

ADVANCED MODELING OF GRID-CONNECTED DFIG-WTGS FOR STABILITY STUDIES

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ADVANCED MODELING OF GRID-CONNECTED DFIG-WTGS FOR STABILITY STUDIES

by

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Department of Electrical Engineering:

Submitted

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

to the



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Dedicated in the memory of my beloved brother
Late Bhaskarjyoti Buragohain

CERTIFICATE

This is to certify that the thesis entitled '**ADVANCED MODELING OF GRID-CONNECTED DFIG-WTGS FOR STABILITY STUDIES**', being submitted by **Ms. Upasana Buragohain** 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.



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— Upasana Buragohain

Abstract

The modern wind power sector is predominantly powered by doubly-fed induction generators (DFIGs) due to their inherent advantages; however, several stability issues still exist in the system that need to be investigated and addressed. Therefore, in this thesis, a small and large signal stability analysis of the full-order model of the DFIG-based wind turbine generator (WTG) system has been performed first to investigate the impact of various plant and control parameters on system instability. In general, a single grid-connected DFIG-WTG system is relatively stable compared to a grid-connected wind farm having multiple DFIG-WTG systems due to their complex dynamical interactions. The wind farms tend to get disconnected from the power network during medium/severe grid disturbance scenarios. However, the interconnection standards have made it mandatory for the DFIG-WTG system to comply with the high/low-voltage ride-through (H/LVRT) requirements. As a result, a comprehensive assessment has been carried out to investigate the H/LVRT compliance of these wind farms comprising multiple grid-connected DFIG-WTG systems. Further, it has also been observed that the grid-synchronization instability of the DFIG-WTG system is primarily ignited by the dynamics of the Phase-Locked-Loop (PLL). Studying the large-signal grid-synchronization instability phenomenon from the full-order model (sixteenth-order dynamical model) of the DFIG-WTG system is a cumbersome task. To address and overcome this challenge, a reduced-order quasi-static model of the DFIG-WTG system has been developed by amplifying the dynamics of PLL alone (to extensively focus on the study of synchronization stability of DFIG with the grid). The transient stability analysis of the proposed ROM of the DFIG-WTG system has been done by synthesizing an energy function based on Lyapunov's direct method, which has been found to be an effective tool for the same; however, its applicability gets complicated with the higher-order systems comprising of multiple DFIG-WTG in a wind farm. Therefore, as a countermeasure, a new methodology has been proposed to assess the transient stability by applying the trajectory sensitivity analysis (TSA) of states *w.r.t.* parameters of the system, which is pretty generic and can be applied to higher-order systems. The methodology proposed for transient stability analysis by TSA provides more insight into the system's stability

margin and critical values of the influential parameters in contrast to the conventional simulation methods and facilitates ease of computation. Lastly, it has also been identified that a full-order model of the DFIG-WTG system has many states, leading to various possible reduced-order models by combining different states of the system. These may create confusion while selecting a reduced-order model for a particular type of study. Therefore, to overcome this challenge and as a part of the final objective, the final chapter in this thesis investigates the adequacy of synthesizing four different reduced-order DFIG-WTG models for dynamic stability assessment.

The major highlights of the work are summarized as follows:

(a) Time-domain simulations of the grid-connected DFIG-WT system are done for open-loop and closed-loop systems under different sensitive operating conditions. The mathematical model of PLL is developed and applied to the full-order system. The proposed model is used for the dynamic aggregation of multi-machine DFIG-WTG in WPP for the H/LVRT capability study of the same system.

(b) A reduced-order model (ROM) considering only PLL mode has been developed to study grid synchronization stability problems. The proposed ROM is used to develop an analogous second-order equation to find PLL parameters for stable grid synchronization. A new Lyapunov function has been developed for studying large signal stability assessments. The proposed methodology was extended to a wind farm having N numbers of DFIG-WTG systems. Modeling adequacy analysis of four different proposed reduced-order models of the DFIG-WTG system for dynamic stability assessment has been done.

(c) A new methodology has been developed to do transient stability analysis of the DFIG-WTG system using trajectory sensitivity of states of the system *w.r.t.* to parameters. This methodology can also be used to find the system's critical parameters and transient stability margin.

Key Words: DFIG-based wind turbine generator system, Lyapunov's Method, Reduced-order-Model, Small-signal Stability, Transient Synchronization Stability.

सारांश

आधुनिक पवन ऊर्जा क्षेत्र अपने अंतर्निहित लाभों के कारण मुख्य रूप से डबल-फेड इंडक्शन जेनरेटर (डीएफआईजी) द्वारा संचालित है; हालाँकि, सिस्टम में स्थिरता के कई मुद्दे अभी भी मौजूद हैं जिनकी जांच और समाधान करने की आवश्यकता है। इसलिए, इस थीसिस में, सिस्टम अस्थिरता पर विभिन्न संयंत्र और नियंत्रण मापदंडों के प्रभाव की जांच करने के लिए सबसे पहले डीएफआईजी-आधारित पवन टरबाइन जेनरेटर (डब्ल्यूटीजी) प्रणाली के पूर्ण-ऑर्डर मॉडल का एक छोटा और बड़ा सिग्नल स्थिरता विश्लेषण किया गया है। सामान्य तौर पर, एक एकल ग्रिड-कनेक्टेड डीएफआईजी-डब्ल्यूटीजी प्रणाली अपने जटिल गतिशील इंटरैक्शन के कारण एकाधिक डीएफआईजी-डब्ल्यूटीजी सिस्टम वाले ग्रिड-कनेक्टेड पवन फार्म की तुलना में अपेक्षाकृत स्थिर होती है। मध्यम/गंभीर ग्रिड गड़बड़ी परिदृश्यों के दौरान पवन फार्म बिजली नेटवर्क से डिस्कनेक्ट हो जाते हैं। हालाँकि, इंटरकनेक्शन मानकों ने डीएफआईजी-डब्ल्यूटीजी प्रणाली के लिए उच्च/निम्न-वोल्टेज राइड-थ्रू (एच/एलवीआरटी) आवश्यकताओं का अनुपालन करना अनिवार्य बना दिया है। परिणामस्वरूप, कई ग्रिड से जुड़े डीएफआईजी-डब्ल्यूटीजी सिस्टम वाले इन पवन फार्मों के एच/एलवीआरटी अनुपालन की जांच के लिए एक व्यापक मूल्यांकन अतिरिक्त रूप से किया गया है। इसके अलावा, यह भी देखा गया है कि डीएफआईजी-डब्ल्यूटीजी प्रणाली की ग्रिड-सिंक्रनाइजेशन अस्थिरता मुख्य रूप से चरण-लॉक-लूप (पीएलएल) की गतिशीलता से प्रज्वलित होती है। और, डीएफआईजी-डब्ल्यूटीजी प्रणाली के पूर्ण-ऑर्डर मॉडल (सोलहर्वे-ऑर्डर डायनेमिक मॉडल) से बड़े-सिग्नल ग्रिड-सिंक्रनाइजेशन अस्थिरता घटना का अध्ययन करना एक बोझिल काम है। इस चुनौती को संबोधित करने और दूर करने के लिए, अकेले पीएलएल की गतिशीलता को बढ़ाकर (ग्रिड के साथ डीएफआईजी की सिंक्रनाइजेशन स्थिरता के अध्ययन पर व्यापक रूप से ध्यान केंद्रित करने के लिए) डीएफआईजी-डब्ल्यूटीजी प्रणाली का एक कम-ऑर्डर अर्ध-स्थैतिक मॉडल विकसित किया गया है। DFIG-WTG प्रणाली के प्रस्तावित ROM का क्षणिक स्थिरता विश्लेषण ल्यपुनोव की प्रत्यक्ष विधि के आधार पर एक ऊर्जा फ़ंक्शन को संश्लेषित करके किया गया है, जिसे इसके लिए एक प्रभावी उपकरण पाया गया है; हालाँकि, पवन फार्म में कई डीएफआईजी-डब्ल्यूटीजी से युक्त उच्च-क्रम प्रणालियों के साथ इसकी प्रयोज्यता जटिल हो जाती है। इसलिए, एक जवाबी उपाय के रूप में, राज्यों के प्रक्षेपवक्र संवेदनशीलता विश्लेषण (टीएसए) को लागू करके क्षणिक स्थिरता का आकलन करने के लिए एक नई पद्धति प्रस्तावित की गई है। सिस्टम के पैरामीटर, जो काफी सामान्य है और इसे उच्च-क्रम वाले सिस्टम पर लागू किया जा सकता है। टीएसए द्वारा क्षणिक स्थिरता विश्लेषण के लिए प्रस्तावित पद्धति पारंपरिक सिमुलेशन विधियों के विपरीत सिस्टम की स्थिरता मार्जिन और प्रभावशाली मापदंडों के महत्वपूर्ण मूल्यों में अधिक अंतर्दृष्टि प्रदान करती है और गणना में आसानी की सुविधा प्रदान करती है। अंत में, यह भी पहचाना गया है कि डीएफआईजी-डब्ल्यूटीजी प्रणाली के पूर्ण-ऑर्डर मॉडल में बड़ी संख्या में राज्य होते हैं जो सिस्टम के विभिन्न राज्यों को जोड़कर विभिन्न संभावित कम-ऑर्डर मॉडल की ओर ले जाते हैं। किसी विशेष प्रकार के अध्ययन के लिए कम-ऑर्डर मॉडल का चयन करते समय ये भ्रम पैदा कर सकते हैं। इसलिए, इस चुनौती पर काबू पाने के लिए और अंतिम उद्देश्य के एक भाग के रूप में, इस थीसिस का अंतिम अध्याय गतिशील स्थिरता मूल्यांकन के लिए चार अलग-अलग कम-क्रम वाले डीएफआईजी-डब्ल्यूटीजी मॉडल को संश्लेषित करने की पर्याप्तता की जांच करता है।

कार्य की प्रमुख झलकियाँ इस प्रकार संक्षेप में प्रस्तुत की गई हैं:

(ए) ग्रिड-कनेक्टेड डीएफआईजी-डब्ल्यूटी सिस्टम का टाइम-डोमेन सिमुलेशन विभिन्न संवेदनशील परिचालन स्थितियों के तहत ओपन-लूप और बंद-लूप सिस्टम के लिए किया जाता है। पीएलएल का गणितीय मॉडल विकसित किया गया है और पूर्ण-ऑर्डर प्रणाली पर लागू किया गया है। प्रस्तावित मॉडल का उपयोग उसी प्रणाली के एच/एलवीआरटी क्षमता अध्ययन के लिए डब्ल्यूपीपी में मल्टी-मशीन डीएफआईजी-डब्ल्यूटीजी के गतिशील एकत्रीकरण के लिए किया जाता है।

(बी) ग्रिड सिंक्रनाइज़ेशन स्थिरता समस्याओं का अध्ययन करने के लिए केवल पीएलएल मोड पर विचार करते हुए एक कम-ऑर्डर मॉडल (रोम) विकसित किया गया है। प्रस्तावित ROM का उपयोग स्थिर ग्रिड सिंक्रनाइज़ेशन के लिए PLL मापदंडों को खोजने के लिए एक समान दूसरे क्रम के समीकरण को विकसित करने के लिए किया जाता है। बड़े सिग्नल स्थिरता आकलन का अध्ययन करने के लिए एक नया ल्यपुनोव फ़ंक्शन विकसित किया गया है। प्रस्तावित कार्यप्रणाली को डीएफआईजी-डब्ल्यूटीजी प्रणालियों की एन संख्या वाले पवन फार्म तक विस्तारित किया गया था। गतिशील स्थिरता मूल्यांकन के लिए डीएफआईजी-डब्ल्यूटीजी प्रणाली के चार अलग-अलग प्रस्तावित कम-ऑर्डर मॉडल का मॉडलिंग पर्याप्तता विश्लेषण किया गया है।

(सी) मापदंडों के संबंध में सिस्टम की स्थितियों की प्रक्षेपवक्र संवेदनशीलता का उपयोग करके डीएफआईजी-डब्ल्यूटीजी प्रणाली की क्षणिक स्थिरता विश्लेषण करने के लिए एक नई पद्धति विकसित की गई है। इस पद्धति का उपयोग सिस्टम के महत्वपूर्ण मापदंडों और क्षणिक स्थिरता मार्जिन को खोजने के लिए भी किया जा सकता है।

मुख्य शब्द: डीएफआईजी-आधारित पवन टरबाइन जनरेटर प्रणाली, रिड्यूस्ड-ऑर्डर-मॉडल, ल्यपुनोव की विधि, लघु-सिग्नल स्थिरता, क्षणिक तुल्यकालन स्थिरता।

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Nomenclature

Acronyms/Abbreviations

PCC Point of Common Coupling.

PI Proportional and Integral.

PLL Phase-Locked-Loop.

TSA Trajectory Sensitivity Analysis.

GSC Grid side converter.

LVRT Low voltage right through.

MPPT Maximum power point tracker.

RSC Rotor side converter.

VSC Voltage source converter.

DFIG-WTG Doubly Fed Induction Generator based Wind Turbine Generator

ROM Reduced order model.

List of Suffixes/Superscripts

k With respect to DFIG k , $k = 1, 2, \dots, N$.

List of Symbols

$\Delta\omega_{PLL}$ Difference between ω_{PLL} and ω_n .

δ_{PLL} Phase angle estimated by PLL.

ω_{elB} Base speed of electrical rotating speed.

ω_n Nominal frequency of the grid.

ω_{PLL} Angular frequency estimated by PLL.

ω_t Rotating speed of the wind turbine.

C_{dc} DC-link capacitor.

E Internally induced EMF of the DFIG.

H_g, H_t Inertia constant of generator and wind turbine.

i_s, i_g Stator and rotor circuit current.

i_{qg}, i_{dg} Grid side converter's q axis and d axis current respectively.

i_{qg} Grid side converter's q axis current.

i_{qs}, i_{ds} Stator's q axis and d axis current respectively.

k, c The friction coefficient and damping coefficient of the rotating shaft connected between the generator and the wind turbine.

k_{i_n} Integral gain of n^{th} PI controller of RSC or GSC.

$k_{i_{PLL}}$ Integral gain of PI controller of PLL.

K_{opt} Maximum power extracted coefficient of the wind turbine that happens at base wind speed.

k_{pn} Proportional gain of n^{th} PI controller of RSC or GSC.

k_{pPLL} Proportional gain of PI controller of PLL.

L_m, X_m Mutual inductance and reactance between stator and rotor circuit.

L_{ss}, R_{ss} Inductance of stator circuit, rotor circuit.

P_t Mechanical power of the wind turbine.

R_s, R_r Resistance of stator circuit, rotor circuit.

R_{grid} Equivalent resistance of the grid.

T_e Electrical torque rotor of the generator.

T_{sh} Mechanical torque of the rotating shaft connected between the wind turbine and the generator.

v_{grid}, v_{wind} Infinite bus voltage and wind speed.

$V_s \angle \gamma_e$ Voltage phasor of the terminal voltage of the DFIG-WTG system.

X_{gk}, L_{gk} Equivalent reactance, inductance of the transmission line between DFIGs k and $k - 1$ respectively.

X_{grid} Equivalent reactance of the grid.

X_g, L_g, U_g Equivalent reactance, the inductance of the grid and infinite bus voltage, respectively.

Z_{grid} Equivalent impedance of the grid.