同行专家业内评价意见书编号：20250861019

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：沈睿

学号：22260175

申报工程师职称专业类别（领域）：交通运输

浙江工程师学院（浙江大学工程师学院）制

2025年03月11日

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## 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(不少于200字)**

作为交通运输专业（交通电气化方向）的学生，我系统掌握了电机系统健康管理的核心理论和专业技术知识。首先，我深入学习了温度控制与热电偶的原理，掌握了如何精确测量电机定子绝缘温度，并利用PID控制PWM波占空比来实现温度控制。这加深了我对控制系统和信号处理的理解。其次，我掌握了电机绝缘热固耦合应力的理论，并通过有限元分析和理论知识建立了绝缘热固耦合应力模型。此外，我学习了机器学习算法，并将其应用于绝缘热固耦合应力模型的修正，提高了数据分析能力。同时，我还掌握了嵌入式系统的开发技能，将AI模型部署至嵌入式设备，完成实时计算。通过本次实践，我不仅巩固了课堂所学的基础理论，还将其应用于实际工程问题，提升了解决复杂技术难题的能力。

**2.工程实践的经历(不少于200字)**

在中控技术股份有限公司的实习实践中，我主要参与了电机定子绝缘寿命评估项目，并承担了多个技术任务。在温度控制方面，我设计并调试了热电偶温度采集系统，实现了高精度数据采集；在控制系统优化中，我运用PID控制算法调节PWM波占空比，确保温度控制的稳定性和精确性。此外，我利用有限元仿真计算不同温度不同结构下的热固耦合应力，并训练浅层神经网络模型，以提高热固耦合应力模型的准确性。在嵌入式开发方面，我成功地将AI模型部署至嵌入式设备，实现了实时计算和LCD屏幕的数据展示。整个实践过程中，我不仅提升了工程实践能力，还学会了团队协作、跨学科融合以及如何通过实验优化系统性能。本次实践让我更深入地理解了如何将理论知识与工程实践结合，以解决复杂工业问题。

**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（不少于1000字）**

项目背景

在中控技术股份有限公司实习期间，我参与了一个关于电机定子绝缘寿命评估的项目，该项目旨在研究不同热循环工况下热固耦合应力对电机定子绝缘寿命的影响，并获取相应的热固耦合应力模型，进而在此基础上建立电机绝缘寿命预测模型。该研究对于电机的可靠性评估、维护策略优化以及延长设备使用寿命具有重要意义。然而，项目初期，我们面临多个工程难题，如温度控制精度不足、AI模型预测准确性不高、嵌入式设备计算能力有限等。

问题分析

1.温度控制不稳定

由于电机定子工作时温度变化较大，导致热电偶采集的数据存在波动，PID控制难以实现精准调节，进而影响实验数据的稳定性。

2.热固耦合应力计算复杂

计算电机定子在不同温度下的热固耦合应力需要大量有限元仿真数据，而传统方法计算量大，难以满足实时性要求。

3.热固耦合应力模型精度不足

初期使理论模型对热固耦合应力进行计算，但误差较大，难以准确反映电机在不同工况下的热固耦合应力趋势。

4.嵌入式设备计算能力受限

AI模型训练后需要部署至嵌入式系统进行实时计算，但由于嵌入式设备计算资源有限，模型运行效率低，影响数据实时性。

解决方案

1. 改进温度控制系统
针对温度控制不稳定的问题，我优化了PID控制算法，并采用变温PID控制策略，即根据不同温度范围动态调整PID参数，以提高系统对温度变化的适应能力。此外，通过增加平均设置，减少了测量数据的波动性，最终实现了高精度温度控制。
2. 优化热固耦合应力计算
为了减少计算量，我采用有限元仿真和解析模型相结合的方法，预先计算不同温度和电机结构情况下的热固耦合应力数据，并将这些数据用于机器学习模型的训练，从而避免实时计算的高资源消耗。
3. 提高热固耦合应力模型的准确性
为了提升预测精度，我采用了浅层神经网络（Shallow Neural Network, SNN）修正热固耦合应力模型，并进行了多次参数优化。相比线性回归模型，神经网络能够更好地捕捉复杂的非线性关系，进而使得寿命预测更加准确。
4. 低功耗嵌入式AI部署
针对嵌入式设备计算能力受限的问题，我对训练好的神经网络模型进行了模型压缩和优化，以确保AI模型能够在低功耗设备上快速运行。
实施效果
优化后的系统在多项测试中表现优异：
温度控制精度提高：变温PID算法的应用使温度控制精度不断提升，满足了实验要求。
热固耦合应力计算效率提高：通过神经网络+解析模型的优化，使得热固耦合应力模型能够在嵌入式设备上实时运行。
寿命预测误差降低：根据这套系统进一步研究热固耦合应力对电机绝缘寿命模型的影响，并根据理论和实验数据建立了寿命预测模型。最后通过额外试验验证了性能退化模型和寿命预测模型的准确性。退化模型预测值与实际测量值之间的平均误差率为4.2%，最大误差率为7.8%。寿命结果的误差率为5.3%。更准确地反映了电机的寿命趋势。
系统运行稳定：优化后的AI模型能够在嵌入式设备上流畅运行，并通过LCD屏幕展示温度、寿命预测等关键数据，提高了系统的可视化效果。
工程应用与价值
该优化方案成功应用于企业的电机健康管理系统，带来了显著的经济和社会效益：
降低维护成本：精确的寿命预测使得企业能够合理安排电机维护，避免不必要的更换，降低了设备维护成本。
提高设备利用率：精准的寿命评估帮助企业优化生产计划，减少因电机故障导致的生产停滞，提高了生产效率。
节能环保：优化后的温度控制系统减少了电机过热问题，降低了能源消耗，同时延长了设备使用寿命，符合绿色制造的发展方向。
总结
本案例展示了如何在实际工程中综合运用控制理论、机器学习、有限元分析和嵌入式开发等多学科知识，解决复杂的工程问题。通过改进温度控制、优化热固耦合应力计算、提升AI模型预测能力以及优化嵌入式部署，我们成功提升了电机健康管理系统的性能。此次工程实践不仅锻炼了我的专业技能，也让我深刻认识到理论与实践结合的重要性，为未来从事智能制造和工业AI领域的研究奠定了坚实基础。

（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】

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| 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 |
|---|---|---|---|---|---|
| Modeling and Analysis of Thermal-mechanical Stress in Motor Insulation | 会议论文 | 2023年12月14日 | 2023 26th International Conference on Electrical Machines and Systems (ICEMS) | 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】

MathorCup高校数学建模挑战赛国家级二等奖
中国研究生双碳创新与创意大赛国家级三等奖

| （三）在校期间课程、专业实践训练及学位论文相关情况 | |
|---|---|
| 课程成绩情况 | 按课程学分核算的平均成绩： 88 分 |
| 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) | 累计时间： 1 年（要求1年及以上）<br>考核成绩： 88 分 |
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22260175

## 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：<br>☑优秀 □良好 □合格 □不合格<br>德育导师/定向生所在工作单位分管领导签字（公章）：2025年3月16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：<br>□通过 □不通过（具体原因： ）<br>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：22260175 | 姓名：沈睿 | 性别：女 | 学院：工程师学院 | 专业：交通运输 | 学制：2.5年 |
|---|---|---|---|---|---|
| 毕业时最低应获：24.0学分 | | 已获得：26.0学分 | | 入学年月：2022-09 | 毕业年月： |
| 学位证书号： | | | 毕业证书号： | | 授予学位： |

| 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 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2022-2023学年秋季学期 | 新时代中国特色社会主义理论与实践 | | 2.0 | 92 | 专业学位课 | 2022-2023学年冬季学期 | 产业技术发展前沿 | | 1.5 | 80 | 专业学位课 |
| 2022-2023学年秋季学期 | 工程技术创新前沿 | | 1.5 | 89 | 专业学位课 | 2022-2023学年春季学期 | 电气装备健康管理 | | 2.0 | 89 | 专业选修课 |
| 2022-2023学年秋冬学期 | 研究生论文写作指导 | | 1.0 | 88 | 专业选修课 | 2022-2023学年春季学期 | 自然辩证法概论 | | 1.0 | 93 | 专业学位课 |
| 2022-2023学年秋冬学期 | 工程伦理 | | 2.0 | 97 | 专业学位课 | 2022-2023学年春季学期 | 研究生英语基础技能 | | 1.0 | 80 | 公共学位课 |
| 2022-2023学年秋冬学期 | 高阶工程认知实践 | | 3.0 | 78 | 专业学位课 | 2022-2023学年夏季学期 | 工程师创新创业思维 | | 2.0 | 92 | 专业选修课 |
| 2022-2023学年冬季学期 | 研究生英语 | | 2.0 | 85 | 专业学位课 | 2022-2023学年夏季学期 | 智能交通系统与实践应用 | | 2.0 | 91 | 专业学位课 |
| 2022-2023学年冬季学期 | 工程中的有限元方法 | | 2.0 | 100 | 专业选修课 | | 硕士生读书报告 | | 2.0 | 通过 | |
| 2022-2023学年冬季学期 | 智慧交通仿真实践 | | 1.0 | 83 | 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：浙江大学研究生院（60）成绩校核章

成绩校核人：张梦依

打印日期：2025-03-20

**经检索"Engineering Village"，下述论文被《Ei Compendex》收录。（检索时间：2024 年 10 月 21 日）。**

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Title:Modeling and Analysis of Thermal-mechanical Stress in Motor Insulation
Authors:Shen, Rui (1); Wang, Rui (2); Zhang, Jian (1); Fang, Youtong (2); Yang, Yong (3); Tian, Jie (4)
Author affiliation:(1) Zhejiang University, Polytechnic Institute, Hangzhou, China; (2) Zhejiang University, College of Electrical Engineering, Hangzhou, China; (3) Powernice Intelligent Technology Co., Ltd, Ningbo, China; (4) Wuhan Second Ship Design and Research Institute, Wuhan, China
Corresponding author:Tian, Jie(tianjie_eee_126@126.com)
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Numerical data indexing:Percentage 5.00E+00%
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教育部科技查新工作站（Z09）
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2024 年 10 月 21 日

# Modeling and Analysis of Thermal-mechanical Stress in Motor Insulation

**Publisher: IEEE** Cite This PDF

Rui Shen; Rui Wang; Jian Zhang; Youtong Fang; Yong Yang; Jie Tian **All Authors**



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**Abstract:**
High temperature generates thermal-mechanical stress (TMS), which causes aging of the electrical insulation system in the stator windings. In this paper, a TMS analytical model for motor insulation is proposed, and the model is modified by using a shallow neural network. Then, the accuracy of the TMS analytical model was verified by finite element simulation, and finally verified by experiments. The average error obtained after comparison with the analytical model is less than 5%.

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# Modeling and Analysis of Thermal-mechanical Stress in Motor Insulation

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***Abstract*—High temperature generates thermal-mechanical stress (TMS), which causes aging of the electrical insulation system in the stator windings. In this paper, a TMS analytical model for motor insulation is proposed, and the model is modified by using a shallow neural network. Then, the accuracy of the TMS analytical model was verified by finite element simulation, and finally verified by experiments. The average error obtained after comparison with the analytical model is less than 5%.**

***Keywords—thermo-mechanical stress, stator insulation system, shallow neural network, finite element analysis***

## I. Introduction

For motors, the main thermal aging factors are divided into aging caused by constant temperature, and aging caused by thermal cycling. The motor is impregnated with epoxy resin, which prevents thermal oxidation caused by the exposure of the winding coating to air. However, under thermal cycling, different thermal expansion coefficients and different temperature distributions between epoxy resin and winding coating and copper wires can cause thermally induced mechanical stress. Due to thermal-mechanical stress, the stator electrical insulation system (EIS) may degrade and fail. TMS is considered a key factor in causing insulation degradation.

There has been a lot of research on TMS. By studying the influence of thermal-mechanical stress on the insulation system of low-voltage motor, it is proved that TMS plays an important role in the dynamic heat aging process of winding insulation system[1]. For wind turbine generators (WTG), the high thermal stress and TMS caused by their entry and cut-off were studied[2]. The service life of machines subjected to thermal cycling stress is studied by accelerated aging tests. The results show that as the thermal cycling stress increases, there is a severe but predictable decrease in lifetime[3]. The internal stress level within the machine insulation and the corresponding stress cycle curve are determined by using finite element analysis[4]. It shows that TMS has an important influence on the service life of the motor.

For the analytical model of TMS in electric motors, researchers have derived the analytical expression of thermally induced mechanical stress. In order to reveal the relationship between thermo-mechanical stress and various influencing parameters, the analytical equation of TMS for a single bar and the analytical equation for TMS for the bonded layers have been derived[5][6]. The analytic model of a single bar shows that the TMS on a single bar is proportional to its Young's modulus, coefficient of thermal expansion, and temperature change, independent of the total length. The analytical model of the bonded layer shows that the TMS in the bonded layer is proportional to the difference in the coefficient of thermal expansion and the temperature change between the two layers bound to it[7]. Subsequently, relevant researchers also carried out experimental verification. However, these analytical models often only focus on the study of TMS of specific structures under ideal conditions, and only consider the influence of temperature, without considering the shape of the motor as a whole. Therefore, it is of great significance to analyze the insulation TMS of the motor with temperature from the perspective as a whole.

In this paper, a preliminary analytical model of TMS for motor insulation under temperature change is proposed. The slot shape factor and copper fill factor are introduced, and the model is corrected by using a shallow neural network. The analytical model is verified by finite element simulation(FEA), and finally the accuracy of the analytical model is further proved by experiments.

## II. Numerical Model

### *A. Stator insulation model*

The two-dimensional cross-sectional view of the stator insulation system is shown in Figure 1, including windings, winding insulation coatings, dip paints and other components. During the operation of the motor, the difference in the thermal expansion coefficient of epoxy resin impregnation, winding and stator core will cause great TMS in impregnation. Epoxy resin impregnation is an important part of the winding inter-turn insulation and accounts for a relatively large proportion, so the TMS of motor insulation takes the stress analysis of epoxy resin impregnation as the main goal.

When deriving the insulation TMS analysis model, on the one hand, the insulation, stator core and winding are bonded and the structure is complex; On the other hand, the model needs to consider the structural parameters such as the inner diameter, outer diameter, shaft length, cogging, and groove full ratio of the motor, which makes the derivation of the motor insulation TMS analysis model complicated. In order to accurately calculate the thermomechanical stress of motor insulation, the analytical model derivation adopts a combination of model simplification preliminary derivation and later sensitivity analysis correction.

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# Certificate of Paper Acceptance

For the 26th International Conference on Electrical Machines and Systems

Dear authors,

We are pleased to inform you that your paper titled **Modeling and Analysis of Thermal-mechanical Stress in Motor Insulation** with authors of **Rui Shen, Rui Wang, Jian Zhang, Youtong Fang, Yong Yang, Jie Tian** submitted to the 26$^{th}$ International Conference on Electrical Machines and Systems (ICEMS 2023) has been **accepted by the conference**. Further comments can be found in the submission system.

The ICEMS 2023 will be held in Zhuhai, Guangdong Province, China, during Nov. 5-8, 2023, which is jointly organized by the China Electrotechnical Society, KIEE Electrical Machinery and Energy Conversion Systems Society, and IEEJ Industry Applications Society, hosted by Huazhong University of Science and Technology. The ICEMS 2023 will provide an extensive and exciting platform to gather the world leading scientists, researchers and engineers in the field of electrical machines and systems together to showcase the state-of-art ideas, methods and prototypes. You are invited to participate in the conference to present your paper. Your expertise and experience will greatly contribute to the success of the conference.

Best regards,

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