वयन में आसानी जैसे अन्य लाभ भी प्रदान करती है।

इन्वर्टर वर्चस्व वाले माइक्रोग्रिड्स के लिए, वांछित ऑपरेशन को प्राप्त करने के लिए विभिन्न स्तर के पदानुक्रमित नियंत्रण हैं। माइक्रोग्रिड ऑपरेशन की एक प्रमुख आवश्यकता विभिन्न स्रोतों के बीच सटीक बिजली साझाकरण है जो ड्रूप शास्र के आधार पर प्राथमिक स्तर के नियंत्रण का उपयोग करके कार्यान्वित की जाती है। ड्रूप नियंत्रण खासतौर पर इन्वर्टर वर्चस्व प्रणाली में कम स्थिरता सीमा से ग्रस्त है। यह थीसिस ड्रूप नियंत्रण के कारण उत्पन्न होने वाली कम आवृत्ति दोलनों (एलएफओ) पर ध्यान केंद्रित करने के साथ ड्रूप नियंत्रण मोड में काम कर रहे माइक्रोग्रिड्स के लिए स्थिरता विश्लेषण और नियंत्रण डिजाइन प्रस्तुत करता है।

यह काम एक बिजली प्रणाली स्थायीकारक (पीएसएस) को एक ड्रूप-नियंत्रित इन्वर्टर-आधारित स्वायत्त माइक्रोग्रिड्स के स्थायित्व में सुधार के लिए डिजाइन करने से शुरू होता है। स्थायीकारक को लीड कम्पेन्सेटर के रूप में डिजाइन किया गया है जो ग्रिड के इन्वर्टर के ड्रूप नियंत्रक से जुड़े अंतराल को कम करने के लिए है। प्रस्तावित स्थायीकारक एलएफओ को पर्याप्त लाभ प्रदान करता है यहां तक कि ड्रूप गुणक के उच्च मूल्य पर भी जो आमतौर पर अस्थिर होते हैं। इस थीसिस में डिजाइन किया गया पीएसएस एक सामान्यीकृत है और पीएसएस के मापदंडों का चयन करने के लिए एक चरण-दर-चरण विधि भी इस थीसिस में प्रस्तुत की गई है।

इसके बाद, यह थीसिस इन्वर्टर-आधारित स्वायत्त फोटोवोल्टिक (पीवी) माइक्रोग्रिड के लिए एक संशोधित विकेन्द्रीकृत ड्रूप नियंत्रक का प्रस्ताव करता है जो तीन प्रमुख लाभ प्रदान करता है, यानी सक्रिय शक्ति साझाकरण में सुधार करता है, सिस्टम स्थिरता को बढ़ाता है, और नियंत्रण पाश में केवल एक सहायक संकेत का उपयोग करके आवृत्ति विचलन को कम करने के लिए द्वितीयक नियंत्रण क्रिया करता

है। प्रस्तावित नियंत्रक इनवर्टर के शक्ति नियंत्रण लूप में एक सहायक नियंत्रण संकेत जोड़कर क्षणिक और साथ ही स्थिर अवस्था में पारंपरिक ड्रूप तंत्र को संशोधित करता है। प्रस्तावित संशोधन के साथ, लोड परिवर्तन के तत्काल से 1.8 सेकंड के भीतर आवृत्ति बहाल हो जाती है और एलएफओ में लाभ अनुपात में 75% की वृद्धि हासिल की जाती है।

इस थीसिस ने ड्रूप नियंत्रित स्वायत्त माइक्रोग्रिड में एलएफओ के अध्ययन के लिए एक नए मॉडलिंग दृष्टिकोण का भी प्रस्ताव किया है। इन्वर्टर आधारित स्वायत्त माइक्रोग्रिड का ट्रांसफर फंक्शन आधारित बंद लूप छोटा सिग्नल मॉडल विभिन्न इन्वर्टर के बीच शक्ति साझाकरण का अध्ययन करने के लिए विकसित किया गया है। यह मॉडल प्रणाली में लोड बदलाव के बाद प्रत्येक स्रोत के बिजली उत्पादन को खोजने के लिए नेटवर्क के माध्यम से गतिशील शक्ति प्रवाह की अवधारणा का उपयोग करता है। प्रस्तावित दृष्टिकोण स्वीकार्य सटीकता के साथ गणना समय और जटिलता को कम करने में मदद करता है। प्रस्तावित मॉडलिंग दृष्टिकोण के साथ गणना का समय 9 मिनट से कम होकर 7 सेकंड हो जाता है।

इसके बाद, इन्वर्टर आधारित स्वायत्त एसी माइक्रोग्रिड के डिजाइन और विस्तार के लिए उपयुक्त स्थानों की पहचान करने के लिए प्रतिबाधा आधारित मॉडलिंग दृष्टिकोण का एक प्रयोग प्रस्तुत किया गया है। इसका उद्देश्य पर्याप्त स्थिरता गुंजाइश सुनिश्चित करते हुए अतिरिक्त घटकों की नियुक्ति के लिए आदर्श स्थान का पता लगाना है जिसमें नए इन्वर्टर-आधारित स्रोत, माइक्रोग्रिड अवमन्दक नियंत्रक आदि शामिल हो सकते हैं। ये उद्देश्य पहले प्रणाली स्थिरता के संबंध में सबसे कमजोर और सबसे मजबूत नोड्स की पहचान करके प्राप्त किए जाते हैं और फिर समग्र प्रणाली स्थिरता पर डिजाइन और विस्तार के लिए विभिन्न नोड्स चुनने के प्रभावों का अवलोकन करते हैं। दिए गए दृष्टिकोण के साथ, नए स्थायीकारक, नए ग्रिड बनाने वाले इन्वर्टर और नए ग्रिड अनुसरण करने वाले इन्वर्टर के स्थानन के साथ प्रणाली की स्थिरता को लाभ अनुपात के मामले में क्रमशः 0.47% से 29.26%, 10.3% से 29.3% और 1.1% से 9.9% तक बढ़ाया जा सकता है।

अंत में, माइक्रोग्रिड जिसमें स्थैतिक और घूर्णन दोनों स्रोत शामिल हैं के प्रदर्शन को बेहतर बनाने के लिए, यह थीसिस एसी माइक्रोग्रिड्स में अलग-अलग ड्रूप योजनाओं की तुलना में प्रदर्शन प्रस्तुत करती है जहां दोनों घूर्णन मशीन-आधारित स्रोत (डीजल इंजन उत्पादन-यन्त्र) और स्थैतिक इन्वर्टर-आधारित स्रोत मौजूद हैं। क्षणिक प्रदर्शन का मूल्यांकन करके ड्रूप नियंत्रण के लिए उपयुक्त योजना का विकल्प प्रणाली स्थिरता को ध्यान में रखते हुए सुझाया गया है ताकि माइक्रोग्रिड का एक स्थायी संचालन इसकी स्थिरता को खोए बिना प्राप्त हो।

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# Abbreviations

DG	Distributed generation
DER	Distributed energy resources
DEG	Diesel engine generator
RES	Renewable energy sources
WT	Wind turbine
PV	Photovoltaic
MT	Microturbine
FC	Fuel Cell
MG	Microgrid
ESS	Energy storage system
VSI	Voltage source inverter
LFO	Low frequency oscillation
PSS	Power system stabilizer
PI	Proportional integral
RT	Real time
PWM	Pulse width modulation
IVT	Initial value theorem
FVT	Final value theorem
MPPT	Maximum power point tracking
AGC	Automatic generation control

DPF	Dynamic power flow
MOR	Model order reduction
GNC	Generalized nyquist criterion
CPL	Constant power load
PLL	Phase locked loop
PCC	Point of common coupling
PSO	Particle swarm optimization

# Nomenclature

$\omega$	Operating frequency of DG
$\omega_n$	Nominal frequency set point of DG
$\omega_c$	Cut-off frequency of low pass filter
$\theta$	Reference phase
$F$	Feed-forward gain of voltage controller
$m, n$	Active and reactive power droop coefficients
$V_n$	Nominal d-axis voltage set point of DG
$v_{cd}, v_{cq}$	d-q components of output voltage of inverter
$v_{id}, v_{iq}$	d-q components of inverter voltage
$v_{id}^*, v_{iq}^*$	d-q components of reference voltage of inverter
$p, q$	Instantaneous value of active and reactive power
$P, Q$	Average value of active and reactive power
$\delta$	Difference of angle between the individual reference reference frame and common reference frame
$v_{cd}^*, v_{cq}^*$	d-q components of reference output voltage of inverter
$i_{ld}^*, i_{lq}^*$	d-q components of reference coupling inductor current of inverter
$i_{od}, i_{oq}$	d-q components of output current of inverter
$i_{ld}, i_{lq}$	d-q components of inductor coupling current
$K_{pv}, K_{iv}$	Proportional and integral gain of voltage controller of grid forming inverter
$K_{pc}, K_{ic}$	Proportional and integral gain of current controller of grid forming inverter
$L_f, r_f, C_f$	Per phase inductance, resistance, and capacitance of filter

$L_c, r_c$	Inductance and resistance of coupling branch of inverter
$L_{Line}, R_{line}$	Inductance and resistance of connecting lines
$L_{Load}, R_{Load}$	Inductance and resistance of loads
$i_{lineDQ}$	d-q components of connecting line currents
$i_{loadDQ}$	d-q components of load currents
$K_p^{PLL}, K_i^{PLL}$	Proportional and integral gain of PLL
$K_{pp}, K_{ip}$	Proportional and integral gain of power controller of grid feeding inverter
$K_p, K_i$	Proportional and integral gain of current controller of grid feeding inverter