STABILITY IMPROVEMENT OF GRID TIED INVERTER SYSTEMS

ARPAN MALKHANDI

DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY DELHI

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STABILITY IMPROVEMENT OF GRID TIED INVERTER SYSTEMS

by

ARPAN MALKHANDI

Department of Electrical Engineering

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I dedicate this thesis to baba, maa and all my teachers

Certificate

This is to certify that the dissertation entitled '**Stability Improvement of Grid Tied Inverter Systems**', being submitted by **Mr. Arpan Malkhandi** for the award of the degree of **Doctor of Philosophy** is a record of bonafide research work carried out by him in the Department of Electrical Engineering at Indian Institute of Technology Delhi, New Delhi.

Mr. Arpan Malkhandi has worked under our supervision and has fulfilled the requirements for the submission of this dissertation, which to our knowledge has reached the requisite standard. The results obtained here have not been submitted to any other University or Institute for the award of any degree.

. . . .

Prof. Nilanjan Senroy
Professor
Department of Electrical Engineering
Indian Institute of Technology Delhi
Hauz Khas, New Delhi 110016, India

. . . .

Prof. Sukumar Mishra
Professor
Department of Electrical Engineering
Indian Institute of Technology Delhi
Hauz Khas, New Delhi 110016, India

Date:

Declaration

I hereby declare that except where specific reference is made to the work of others, the contents of this dissertation are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other university. This dissertation is my own work and contains nothing which is the outcome of work done in collaboration with others, except as specified in the text and Acknowledgements.

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Abstract

The recent logistical issues in coal and gas supply have led to global initiatives to perform green energy transitions. Following this endeavour, most nations have taken up a steep challenge to convert a large portion of energy generation to renewable form. This warrants the replacement of conventional synchronous generator-based energy sources with modern power electronic-based voltage source energy converter-based energy sources. A huge proliferation of these non-linear switched energy sources into the existing utility grid may result in sustained oscillations in the voltage and current profile. Solving this stability issue is of paramount importance for the safe and sustainable integration of renewable energy.

Therefore, the focus of the thesis is to improve the stability of a converter system when it is tied to the utility grid. It has been observed that the voltage and current waveform at the point of integration of the converter contains inter harmonic frequency components. These components don't die down with time and are observed in a steady state. It is to be noted that, these oscillations are not produced due to any design issues of the converter. However, the magnitude and frequency of these sustained oscillation change when the equivalent Thevenin's impedance of the grid changes. The work performs a root cause analysis of the instability phenomenon and proposes mitigation measures from the viewpoint of the grid operator as well as the inverter manufacturer.

Investigation into the cause of such oscillations has been performed with the help of impedance-based stability analysis. Impedance-based stability analysis is a recent advancement in the field of stability assessment and is widely discussed in the literature. The analysis requires the wideband impedance information of the grid side and the converter side seen at the point of interconnection. It is observed that at the frequency corresponding to the point

of intersection of the wideband grid impedance and the wideband inverter impedance, an oscillation is generated. A weak grid condition with high grid impedance is the cause of such a scenario. Therefore, mitigation measure involves re-engineering the wideband impedances. The real-time re-engineering of the grid impedance may not feasible, therefore the thesis proposes indices that may help grid operators to perform future integrations, considering contingencies that may make the grid weak and consequently result in oscillation. A novel formulation is developed which describes the impact of change in line impedance on the equivalent Thevenin's impedance of each bus in the power network. The development of these indices forms a planning approach towards the alleviation of the instability problem.

Specifically, the sensitivity indices illustrate the contribution of line outages to the weakness/strength of every bus in the system. The proposed indices rank buses on their susceptibility to becoming weak due to changes in the network topology. To show the effect of line outages on the system voltage profile and further validate the proposed ranking indices, power hardware in loop (PHIL) experiment has been conducted where a physical 5kW grid tied inverter is connected to a particular bus in the IEEE 30 bus system. The results show that the indices successfully map the lines and buses according to their potential to weaken/strengthen the power system. With the help of the developed indices, the system operator can choose buses whose strength will not change significantly due to contingencies. However, a techno-economic and geographical constraint can force an operator to integrate a grid tied inverter at a highly critical bus, as shown by the sensitivity indices. In such a scenario, an operational approach to mitigation of the instability is proposed.

The operational approach involved re-engineering the wideband inverter impedance. It is observed that the inverter impedance is a function of the control system structure and the passive elements like filters. Therefore, initially, the contribution of the control parameter gains in changing the wideband impedance profile has been explored. Conventional sensitivity involving the first differential has a serious drawback for non-linear systems. Therefore an uncertainty propagation-based approach is proposed which highlights the contribution of the control parameters irrespective of the current system states. This parametric contribution knowledge may help in location-specific off-line parameter tuning of the inverter by the inverter manufacturer before project commissioning.

Post-commissioning of the inverter, due to grid strength variability, an unstable scenario can arise. Therefore, an adaptive augmentation to the existing control system which will perform dynamic gain tuning of the existing control system has been proposed. The augmentation works in two stages. Firstly, the existing Thevenin grid impedance is measured. The measurement is used in a sensitivity formulation, which forms additional feedback to the existing control system. Such a grid cognizant control system requires an accurate estimate of the grid Thevenin's impedance. Therefore, a novel grid impedance estimation technique at fundamental as well as wideband frequencies has also been proposed in the thesis. The impedance estimation technique can estimate grid impedance in half cycle duration and has a significant advantage over the state-of-the-art in terms of estimation speed and accuracy. The proposed augmented control technique can be implemented by inverter manufacturers in a digital signal processor/ FPGA controller in real-time.

Thus, to summarize, the thesis gives a planning as well as an operational solution for the removal of oscillatory instability arising at the point of integration. The planning measure can be used by grid operators to perform new integration planning while the operational solution can be used by inverter manufacturers to counteract the problem arising due to the dynamics of the grid.

सार

थीसिस का फोकस एक इन्वर्टर सिस्टम की स्थिरता में सुधार करना है जब यह उपयोगिता ग्रिड से बंधा होता है। यह देखा गया है कि ग्रिड में पावर इलेक्ट्रॉनिक इनवर्टर का एकीकरण वोल्टेज में अंतर हार्मोनिक आवृत्ति घटकों और एकीकरण के बिंदु पर वर्तमान तरंग को जन्म देता है। ग्रिड में एकीकरण का बिंदु बदलने पर इस तरह के निरंतर दोलन परिमाण और आवृत्ति में भिन्न होते हैं। कार्य कारण का विश्लेषण करता है और ग्रिड ऑपरेटर के साथ-साथ इन्वर्टर निर्माता के दृष्टिकोण से शमन उपायों का प्रस्ताव करता है। इस तरह के दोलनों के कारण की जांच प्रतिबाधा-आधारित स्थिरता विश्लेषण की मदद से की गई है। यह देखा गया है कि वाइडबैंड ग्रिड प्रतिबाधा और वाइडबैंड इन्वर्टर प्रतिबाधा के चौराहे के बिंदु के अनुरूप आवृत्ति पर, एक दोलन मनाया जाता है। उच्च ग्रिड प्रतिबाधा के साथ एक कमजोर ग्रिड स्थिति इस तरह के परिदृश्य का कारण है। इसलिए, शमन उपाय में वाइडबैंड प्रतिबाधाओं को फिर से इंजीनियरिंग करना शामिल है। जबकि एकीकरण के बिंदु पर ग्रिड प्रतिबाधा को फिर से इंजीनियरिंग करना संभव नहीं है, थीसिस उन सूचकांकों का प्रस्ताव करती है जो ग्रिड ऑपरेटरों को भविष्य के एकीकरण करने में मदद कर सकते हैं, आकस्मिकताओं पर विचार करते हुए जो ग्रिड को कमजोर बना सकते हैं और परिणामस्वरूप दोलन हो सकता है। यह अस्थिरता की समस्या को कम करने की दिशा में एक नियोजन दृष्टिकोण बनाता है। संवेदनशीलता सूचकांक प्रणाली में प्रत्येक बस की कमजोरी/ताकत के लिए लाइन आउटेज के योगदान को दर्शाते हैं। प्रस्तावित सूचकांक नेटवर्क टोपोलॉजी में बदलाव के कारण कमजोर होने की संवेदनशीलता पर बसों को रैंक करते हैं। सिस्टम वोल्टेज प्रोफाइल पर लाइन आउटेज के प्रभाव को दिखाने और प्रस्तावित रैंकिंग सूचकांकों को और अधिक मान्य करने के लिए, लूप (फिल) प्रयोग में एक पावर हार्डवेयर आयोजित किया गया है जहां एक भौतिक 5 किलोवाट ग्रिड बंधे इन्वर्टर आईईईई 30 बस सिस्टम में एक विशेष बस से जुड़ा हुआ है। परिणाम बताते हैं कि सूचकांक बिजली प्रणाली को कमजोर/मजबूत करने की अपनी क्षमता के अनुसार लाइनों और बसों को सफलतापूर्वक मैप करते हैं। विकसित सूचकांकों की मदद से, सिस्टम ऑपरेटर उन बसों का चयन कर सकता है जिनकी ताकत आकस्मिकताओं के कारण महत्वपूर्ण रूप से नहीं बदलेगी। हालांकि, एक तकनीकी-आर्थिक और भौगोलिक बाधा एक ऑपरेटर को अत्यधिक महत्वपूर्ण बस में ग्रिड बंधे इन्वर्टर को एकीकृत करने के लिए मजबूर कर सकती है, जैसा कि संवेदनशीलता सूचकांकों द्वारा दिखाया गया है। ऐसे परिदृश्य में, अस्थिरता को कम करने के लिए एक परिचालन दृष्टिकोण प्रस्तावित है। परिचालन दृष्टिकोण में वाइडबैंड इन्वर्टर प्रतिबाधा को फिर से इंजीनियरिंग करना शामिल था। यह देखा गया है

कि इन्वर्टर प्रतिबाधा नियंत्रण प्रणाली और फिल्टर जैसे निष्क्रिय तत्वों का एक कार्य है। इसलिए, प्रारंभ में, वाइडबैंड प्रतिबाधा प्रोफ़ाइल को बदलने में नियंत्रण पैरामीटर लाभ के योगदान का पता लगाया गया है। ज्ञान परियोजना कमीशन से पहले इन्वर्टर निर्माता द्वारा इन्वर्टर के स्थान-विशिष्ट ऑफ-लाइन पैरामीटर ट्यूनिंग में मदद कर सकता है। इन्वर्टर के कमीशन के बाद, ग्रिड ताकत परिवर्तनशीलता के कारण, एक अस्थिर परिदृश्य उत्पन्न हो सकता है। इसलिए, मौजूदा नियंत्रण प्रणाली के लिए एक अनुकूली वृद्धि जो मौजूदा नियंत्रण प्रणाली के गतिशील लाभ ट्यूनिंग का प्रदर्शन करेगी, प्रस्तावित की गई है। नियंत्रण वृद्धि डिजाइन एक संवेदनशीलता सूचकांक सूत्रीकरण का उपयोग करके किया जाता है। इस तरह के ग्रिड कॉग्निजेंट कंट्रोल सिस्टम को ग्रिड थेवेनिन की प्रतिबाधा के सटीक अनुमान की आवश्यकता होती है। इसलिए, मौलिक और वाइडबैंड आवृत्तियों पर ग्रिड प्रतिबाधा अनुमान प्रस्तावित किया गया है। इस प्रकार, संक्षेप में, थीसिस नियोजन के साथ-साथ एकीकरण के बिंदु पर उत्पन्न होने वाली दोलन अस्थिरता को हटाने के लिए एक परिचालन समाधान भी देती है। नियोजन उपाय का उपयोग ग्रिड ऑपरेटरों द्वारा नई एकीकरण योजना बनाने के लिए किया जा सकता है जबकि परिचालन समाधान का उपयोग इन्वर्टर निर्माताओं द्वारा ग्रिड की गतिशीलता के कारण उत्पन्न होने वाली समस्या का मुकाबला करने के लिए किया जा सकता है।

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Nomenclature

Abbreviations

AC	Alternating Current
AEMO	Australian Electric Market Operator
ARENA	Australian Renewable Energy Agency
BESS	Battery Energy Storage Systems
COP26	26th UN Climate Change Conference of the Parties
DC	Direct Current
DSO	Distribution System Operator
DUT	Device under Test
EU	Energy Utility
FRBC	Forbidden Region Based Criteria
GNC	Generalised Nyquist Criteria
GTI	Grid Tied Inverter
GW	Giga Watt
HV	High Voltage

IBR Inverter based resource

IEA International Energy Agency

LV Low Voltage

MPPT Maximum Power Point Tracking

MV Medium Voltage

MW Mega Watt

OEM Original Equipment Manufacturer

PHIL Power Hardware in Loop

POI Point of Interconnection

PV Photovoltaic

RE Renewable Energy

REEC Renewable Energy Electric Control

REPC Renewable Energy Plant Control

SCC Short Circuit Capacity

SCR Short Circuit Ratio

SG Synchronous Generator

THD Total Harmonic Distortion

TSO Transmission System Operator

WT Wind Turbine

Symbols

i	Instantaneous current
L_{th}	Thevenin's Equivalent Inductance
r	Return Ratio Trajectory
R_{th}	Thevenin's Equivalent Resistance
v	Instantaneous voltage
Z_{th}^{c}	Equivalent Thevenin's Impedance of the Converter
Z_{th}^{g}	Equivalent Thevenin's Impedance of the Grid
Z_{th}	Thevenin's Equivalent Impedance