同行专家业内评价意见书编号：20240858127

附件1

浙江工程师学院（浙江大学工程师学院）
同行专家业内评价意见书

姓名：王子骏

学号：22160188

申报工程师职称专业类别（领域）：能源动力

浙江工程师学院（浙江大学工程师学院）制

2024年03月20日

一、个人申报

（一）基本情况【围绕《浙江工程师学院（浙江大学工程师学院）工程类专业学位研究生工程师职称评审参考指标》，结合该专业类别（领域）工程师职称评审相关标准，举例说明】

1.对本专业基础理论知识和专业技术知识掌握情况

本人对于本专业的基础理论知识和专业技术具有深入的理解与应用能力。本人熟悉电力系统的动静态稳定性理论，掌握了电力系统分析的基本方法，如负荷流分析、故障分析、稳定性分析等，并能使用这些理论和技术来解决实际的电力系统问题。

在专业技术方面，能够运用现代电力系统的稳定控制理论，对电力系统的暂态稳定、电压稳定、频率稳定等多方面稳定问题进行分析和控制。能够熟练使用电力系统分析软件，如MATLAB/Simulink等，来建模、仿真和分析电力系统的稳态和暂态行为。此外，我也了解并研究智能电网技术，特别是在分布式发电、能源存储、以及需求响应方面的应用，这些都是提升电力系统稳定性的关键技术。

综合这些知识与技能的学习，使我能够针对当前及未来电力系统稳定性挑战提出创新解决方案，并为电力系统的稳定运行和可持续发展做出贡献。

2.工程实践经历

本人主要参与新型电力系统领域集成项目一项，国家电网总部科技项目一项，省级电网应用性课题研究项目一项。完成对上述项目具有指导作用的有关情报资料的搜集、整理、汇编，提出系统研究报告三份;并完成本专业领域的技术分析，给出合理的分析结论及建议，提出可行的改进方案和验证方法。

3.在实际工作中综合运用所学知识解决复杂工程问题的案例

在专业实践的过程中，本人作为主要项目研究人员参与了“高比例新能源大电网同步稳定机理及控制理论”及“电压源型风电机组关键技术及示范”项目。为完成实践内容，深入学习了电力系统的基本理论知识，包括电力系统建模，稳定性分析以及控制设计理论。在实际深入南瑞稳定公司实践之后，对目前送端电网的稳定性问题更加了解，对新能源送端电网的实际工程情况有了深刻的了解。

本人在项目过程中主要负责新能源设备的稳定性分析及分散控制设计方法的研究，我国在推进新能源可靠替代过程中逐步有序减少传统能源，并大力度规划建设以大型风光电基地为基础的送端电网，而随着新能源比例的不断增加，送端电网的同步失稳风险日益突出，而新能源设备结构形态和运行特征与传统同步机等设备存在显著差异，因此如何研究新能源设备特性性并提出适用于高比例新能源送端电网的分散控制是个难题。此外，在项目研究过程中，合作单位运达及中国电科院在现场实验中发现虚拟同步直驱风机在并网运行容易发生振荡问题，其振荡特性尚不清晰。

为此，针对虚拟同步直驱风机并网系统，建立了考虑机侧动态的风机系统统一阻尼转矩模型，实现了风机各环节动态的准确刻画，且通过拓展可考虑更多环节并分析其动态影响。然后，基于阻尼转矩法分析了风机设备各环节动态对并网系统低频动态的影响，揭示了机侧转子动态产生的负阻尼转矩是导致风机低频振荡的主要原因，并通过研究系参数对各等效转矩的影响，分析了参数对系统低频振荡的影响规律。进一步，从工程实用方面出发，针对功率跟踪回路提出了削弱机侧负阻尼的阻尼补偿分散控制方法，并基于三阶简化模型实现控制参数的快速整定，有效提升了风机系统的低频稳定性。同时，搭建了风机单机并网系统及十机三十九节点系统的仿真模型，验证了理论分析的正确性和控制的有效性。

此外，针对新能源设备在暂态下由于电流限幅导致的非线性特性切换，建立了考虑机侧动态的风机系统暂态分析模型，基于虚拟功角曲线及等面积定则分析了构网型风机系统的暂态特性，并揭示了机侧动态对风机暂态动态的负面作用。进一步基于系统的暂态分析，提出了适用于风机系统的暂态稳定分散控制以提升设备的暂态稳定性能，并基于MATLAB/Simulink仿真平台搭建电磁暂态仿真模型，验证了分析的准确性和控制的有效性。

在项目研究过程中，相关研究内容也形成了成果，并撰写多篇学术论文与多项专利，以第一作者身份在电力系统自动化与浙江大学学报（工学版）等权威期刊发表两篇EI期刊论文，并发表两篇EI会议论文。在此过程中，也进一步培养严谨科学的科研态度，具体包括文献的查阅与整理，仿真数据的分析与表述，注重仿真经验的总结，同时对新型电力系统的发展与调整有了更加深入的认识，通过专业知识和工程实际相结合，有效提升了解决工程问题的能力。

（二）取得的业绩（代表作）【限填3项，须提交证明原件（包括发表的论文、出版的著作、专利证书、获奖证书、科技项目立项文件或合同、企业证明等）供核实，并提供复印件一份】					
1. 公开成果代表作【论文发表、专利成果、软件著作权、标准规范与行业工法制定、著作编写、科技成果获奖、学位论文等】					
成果名称	成果类别 [含论文、授权专利（含发明专利申请）、软件著作权、标准、工法、著作、获奖、学位论文等]	发表时间/授权或申请时间等	刊物名称/专利授权或申请号等	本人排名/总人数	备注
虚拟同步直驱风机低频振荡机理分析及阻尼补偿控制	一级期刊	2023年11月02日	电力系统自动化	1/6	EI期刊收录
Transient Stability Analysis of WTs Based on VSG-PMSG Considering the Machine-side Dynamics	会议论文	2023年08月24日	PSGEC	1/6	EI会议收录
A Hybrid Phase-Locked Loop for the Transient Stability Enhancement of Voltage Source Converters	会议论文	2021年12月24日	POWERCON	1/6	EI会议收录

2. 其他代表作【主持或参与的课题研究项目、科技成果应用转化推广、企业技术难题解决方案、自主研发设计的产品或样机、技术报告、设计图纸、软课题研究报告、可行性研究报告、规划设计方案、施工或调试报告、工程实验、技术培训教材、推动行业发展中发挥的作用及取得的经济社会效益等】

<table>
<tr><td colspan="2">（三）在校期间课程、专业实践训练及学位论文相关情况</td></tr>
<tr><td>课程成绩情况</td><td>按课程学分核算的平均成绩： 87 分</td></tr>
<tr><td>专业实践训练时间及考核情况(具有三年及以上工作经历的不作要求)</td><td>累计时间： 1.1 年（要求1年及以上）
考核成绩： 92 分（要求80分及以上）</td></tr>
<tr><td colspan="2">本人承诺</td></tr>
<tr><td colspan="2">个人声明：本人上述所填资料均为真实有效，如有虚假，愿承担一切责任，特此声明！

申报人签名：王子骏</td></tr>
</table>

22160188

二、日常表现考核评价及申报材料审核公示结果

日常表现考核评价	非定向生由德育导师考核评价、定向生由所在工作单位考核评价： ☑优秀　　☐良好　　☐合格　　☐不合格 德育导师/定向生所在工作单位分管领导签字（公章）：　　年　月　日
申报材料审核公示	根据评审条件，工程师学院已对申报人员进行材料审核（学位课程成绩、专业实践训练时间及考核、学位论文、代表作等情况），并将符合要求的申报材料在学院网站公示不少于5个工作日，具体公示结果如下： ☐通过　　☐不通过（具体原因：　　　　　　　） 工程师学院教学管理办**公室**审核签字（公章）：　　年　月　日

浙 江 大 学 研 究 生 院

攻读硕士学位研究生成绩表

学号：22160188　姓名：王子骏　性别：男　学院：工程师学院　专业：电气工程　学制：2.5年

毕业时最低应获：26.0学分　已获得：26.0学分　入学年月：2021-09　毕业年月：2024-03

学位证书号：1033532024602197　毕业证书号：103351202402600423　授予学位：能源动力硕士

学习时间	课程名称	备注	学分	成绩	课程性质	学习时间	课程名称	备注	学分	成绩	课程性质
2021-2022学年秋季学期	新能源发电与变流技术		2.0	97	专业学位课	2021-2022学年春季学期	自然辩证法概论		1.0	77	公共学位课
2021-2022学年秋冬季学期	计算机实时控制技术		2.0	88	专业学位课	2021-2022学年夏季学期	研究生英语		2.0	76	公共学位课
2021-2022学年秋冬季学期	现代控制理论		3.0	98	专业学位课	2021-2022学年春夏季学期	微电网技术工程实践		4.0	90	专业学位课
2021-2022学年冬季学期	综合能源系统集成优化		2.0	87	专业学位课	2021-2022学年夏季学期	电气装备健康管理		2.0	91	专业选修课
2021-2022学年秋冬季学期	中国特色社会主义理论与实践研究		2.0	88	公共学位课	2022-2023学年秋冬季学期	研究生论文写作指导		1.0	89	专业学位课
2021-2022学年冬季学期	工程伦理		2.0	91	公共学位课	2022-2023学年春季学期	研究生英语基础技能		1.0	73	公共学位课
2021-2022学年冬季学期	工程中的有限元方法		2.0	96	专业选修课						

说明：1.研究生课程按三种方法计分：百分制，两级制（通过、不通过），五级制（优、良、中、及格、不及格）。

2.备注中“*”表示重修课程。

学院成绩校核章：

成绩校核人：张梦依

打印日期：2024-04-02

浙江大学研究生院 (60) 成绩校核章

DOI:10.7500/AEPS20230328002

虚拟同步直驱风机低频振荡机理分析及阻尼补偿控制

王子骏[1],庄可好[2],辛焕海[1,2],李少林[3],齐 琛[3],程雪坤[4]
(1. 浙江大学工程师学院,浙江省杭州市 310027;2. 浙江大学电气工程学院,浙江省杭州市 310027;
3. 中国电力科学研究院有限公司,北京市 100192;4. 国网冀北电力有限公司电力科学研究院,北京市 100045)

摘要: 虚拟同步机技术可有效提升电网的电压支撑能力,但也引入了复杂的低频振荡问题。目前,对传统虚拟同步机的低频振荡研究大多忽略直流侧及机侧动态,难以准确刻画虚拟同步直驱风机的低频振荡特性。为解决上述问题,首先,建立了计及机侧动态和直流电压动态的统一阻尼转矩模型,利用阻尼转矩法揭示了机侧转子动态产生的负阻尼转矩是导致风机低频振荡的主要原因,并分析了各环节对风机低频振荡特性的影响规律。进一步,提出了阻尼补偿控制以削弱机侧动态的负阻尼效应,有效提升了机侧耦合下风机并网系统的稳定性。最后,简要分析了所提控制在多机系统的适用性,并基于MATLAB/Simulink仿真验证了理论分析的准确性和所提控制的有效性。

关键词: 低频振荡;虚拟同步机;直驱风机;阻尼转矩法;稳定性

0 引言

为实现中国“碳达峰·碳中和”的战略目标,风光等新能源设备的装机容量不断提升,电力系统呈现低短路比、低惯量的特征,使得系统稳定运行面临着严峻挑战[1-3]。为保障高比例新能源电力系统稳定运行,新能源也逐渐由被动跟随向主动支撑转变。其中,在传统电流源机组中采用虚拟惯量控制可使新能源参与电网的频率调节[4-5],但难以为电网提供电压支撑[6-7],无法突破低短路比电网的约束。相比之下,新能源采用虚拟同步机(virtual synchronous generator,VSG)技术可模拟电压源特性,同时实现对电网的电压/惯量支撑[8],并突破低短路比电网对新能源功率稳定送出的制约。目前,中国沙漠戈壁等地区的大规模新能源基地在不断建设,亟须研究可靠的虚拟同步控制技术。与小容量的微电网系统不同,若完全依赖储能型VSG提升送端系统短路比,所需储能的建设成本将极为高昂。因此,依赖新能源自身能量环节的虚拟同步控制逐渐受到工程界及学术界的重视[9-12]。但新能源设备通过控制模拟转子动态也不可避免地继承了同步机的低频振荡问题,且因设备复杂的级联控制环节,其低频振荡特性与同步机特性也有所不同,引起了国内外学者的关注和研究[13-14]。

目前,传统VSG并网系统(本文指利用储能实现虚拟同步的新能源设备)多假设直流电压恒定且功率参考值为给定常数,其低频振荡研究已经较为成熟[15-18]。文献[15-16]建立了考虑电压外环的VSG小信号状态空间模型,发现增大虚拟阻抗及有源阻尼系数有利于提高系统低频稳定性。当VSG引入频率检测环节时,会产生负阻尼转矩并恶化系统低频特性,使得VSG更容易引发系统低频振荡[17]。进一步,文献[18]建立了多VSG系统的闭环模型,指出当各VSG开环模式相近时会降低系统低频稳定性,并提出了多VSG参数整定方法。但上述分析仅适用于传统VSG,对于依赖新能源自身能量环节的虚拟同步设备缺乏深入研究。

永磁直驱风机作为新能源主流机组之一,其依赖自身能量环节的虚拟同步研究受到广泛关注[9,19-20]。其中,典型的虚拟同步直驱风机控制结构中,其网侧虚拟同步控制的功率参考值由降载后的最大功率点跟踪(deloading maximum power point tracking,DL-MPPT)给定,机侧变流器则控制直流电压恒定。由于直驱风机的机侧动态与网侧虚拟同步动态耦合,其低频振荡特性比传统VSG更加复杂。为此,国内外学者开始考虑直流动态和机侧动态展开研究,但尚处于起步阶段。文献[21]建立了直驱风机的阻抗模型,提出了直流动态对VSG系统影响的量化方法,并分析了直流参数的影响,但未考虑功率跟踪下风机转子与网侧虚拟同步控制的耦合关系。此外,基于虚拟同步直驱风机的全阶状态空

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上网日期:2023-12-21。
国家电网有限公司总部科技项目(电压源型风电机组关键技术及示范,4000-202114068A-0-0-00)。

经检索"Engineering Village"，下述论文被《Ei Compendex》收录。（检索时间：2024 年 3 月 11 日）。

1.

Low-frequency Oscillation Mechanism Analysis and Damping Compensation Control of Virtual Synchronous Direct-driven Wind Turbine Generators

Accession number: 20240515481153
Title of translation: 虚拟同步直驱风机低频振荡机理分析及阻尼补偿控制
Authors: Wang, Zijun (1); Zhuang, Kehao (2); Xin, Huanhai (1, 2); Li, Shaolin (3); Qi, Chen (3); Cheng, Xuekun (4)
Author affiliation: (1) Polytechnic Institute, Zhejiang University, Hangzhou; 310027, China; (2) College of Electrical Engineering, Zhejiang University, Hangzhou; 310027, China; (3) China Electric Power Research Institute, Beijing; 100192, China; (4) Electric Power Research Institute of State Grid Jibei Electric Power Co., Ltd., Beijing; 100045, China
Corresponding author: Xin, Huanhai(xinhh@zju.edu.cn)
Source title: Dianli Xitong Zidonghua/Automation of Electric Power Systems
Abbreviated source title: Dianli Xitong Zidonghue
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Publication year: 2024
Pages: 95-104
Language: Chinese
ISSN: 10001026
CODEN: DXZIE9
Document type: Journal article (JA)
Publisher: Automation of Electric Power Systems Press
Number of references: 33
Main heading: Synchronous generators
Controlled terms: Computer control systems - Damping - Dynamics - Electric machine control - MATLAB - Torque - Turbogenerators - Wind Turbine Generators
Uncontrolled terms: Compensation control - Damping torque method - Damping torques - Direct-driven wind turbine - Direct-driven wind turbine generator - Frequency oscillations - Low-frequency oscillation - Lower frequencies - Virtual synchronoi generator - Wind turbine generators
Classification code: 615.8 Wind Power (Before 1993, use code 611) - 705.2 Electric Generators - 705.2.1 AC Generators - 723.5 Computer Applications - 731.1 Control Systems - 731.2 Control System Applications - 921 Mathematics - 931.1 Mechanics - 931.2 Physical Properties of Gases, Liquids and Solids
DOI: 10.7500/AEPS20230328002
Funding Details: Number: 4000-202114068A-0-0-00, Acronym: SGCC, Sponsor: State Grid Corporation of China;
Compendex references: YES
Database: Compendex
Data Provider: Engineering Village

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Transient Stability Analysis of WTs Based on VSG-PMSG Considering the Machine-side Dynamics

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***Abstract*—Wind turbines (WTs) using virtual synchronous generator (VSG) technology can effectively improve the voltage/frequency support capability of power grid. But it also brings complex transient stability problems due to dynamic interaction between machine-side and grid-side. In this paper, the transient stability of WTs based on permanent magnet synchronous generator with VSG control (VSG-PMSG) is investigated considering machine-side rotor dynamics. The transient model of VSG-PMSG is first established and then the dynamic response of the VSG-PMSG under frequency fluctuation is analyzed. And excessive damping coefficient or severe frequency drop will increase the risk of synchronous instability of the VSG-PMSG. Moreover, the transient characteristics of VSG-PMSG under voltage drop have also been studied. And the machine-side dynamics will reduce the transient stability margin of VSG-PMSG by changing the acceleration and deceleration area. Finally, the time-domain simulations based on MATLAB/Simulink are given to verify the correctness of the stability analysis.**

Keywords—virtual synchronous generator, transient stability, permanent magnet synchronous generator, frequency drop, voltage drop

I. INTRODUCTION

At present, the installed capacity of wind turbines(WTs) continues to increase, and the renewable energy sending-end power grid presents the characteristics of a low short-circuit ratio(SCR), which weakens support effect of the power grid for WTs[1]. And it leads to a series of oscillation problems, which greatly limit the ability of wind power transmission. Compared with the lack of stability of WTs using grid-following control under weak power grids, WTs using virtual synchronous generator(VSG) control can actively improve the voltage/frequency support capability of power grid and have better adaptability to weak power grids[2]. In addition, unlike the microgrid system, if sending-end system relies entirely on the energy storage base on VSG (VSG-ES) to increase the SCR, the construction cost of the required energy storage will be extremely high. Therefore, the WTs based on permanent magnet synchronous generator with VSG control (VSG-PMSG), which relies on the synchronization of the WTs' own energy links, has gradually attracted extensive attention and research[3].

At present, the VSG-PMSG mainly pays attention to its small disturbance stability, and the correlation analysis has been relatively mature. The small disturbance model of the VSG-PMSG is established in [4], and it is pointed out that the machine-side dynamics will greatly affect the stability of the WTs under small disturbance. And changing the outer loop control parameters or increasing the virtual excitation can effectively improve the small disturbance stability margin of the WTs [5].

Compared with small disturbance stability analysis, the transient characteristics of VSG-PMSG is more complex under large disturbance, and the related research is still in its infancy[6]. In [7], the influence of voltage outer loop on transient characteristics is analyzed based on equal area rule and energy function method. Based on the traditional transient analysis method of synchronous generator(SG), the transient response of WTs is analyzed in [8], and it is pointed out that overcurrent is easy to occur under transient conditions. In order to prevent overcurrent from damaging the converter, the WTs often set the current limiting link between the inner loop and the outer loop, and the current limiter will greatly affect the transient stability of the system[9]. Then, the characteristic switching caused by droop control current saturation is analyzed in [10], and it is pointed out that the current limiter will lead to the reduction of the system transient stability margin. Furthermore, the transient characteristics of VSG are analyzed considering the current limiter in [11], and a hybrid control is proposed to improve the transient stability margin of the system. However, most of the above studies focus on the grid-side converter(GSC), ignoring the negative effects of machine-side dynamics on the synchronous performance of the WTs. Thus, it's imperative to investigate the transient stability characteristics of the VSG-PMSG to achieve stable operation of the renewable energy sending-end power grid.

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A Hybrid Phase-Locked Loop for the Transient Stability Enhancement of Voltage Source Converters

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***Abstract*—Phase-locked loop (PLL) is widely used in voltage source converter (VSC) to synchronize with grid. This paper comprehensively analyzes the transient stability of the PLL-VSC and obtains the VSC's instability characteristics similar to the synchronous generator. The instability of VSC is mainly caused by insufficient deceleration area and instability without equilibrium point. To improve the transient stability of VSC, a hybrid PLL is proposed. This method dynamically compensates the phase of the PLL to improve the transient stability performance of the system without obtaining the specific parameters of the grid line. The phase compensation of PLL creates new equilibrium points to solve the most problem of insufficient deceleration area or no equilibrium point. Time-domain simulations are given to verify the effectiveness of the theoretical analysis.**

Keywords*—Transient stability, phase-locked loop, hybrid phase-locked, voltage source converter

I. Introduction

Nowadays, voltage source converter (VSC) has been widely used in renewable generations and distributed generation units, and phase-locked loop (PLL) has also been widely used in VSC to realize synchronization. Therefore, the synchronization stability of PLL-VSC has attracted the attention of many researchers. The instability of PLL-VSC under different grid conditions has been increasingly reported, such as small disturbance stability and large disturbance out-of-synchronization (LOS). This poses a severe challenge to the safe and stable operation of the grid with high penetration rate of renewable energy.

In recent years, the synchronization stability of VSC has been extensively studied, but mainly focused on small disturbance stability analysis. Studies have found that the bandwidth of the PLL determines the frequency range of the resistor behavior. The change of the PLL bandwidth under weak grid conditions can easily make the VSC unstable [1]. At present, the transient analysis of the VSC grid-connected system is focused on the scattered research in specific simple scenarios. The mathematical model of the VSC with droop control is established, and its transient stability is analyzed based on the virtual power angle and the equal-area criterion (EAC) [2]. Through analyzing the PLL dynamics, an analysis model similar to the synchronous generator rotor movement model is established, which is used to the VSC transient stability analysis based on EAC [3].

At present, many methods have been proposed to solve the transient stability problem of VSC, which are mainly divided into two aspects: parameter optimization and control design. For parameter optimization, it is found that when damping is considered, increasing the proportional gain of the PI controller of PLL and reducing the integral gain can increase the damping and increase the stability margin of the system [3]. Compared to parameter optimization, more research currently focuses on control design to improve the transient stability of VSC. It is found that dynamically adjust the reference value of active current according to the residual voltage after the voltage drop can reduce the possibility of losing synchronization [4]. The other method improves the transient stability by changing the PLL into an open-loop system or a first-order system in the transient process. This type of control method is more practical in engineering and can prevent transient synchronization instability caused by excessive overshoot. The integrator of the PLL is blocked during a fault so that the PLL can maintain synchronization while improving transient stability [5]-[6]. In addition, adaptive methods have also been extensively studied. An adaptive PLL is proposed, which can automatically switch the working state of the PLL according to the frequency deviation. Therefore, the PLL works normally during normal operation, but when a transient disturbance occurs, it will automatically increase the damping ratio to improves the transient stability of the system[7]. But all of the above methods can't deal with the transient instability problem without equilibrium points. Since the output current of the converter has a voltage drop on the grid impedance, the compensation impedance voltage method compensates the voltage drop so that the system connected to the inverter can be equivalent to an infinite grid. This control method can theoretically realize the global stability of the PLL and completely solve the transient instability problem. However,

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