НАО «Алматинский Университет Энергетики и Связи
имени Гумарбека Даукеева»

ТАЖИБАЕВ АДИЛБЕК АМИРБЕКОВИЧ

**Исследование и разработка методов и средств построения
клиенториентированной комплексной автоматизированной системы
расчета и изготовления трансформаторов**

6D071900 – Радиотехника, электроника и телекоммуникации

Диссертация на соискание степени
доктора философии PhD
в форме серии статей

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АННОТАЦИЯ
диссертационного исследования ТАЖИБАЕВА АДИЛБЕКА АМИРБЕКОВИЧА
на тему: «ИССЛЕДОВАНИЕ И РАЗРАБОТКА МЕТОДОВ И СРЕДСТВ ПОСТРОЕНИЯ КЛИЕНТОРИЕНТИРОВАННОЙ КОМПЛЕКСНОЙ АВТОМАТИЗИРОВАННОЙ СИСТЕМЫ РАСЧЕТА И ИЗГОТОВЛЕНИЯ ТРАНСФОРМАТОРОВ», представленной на соискание степени доктора философии (PhD) по специальности 8D07103 – «Автоматизация и управление»

Общая характеристика работы. Диссертационное исследование представлено к защите в форме серии статей в соответствии с пунктом 5-1Правил присуждения степеней (Приказ Министра науки и высшего образования РК №127 от 31 марта 2011 с изменениями и дополнениями от 18 июля 2024 года). Основанием для выбора данной формы является наличие у соискателя 3 (трех) публикаций в международных рецензируемых научных изданиях, входящих в 1-й и 2-й квартили (Q1, Q2) базы данных Web of Science Core Collection. Совокупность представленных статей образует единое завершенное научное исследование, объединенное общей целью, методологией и объектом исследования.

Цель диссертационного исследования – повышение качества и сокращение сроков изготовления трансформаторного оборудования путем создания комплексной автоматизированной системы, которая объединяет контуры проектирования (CAD), инженерного анализа (CAE) и технологического управления (CAM) в единую цифровую среду с обратной связью.

Задачи исследования:

1. Разработать метод численного анализа и минимизации виброакустической активности реакторного оборудования для интеграции в расчетный модуль системы (Решение в статье №3 – «Cogent Engineering»).

2. Провести экспериментальное исследование и разработать алгоритмы оптимизации процесса сушки твердой изоляции для технологического модуля системы (Решение в статье №2 – «Results in Engineering»).

3. Разработать архитектуру и принципы построения клиентоориентированных систем проектирования, учитывающих требования заказчика на ранних этапах (Решение в статье №1 – «Journal of Computational and Cognitive Engineering»).

4. Создать программно-алгоритмические средства (САПР) для реализации предложенных методов (Решение в статье №1 – Journal of Computational and Cognitive Engineering).

Объектом исследования является автоматизированное управление процессами проектирования и производства высоковольтного маслонаполненного оборудования (трансформаторов и реакторов).

Предмет исследования: методы и алгоритмы автоматизации расчета, конструирования и управления технологическими параметрами изготовления (на примере виброакустических процессов и сушки изоляции).

Методология исследования основана на индуктивном системном подходе. Исследование строилось по принципу «от частного к общему»:

1. На первом этапе (2023–2024 годы) нами были решены задачи идентификации и автоматизации критических технологических подсистем.

– Была разработана математическая модель для подсистемы анализа виброакустики (статья в журнале *Cogent Engineering*, Q2).

– И синтезированы алгоритмы управления процессом сушки изоляции для подсистемы CAM (статья в журнале *Results in Engineering*, Q1).

2. На втором, завершающем этапе (2025 год), на основе полученных моделей и алгоритмов был выполнен теоретический синтез. Была разработана общая архитектура клиентоориентированной системы, которая объединила эти частные решения. Результаты

этого обобщения представлены в обзорно-аналитической статье (*Journal of Computational and Cognitive Engineering,* Q1).

Научная новизна полученных результатов:

1. Впервые обоснована концепция клиентоориентированной автоматизированной системы трансформаторостроения, отличающаяся сквозной интеграцией требований заказчика в технологические переделы (сушка, сборка).

2. Разработан метод оценки виброакустических характеристик шунтирующих реакторов, отличающийся учетом влияния конструктивных демпферов на резонансные частоты активной части.

3. Установлены закономерности кинетики сушки твердой изоляции, позволившие разработать алгоритм выбора оптимального метода термовакуумной обработки для повышения диэлектрической прочности.

Основные положения, выносимые на защиту:

1. Архитектура комплексной системы проектирования, обеспечивающая трансформацию требований заказчика в верифицированные технические решения.

2. Методика расчетного анализа виброактивности реакторов, позволяющая на этапе проектирования обеспечить соответствие санитарным нормам шума.

3. Технологический алгоритм управления процессом сушки изоляции, обеспечивающий максимизацию ресурса трансформатора за счет удаления влаги без деструкции целлюлозы.

Актуальность диссертационного исследования.

Трансформаторостроение как ключевая отрасль энергетического машиностроения остаётся одной из наиболее трудоёмких и консервативных сфер. Традиционные методы проектирования с использованием разрозненных систем САПР, документооборота и планирования не соответствуют современным требованиям по скорости обработки данных, адаптивности и точности расчётов.

В условиях Индустрии 4.0 современное трансформаторостроение сталкивается с системной проблемой. Существующие средства автоматизации носят «островной» характер:

– конструкторы работают в своих CAD-системах;

– расчетчики — в изолированных математических пакетах;

– технологи в цехе управляют процессами (такими как сушка или сборка), зачастую на основе эмпирического опыта, без прямой цифровой связи с исходным проектом.

Этот разрыв информационных потоков приводит к тому, что требования заказчика теряются на стыках этапов, а физические ограничения производства (например, вибрационные риски) не учитываются при проектировании. Это также приводит к увеличению сроков разработки и снижению эксплуатационной надежности.

Таким образом, актуальной научной и практической задачей является создание клиентоориентированной комплексной автоматизированной системы управления процессами расчёта и изготовления трансформаторов (ККАСУПРИТ), объединяющей инженерные расчёты, конструкторско-технологическую документацию, производственные процессы и взаимодействие с заказчиком в едином цифровом контуре предприятия.

Практическая значимость результатов исследований.

Разработанная клиентоориентированная комплексная автоматизированная система управления процессами расчёта и изготовления трансформаторов (ККАСУПРИТ) внедрена в производственную практику предприятий ТОО «Asia Trafo» и ТОО «TRENCO R&D», где продемонстрировала значительный технологический, организационный и экономический эффект. Средняя длительность проектного цикла уменьшилась с 45 до 30 календарных дней, а время согласования технической документации — с 10 до 3 дней. Количество ошибок, выявляемых при передаче данных между расчётными и производственными подразделениями, снизилось более чем в пять раз. В технологической части производства разработанная и внедрённая технология вакуумной сушки под изостатическим

прессованием обеспечила повышение степени полимеризации изоляции, улучшение её диэлектрических свойств и увеличение срока службы трансформаторов на 10–12 %. Время полного цикла сушки сократилось более чем вдвое, а энергозатраты на процесс снизились на 30%. В области виброакустических характеристик шунтирующих реакторов реализованы практические меры по снижению уровня шума на 18 % и вибрации — на 25%.

Экономическая эффективность внедрения ККАСУПРИТ подтверждается снижением прямых затрат на проектирование и сопровождение заказов на 22–25%, сокращением длительности производственного цикла на 20–25% и увеличением производительности инженерных подразделений на 40%. В целом внедрение системы позволило повысить конкурентоспособность предприятий, увеличить количество одновременно выполняемых заказов и расширить экспортный потенциал продукции.

Достоверность результатов. Все полученные результаты подтверждаются результатами компьютерного моделирования в CAD-системе TRDO/TDS, их согласованностью с экспериментальными данными и экспертными оценками. Научные положения и выводы исследования прошли апробацию в виде публикаций в рецензируемых международных журналах (Q1–Q2 Web of Science) и рекомендованных КОКСНВО отечественных изданиях, а также в полученных охранных документах, что подтверждает воспроизводимость и значимость работы.

Соответствие направлениям развития науки или государственным программам.

Исследования выполнялись в соответствии с утверждённым планом исследований и в рамках следующих научных проектов:

– ГСНС/ГМНС № 5 от 10 ноября 2021 г. «Разработка и внедрение клиенториентированной комплексной автоматизированной системы расчёта и изготовления трансформаторов»;

– АР14871951 «Увеличение срока службы трансформаторов методом исследования процессов сушки и прессовки твёрдой изоляции»;

– АР09057919 «Исследование уменьшения вибрации и шума в реакторах на класс напряжения 110–750 кВ с целью увеличения жизненного цикла».

Структура диссертационной работы, представленной в виде серии статей.

Диссертационная работа представлена в виде серии научных статей и охранных документов, опубликованных соискателем лично и в соавторстве, в которых последовательно изложены и обоснованы основные научные положения диссертации.

Диссертационная работа включает следующие публикации:

1. **Tazhibayev A.A.,** Utepbergenov I.T., Skliarova I.V. *Development of Customer-Focused Automated Systems for Transformer Design and Manufacturing: A Comprehensive Review // Journal of Computational and Cognitive Engineering*. – 2025.

(Вклад соискателя – соискатель инициировал и подготовил основную часть обзорного исследования, сформулировал концепцию клиентоориентированных автоматизированных систем, выполнил анализ существующих подходов и обобщение результатов.)

2. **Tazhibayev A.,** Amitov Y., Arynov N., Shingissov N., Kural A. *Experimental investigation and evaluation of drying methods for solid insulation in transformers: A comparative analysis // Results in Engineering*. – 2024.

(Вклад соискателя – соискатель разработал методику экспериментальных исследований, участвовал в обработке и интерпретации экспериментальных данных.)

3. **Tazhibayev A.,** Utepbergenov I.T., Amitov Y., Ateyev D. *Assessing noise and vibration mitigation in low-vibroacoustic shunt reactors // Cogent Engineering*. – 2024.

(Вклад соискателя – соискатель внёс основной вклад в анализ виброакустических характеристик и предложил инженерные решения по их снижению.)

4. **Тажибаев А.А.,** Утепбергенов И.Т., Амитов Е.Т., Атеев Д.Т. *Подход к снижению шума и вибрации шунтирующих реакторов на основе усовершенствования конструкции и*

применяемых материалов // Вестник Алматинского университета энергетики и связи. – 2023.

(Вклад соискателя – соискатель разработал конструктивные предложения и обосновал выбор материалов.)

5. **Тажибаев А.,** Утепбергенов И., Амитов Е., Склярова Ю., Кулакбаев Г. *Analysis of automation strategy for integrated customer-oriented system via smart digital nodes in distribution transformers // Вестник КазАТК.* – 2024.

(Вклад соискателя – соискатель сформулировал архитектуру автоматизированной системы и участвовал в разработке алгоритмов управления.)

6. Амитов Е., **Тажибаев А.,** Атеев Д., Арынов Н., Шингисов Н. *Исследование методов сушки с прессованием твердой изоляции силовых трансформаторов с целью увеличения жизненного цикла // Вестник КазАТК.* – 2024.

(Вклад соискателя – соискатель принимал участие в постановке задачи и анализе результатов исследований.)

В рамках выполнения диссертационной работы также получены охранные документы:

– Свидетельство о внесении в государственный реестр прав на объекты, охраняемые авторским правом №28228 (2022). Клиентоориентированная комплексная автоматизированная система расчета «REng».

(Вклад соискателя – соискатель участвовал в разработке программной архитектуры и функциональных модулей.)

– Патенты на полезные модели и изобретения (2022–2024 гг.), включая высокоэффективные батарейные системы хранения энергии, шунтирующие реакторы, измерительные трансформаторы тока и системы непрерывного контроля трансформаторного оборудования.

– (Вклад соискателя – соискатель принимал участие в разработке технических решений, схемных и конструктивных параметров, а также в подготовке патентной документации.)

Первое выносимое на защиту положение диссертационной работы обосновано в статьях 1 и 5, посвящённых разработке и анализу клиентоориентированных автоматизированных систем расчёта и проектирования трансформаторного оборудования.

Второе положение доказано в статьях 2 и 6, в которых исследуются методы сушки и прессования твёрдой изоляции силовых трансформаторов и их влияние на увеличение жизненного цикла оборудования.

Третье положение подтверждено результатами, представленными в статьях 3 и 4, посвящённых снижению шума и вибрации шунтирующих реакторов за счёт конструктивных и материаловедческих решений.

Полученные патенты и свидетельства непосредственно связаны с практической реализацией научных результатов диссертации и подтверждают их прикладную значимость.

Все публикации удовлетворяют требованиям пункта 5-1 «Правил присуждения учёных степеней».

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ABSTRACT
of the dissertation research by
TAZHIBAYEV ADILBEK AMIRBEKOVICH
on the topic:
**"RESEARCH AND DEVELOPMENT OF METHODS AND TOOLS FOR FORMATION
A CUSTOMER-ORIENTED INTEGRATED AUTOMATED SYSTEM FOR
CALCULATING AND MANUFACTURING TRANSFORMERS"**,
submitted for the degree of Doctor of Philosophy (PhD) in the specialty
8D07103 – Automation and Control

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General Characteristics of the Research. The dissertation research is submitted for defense in the form of a series of scientific articles in accordance with Clause 5-1 of the Rules for Awarding Academic Degrees (Order of the Minister of Science and Higher Education of the Republic of Kazakhstan No. 127 dated March 31, 2011, as amended on July 18, 2024). The choice of this format is justified by the applicant's authorship of three publications in international peer-reviewed scientific journals indexed in the Web of Science Core Collection and ranked in the first and second quartiles (Q1, Q2). The set of submitted articles constitutes a unified, completed scientific study, integrated by a common goal, methodology, and object of research.

Purpose of the Research. The purpose of the dissertation research is to improve quality and reduce production lead time of transformer equipment by creating an integrated automated system that combines design (CAD), engineering analysis (CAE), and manufacturing management (CAM) loops into a single digital environment with feedback.

Research Objectives:

1. To develop a method for numerical analysis and minimization of vibroacoustic activity of reactor equipment for integration into the system's calculation module (solution presented in Article No. 3, *Cogent Engineering*).

2. To conduct experimental research and develop optimization algorithms for the solid insulation drying process for the technological module of the system (solution presented in Article No. 2, *Results in Engineering*).

3. To develop an architecture and principles for building customer-oriented design systems that take customer requirements into account at early design stages (solution presented in Article No. 1, *Journal of Computational and Cognitive Engineering*).

4. To create software and algorithmic tools (CAD systems) for implementing the proposed methods (solution presented in Article No. 1, *Journal of Computational and Cognitive Engineering*).

Object of Research. The object of the research is automated control of design and manufacturing processes of high-voltage oil-filled equipment (transformers and reactors).

Subject of Research: The subject of the research includes methods and algorithms for automating calculations, design, and control of technological manufacturing parameters (with vibroacoustic processes and insulation drying taken as case studies).

Research Methodology. The research methodology is based on an inductive systems approach and follows the principle "from the particular to the general":

Stage 1 (2023–2024): Problems of identification and automation of critical technological subsystems were solved.

-A mathematical model for vibroacoustic analysis was developed (article in *Cogent Engineering*, Q2).

-Control algorithms for the insulation drying process were synthesized for the CAM subsystem (article in *Results in Engineering*, Q1).

Stage 2 (2025): Based on the obtained models and algorithms, theoretical synthesis was performed. A general architecture of a customer-oriented system integrating these partial

solutions was developed. The results were presented in a review and analytical article (*Journal of Computational and Cognitive Engineering*, Q1).

Scientific Novelty:

1. For the first time, the concept of a customer-oriented automated transformer manufacturing system has been substantiated, characterized by end-to-end integration of customer requirements into technological processes (drying, assembly).

2. A method for evaluating vibroacoustic characteristics of shunt reactors has been developed, accounting for the influence of structural dampers on resonance frequencies of the active part.

3. Regularities of solid insulation drying kinetics have been identified, enabling the development of an algorithm for selecting optimal thermo-vacuum treatment methods to enhance dielectric strength.

Main Provisions Submitted for Defense:

1. Architecture of an integrated design system ensuring transformation of customer requirements into verified technical solutions.

2. Methodology for computational analysis of reactor vibroactivity that ensures compliance with sanitary noise standards at the design stage.

3. Technological algorithm for controlling the insulation drying process, ensuring maximization of transformer service life through moisture removal without cellulose degradation.

Relevance of the Research.

Transformer manufacturing, as a key sector of power engineering, remains one of the most labor-intensive and conservative industries. Traditional design approaches based on fragmented CAD systems, document management, and planning tools no longer meet modern requirements for data processing speed, adaptability, and calculation accuracy.

Under Industry 4.0 conditions, transformer manufacturing faces a systemic problem: existing automation tools are fragmented. Designers work in isolated CAD systems, analysts use independent calculation packages, and technologists manage manufacturing processes—such as drying and assembly—often based on empirical experience without direct digital linkage to the original design.

This discontinuity leads to loss of customer requirements at stage interfaces and neglect of physical production constraints (e.g., vibration risks) during design, increasing development time and reducing operational reliability.

Thus, an urgent scientific and practical task is the creation of a customer-oriented integrated automated system for transformer calculation and manufacturing, uniting engineering calculations, design and technological documentation, production processes, and customer interaction within a single digital enterprise environment.

Practical Significance.

The developed customer-oriented integrated automated system for transformer calculation and manufacturing has been implemented at **Asia Trafo LLP** and **TRENCO R&D LLP**, demonstrating significant technological, organizational, and economic effects. The average project cycle duration was reduced from 45 to 30 calendar days, and technical documentation approval time—from 10 to 3 days. Data transfer errors between design and production departments decreased more than fivefold.

The implemented vacuum drying technology under isostatic pressing increased insulation polymerization degree, improved dielectric properties, and extended transformer service life by 10–12%. Drying cycle time was reduced by more than half, and energy consumption decreased by 30%. Vibroacoustic measures reduced shunt reactor noise by 18% and vibration by 25%.

Economic efficiency is confirmed by a 22–25% reduction in direct design and order support costs, a 20–25% decrease in production cycle duration, and a 40% increase in engineering productivity, enhancing enterprise competitiveness and export potential.

Reliability of Results.

All results are confirmed by CAD-based computer modeling (TRDO/TDS), agreement with experimental data, and expert evaluations. Research findings were validated through publications

in international peer-reviewed journals (Q1–Q2 Web of Science), national journals recommended by the Committee for Quality Assurance in Science and Higher Education, and obtained intellectual property protection documents.

Compliance with National Scientific Programs.

The research was conducted in accordance with approved research plans and within the framework of the following projects:

- GSSS/GMSN No. 5 dated November 10, 2021: "Development and implementation of a customer-oriented integrated automated system for transformer calculation and manufacturing".
- AP14871951: "Extending transformer service life through research of solid insulation drying and pressing processes".
- AP09057919: "Investigation of vibration and noise reduction in reactors of 110–750 kV voltage class".

Structure of the Dissertation Submitted in the Form of a Series of Articles.

The dissertation is presented in the form of a series of scientific articles and intellectual property protection documents, published by the applicant individually and in co-authorship, in which the main scientific provisions of the dissertation are consistently presented and substantiated.

The dissertation includes the following publications:

1. **Tazhibayev A.A.**, Utepbergenov I.T., Skliarova I.V. *Development of Customer-Focused Automated Systems for Transformer Design and Manufacturing: A Comprehensive Review // Journal of Computational and Cognitive Engineering.* –2025.

(Author's contribution – the applicant initiated and prepared the main part of the review study, formulated the concept of customer-oriented automated systems, analyzed existing approaches, and generalized the results.)

2. **Tazhibayev A.**, Amitov Y., Arynov N., Shingissov N., Kural A. *Experimental investigation and evaluation of drying methods for solid insulation in transformers: A comparative analysis // Results in Engineering.* – 2024.

(Author's contribution – the applicant developed the experimental research methodology and participated in the processing and interpretation of experimental data.)

3. **Tazhibayev A.**, Utepbergenov I.T., Amitov Y., Ateyev D. *Assessing noise and vibration mitigation in low-vibroacoustic shunt reactors // Cogent Engineering.* – 2024.

(Author's contribution – the applicant made the primary contribution to the analysis of vibroacoustic characteristics and proposed engineering solutions for their reduction.)

4. **Tazhibayev A.A.**, Utepbergenov I.T., Amitov E.T., Ateyev D.T. *An approach to reducing noise and vibration of shunt reactors based on improvements in design and applied materials // Bulletin of the Almaty University of Power Engineering and Telecommunications.* – 2023.

(Author's contribution – the applicant developed design proposals and justified the selection of materials.)

5. **Tazhibayev A.**, Utepbergenov I., Amitov E., Skliarova Y., Kulakbayev G. *Analysis of automation strategy for an integrated customer-oriented system via smart digital nodes in distribution transformers // Bulletin of KazATC.* – 2024.

(Author's contribution – the applicant formulated the architecture of the automated system and participated in the development of control algorithms.)

6. Amitov E., **Tazhibayev A.,** Ateyev D., Arynov N., Shingissov N. *Investigation of drying and pressing methods for solid insulation of power transformers aimed at extending equipment service life // Bulletin of KazATC.* – 2024.

(Author's contribution – the applicant participated in problem formulation and analysis of research results.)

Intellectual Property Protection Documents Obtained Within the Dissertation Research
As part of the dissertation research, the following intellectual property protection documents were obtained:

- Certificate of registration in the State Register of Copyrighted Objects No. 28228 (2022): *Customer-oriented integrated automated calculation system "REng".* *(Author's contribution – the applicant participated in the development of the software architecture and functional modules.).*

- Patents for utility models and inventions (2022–2024), including high-efficiency battery energy storage systems, shunt reactors, current transformers, and continuous monitoring systems for transformer equipment.
(Author's contribution – the applicant participated in the development of technical solutions, schematic and structural parameters, as well as in the preparation of patent documentation.)

The first dissertation provision submitted for defense is substantiated in Publications 1 and 5, which are devoted to the development and analysis of customer-oriented automated systems for calculation and design of transformer equipment.

The second provision is substantiated in Publications 2 and 6, which investigate drying and pressing methods for solid insulation of power transformers and their impact on extending equipment service life.

The third provision is confirmed by the results presented in Publications 3 and 4, which address noise and vibration reduction in shunt reactors through design and materials engineering solutions.

The obtained patents and certificates are directly related to the practical implementation of the dissertation's scientific results and confirm their applied significance.

All publications comply with the requirements of Clause 5-1 of the *Rules for Awarding Academic Degrees*.

АННОТАЦИЯ
ТАЖИБАЕВ АДИЛБЕК АМИРБЕКОВИЧТІҢ
диссертациялық зерттеуіне
Тақырыбы:
«ТРАНСФОРМАТОРЛАРДЫ ЕСЕПТЕУ МЕН ӨНДІРУДІҢ ТҰТЫНУШЫҒА БАҒЫТТАЛҒАН ИНТЕГРАЦИЯЛАНҒАН АВТОМАТТАНДЫРЫЛҒАН ЖҮЙЕСІН ҚҰРУ ӘДІСТЕРІ МЕН ҚҰРАЛДАРЫН ЗЕРТТЕУ ЖӘНЕ ӘЗІРЛЕУ»,
8D07103 – «Автоматтандыру және басқару» білім беру бағдарламасы бойынша философия докторы (PhD) ғылыми дәрежесін алу үшін ұсынылған.

Жұмыстың жалпы сипаттамасы.
Диссертациялық зерттеу Қазақстан Республикасы Ғылым және жоғары білім министрінің 2011 жылғы 31 наурыздағы №127 бұйрығымен бекітілген (2024 жылғы 18 шілдедегі өзгерістер мен толықтыруларды ескере отырып) «Ғылыми дәрежелер беру қағидаларының» 5-1-тармағына сәйкес ғылыми мақалалар сериясы түрінде қорғауға ұсынылған.

Бұл нысанды таңдаудың негізі – ізденушінің Web of Science Core Collection деректер базасының 1-ші және 2-ші квартилдеріне (Q1, Q2) кіретін халықаралық рецензияланатын ғылыми журналдарда жарияланған үш мақаласының болуы.

Ұсынылған мақалалар жиынтығы ортақ мақсатпен, әдіснамамен және зерттеу объектісімен біріктірілген, аяқталған біртұтас ғылыми зерттеуді құрайды.

Диссертациялық зерттеудің мақсаты.
Кері байланысы бар бірыңғай цифрлық ортада жобалау (CAD), инженерлік талдау (CAE) және технологиялық басқару (CAM) контурларын біріктіретін кешенді автоматтандырылған жүйені құру арқылы трансформатор жабдықтарын дайындау сапасын арттыру және өндіру мерзімін қысқарту.

Зерттеу міндеттері:
1. Реакторлық жабдықтың виброакустикалық белсенділігін сандық талдау және оны азайту әдісін әзірлеп, жүйенің есептік модуліне енгізу (шешім №3 мақалада – *Cogent Engineering*).

2. Қатты оқшауламаны кептіру процесін эксперименттік зерттеу және технологиялық модуль үшін оңтайландыру алгоритмдерін әзірлеу (шешім №2 мақалада – *Results in Engineering*).

3. Тапсырыс берушінің талаптарын жобалаудың бастапқы кезеңдерінде ескеретін клиентке бағдарланған жобалау жүйелерінің архитектурасы мен қағидаларын әзірлеу (шешім №1 мақалада – *Journal of Computational and Cognitive Engineering*).

4. Ұсынылған әдістерді іске асыру үшін бағдарламалық-алгоритмдік құралдарды (САПР) әзірлеу (шешім №1 мақалада).

Зерттеу объектісі.
Жоғары кернеулі маймен толтырылған жабдықтарды (трансформаторлар мен реакторларды) жобалау және өндіру процестерін автоматтандырылған басқару.

Зерттеу пәні.
Есептеу, конструкциялау және өндірістік технологиялық параметрлерді басқаруды автоматтандыру әдістері мен алгоритмдері (виброакустикалық процестер мен оқшауламаны кептіру мысалында).

Зерттеу әдіснамасы.
Зерттеу индуктивті жүйелік тәсілге негізделген және «жекеден жалпыға» қағидаты бойынша жүргізілді.

Бірінші кезеңде (2023–2024 жж.) маңызды технологиялық қосалқы жүйелерді сәйкестендіру және автоматтандыру міндеттері шешілді:
- виброакустиканы талдау қосалқы жүйесіне арналған математикалық модель әзірленді

(*Cogent Engineering*, Q2);

- CAM қосалқы жүйесі үшін оқшауламаны кептіру процесін басқару алгоритмдері синтезделді (*Results in Engineering*, Q1).

Екінші, қорытынды кезеңде (2025 ж.) алынған модельдер мен алгоритмдер негізінде теориялық синтез жүргізілді. Жекелеген шешімдерді біріктіретін клиентке бағдарланған жүйенің жалпы архитектурасы әзірленді. Нәтижелер шолу-талдамалық мақалада ұсынылды (*Journal of Computational and Cognitive Engineering*, Q1).

Ғылыми жаңалығы:

1. Алғаш рет трансформатор жасауда клиентке бағдарланған автоматтандырылған жүйе тұжырымдамасы негізделді, ол тапсырыс беруші талаптарының технологиялық кезеңдерге (кептіру, жинақтау) үздіксіз интеграциясымен ерекшеленеді.

2. Шунттаушы реакторлардың виброакустикалық сипаттамаларын бағалау әдісі әзірленді, ол белсенді бөліктің резонанстық жиіліктеріне конструктивтік демпферлердің әсерін ескереді.

3. Қатты оқшауламаны кептіру кинетикасының заңдылықтары анықталып, диэлектрлік беріктікті арттыру үшін оңтайлы термовакуумдық өңдеу әдісін таңдау алгоритмін әзірлеуге мүмкіндік берді.

Қорғауға ұсынылатын негізгі қағидалар:

1. Тапсырыс беруші талаптарын верификацияланған техникалық шешімдерге түрлендіруді қамтамасыз ететін кешенді жобалау жүйесінің архитектурасы.

2. Жобалау сатысында шу бойынша санитарлық нормаларға сәйкестікті қамтамасыз ететін реакторлардың вибробелсенділігін есептік талдау әдістемесі.

3. Целлюлозаны бұзбай ылғалды жою арқылы трансформатордың қызмет ету мерзімін барынша арттыратын оқшауламаны кептіру процесін басқару алгоритмі.

Зерттеудің өзектілігі.

Трансформатор жасау энергетикалық машина жасау саласының негізгі бағыттарының бірі бола отырып, ең еңбек сыйымды және консервативті салалардың қатарында қалып отыр. САПР жүйелерін, құжат айналымын және жоспарлауды бөлек қолдануға негізделген дәстүрлі жобалау тәсілдері деректерді өңдеу жылдамдығы, бейімделгіштік және есептеу дәлдігі бойынша қазіргі талаптарға сай келмейді.

Индустрия 4.0 жағдайында трансформатор жасау саласы жүйелік мәселеге тап болуда: автоматтандыру құралдары «аралдық» сипатқа ие. Конструкторлар жеке CAD жүйелерінде, есептеушілер оқшауланған математикалық пакеттерде, ал цехтағы технологтар кептіру мен жинақтау сияқты процестерді бастапқы жобамен тікелей цифрлық байланыссыз, көбінесе эмпирикалық тәжірибеге сүйене отырып басқарады.

Бұл ақпараттық ағындардың үзілуі тапсырыс беруші талаптарының кезеңдер түйісінде жоғалуына, өндірістік шектеулердің (мысалы, діріл тәуекелдерінің) жобалау кезінде ескерілмеуіне әкеледі. Нәтижесінде әзірлеу мерзімі ұзартып, пайдалану сенімділігі төмендейді.

Осыған байланысты трансформаторларды есептеу және дайындау процестерін басқарудың клиентке бағдарланған кешенді автоматтандырылған жүйесін (ККАСУПРИТ) құру өзекті ғылыми-практикалық міндет болып табылады.

Практикалық маңыздылығы.

Әзірленген ККАСУПРИТ жүйесі «Asia Trafo» ЖШС және «TRENCO R&D» ЖШС кәсіпорындарында өндірістік тәжірибеге енгізіліп, айтарлықтай технологиялық, ұйымдастырушылық және экономикалық тиімділігін көрсетті.

Жобалау циклының орташа ұзақтығы 45 күннен 30 күнге дейін қысқарды, техникалық құжаттаманы келісу уақыты 10 күннен 3 күнге дейін азайды. Есептеу және өндірістік бөлімшелер арасындағы деректерді беру кезінде анықталатын қателер саны бес еседен астам төмендеді.

Вакуумдық кептіруді изостатикалық престеумен біріктіретін технология оқшауламаның полимерлену дәрежесін арттырып, диэлектрлік қасиеттерін жақсартты және

трансформаторлардың қызмет ету мерзімін 10–12 %-ға ұзартты. Кептірудің толық циклы екі еседен астам қысқарып, энергия шығыны 30 %-ға төмендеді. Шунттаушы реакторлардың шу деңгейі 18 %-ға, дірілі 25 %-ға азайтылды.

Экономикалық тиімділік жобалау мен тапсырыстарды сүйемелдеуге кететін тікелей шығындардың 22–25 %-ға төмендеуімен, өндірістік циклдің 20–25 %-ға қысқаруымен және инженерлік бөлімшелердің өнімділігінің 40 %-ға артуымен расталды.

Нәтижелердің дұрыстығы.

Барлық алынған нәтижелер TRDO/TDS CAD жүйесіндегі компьютерлік модельдеу деректерімен, эксперименттік нәтижелермен және сараптамалық бағалаулармен расталған. Зерттеу нәтижелері Q1–Q2 Web of Science журналдарындағы жарияланымдарда, КОКСНВО ұсынған отандық басылымдарда және алынған қорғау құжаттарында апробациядан өтті.

Ғылымды дамыту бағыттарына немесе мемлекеттік бағдарламаларға сәйкестігі.

Зерттеулер бекітілген зерттеу жоспарына сәйкес және келесі ғылыми жобалар аясында орындалды:

- ГСНС/ГМНС №5 (2021 жылғы 10 қараша) – *«Трансформаторларды есептеу және дайындауға арналған клиентке бағдарланған кешенді автоматтандырылған жүйені әзірлеу және енгізу»*;

- AP14871951 – *«Қатты оқшауламаны кептіру және престеу процестерін зерттеу арқылы трансформаторлардың қызмет ету мерзімін ұлғайту»*;

- AP09057919 – *«Қызмет ету мерзімін арттыру мақсатында кернеу класы 110–750 кВ реакторлардағы діріл мен шуды төмендетуді зерттеу»*.

Ғылыми мақалалар сериясы түрінде ұсынылған диссертациялық жұмыстың құрылымы.

Диссертациялық жұмыс ізденушінің жеке өзі және бірлескен авторлықта жариялаған ғылыми мақалалар мен зияткерлік меншік объектілеріне арналған қорғау құжаттары сериясы түрінде ұсынылған. Бұл еңбектерде диссертацияның негізгі ғылыми қағидалары жүйелі түрде баяндалып, негізделген.

Диссертациялық жұмыс келесі жарияланымдарды қамтиды:

1. **Tazhibayev A.A.,** Utepbergenov I.T., Skliarova I.V. *Development of Customer-Focused Automated Systems for Transformer Design and Manufacturing: A Comprehensive Review // Journal of Computational and Cognitive Engineering.* –2025.

(Ізденушінің үлесі – ізденуші шолу зерттеуін бастамалап, оның негізгі бөлігін дайындады, клиентке бағдарланған автоматтандырылған жүйелер тұжырымдамасын қалыптастырды, қолданыстағы тәсілдерге талдау жүргізіп, нәтижелерді жалпылады.)

2. **Tazhibayev A.**, Amitov Y., Arynov N., Shingissov N., Kural A. *Experimental investigation and evaluation of drying methods for solid insulation in transformers: A comparative analysis // Results in Engineering.* – 2024.

(Ізденушінің үлесі – ізденуші эксперименттік зерттеулер әдістемесін әзірледі, эксперименттік деректерді өңдеу мен интерпретациялауға қатысты.)

3. **Tazhibayev A.**, Utepbergenov I.T., Amitov Y., Ateyev D. *Assessing noise and vibration mitigation in low-vibroacoustic shunt reactors // Cogent Engineering.*–2024.

(Ізденушінің үлесі – ізденуші виброакустикалық сипаттамаларды талдауға негізгі үлес қосты және оларды төмендетуге бағытталған инженерлік шешімдер ұсынды.)

4. **Тажибаев А.А.,** Утепбергенов И.Т., Амитов Е.Т., Атеев Д.Т. *Конструкцияны және қолданылатын материалдарды жетілдіру негізінде шунттаушы реакторлардың шуын және дірілін төмендету тәсілі // Алматы энергетика және байланыс университетіні ұхабаршысы.*–2023.

(Ізденушінің үлесі – ізденуші конструктивтік ұсыныстарды әзірлеп, материалдарды таңдауды негіздеді.)

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(Ізденушінің үлесі – ізденуші зерттеу міндетін қоюға және алынған нәтижелерді талдауға қатысты.)

Диссертациялық жұмысты орындау барысында алынған қорғау құжаттары. Диссертациялық жұмысты орындау аясында келесі зияткерлік меншік объектілеріне қорғау құжаттары алынған:

- Авторлық құқықпен қорғалатын объектілердің мемлекеттік тізіліміне енгізу туралы №28228 куәлік (2022 ж.).

«REng» клиентке бағдарланған кешенді автоматтандырылған есептеу жүйесі.

(Ізденушінің үлесі – ізденуші бағдарламалық архитектура мен функционалдық модульдерді әзірлеуге қатысты.)

- Пайдалы модельдер мен өнертабыстарға арналған патенттер (2022–2024 жж.), оның ішінде жоғары тиімді аккумуляторлық энергия сақтау жүйелері, шунттаушы реакторлар, ток өлшеу трансформаторлары және трансформатор жабдықтарын үздіксіз бақылау жүйелері. *(Ізденушінің үлесі – ізденуші техникалық шешімдерді, сұлбалық және конструктивтік параметрлерді әзірлеуге, сондай-ақ патенттік құжаттаманы дайындауға қатысты.)*

Диссертациялық жұмыстың қорғауға ұсынылатын бірінші қағидасы трансформатор жабдықтарын есептеу және жобалауға арналған клиентке бағдарланған автоматтандырылған жүйелерді әзірлеу мен талдауға арналған 1 және 5-мақалаларда негізделген.

Екінші қағида қатты оқшауламаны кептіру және престеу әдістерін, сондай-ақ олардың жабдықтың қызмет ету мерзімін арттыруға әсерін зерттейтін 2 және 6-мақалаларда дәлелденген.

Үшінші қағида конструктивтік және материалтанулық шешімдер арқылы шунттаушы реакторлардың шуын және дірілін төмендетуге арналған 3 және 4-мақалаларда ұсынылған нәтижелермен расталған.

Алынған патенттер мен куәліктер диссертациялық жұмыстың ғылыми нәтижелерін тәжірибеде іске асырумен тікелей байланысты және олардың қолданбалы маңыздылығын растайды.

Барлық жарияланымдар «Ғылыми дәрежелер беру қағидаларының» 5-1-тармағының талаптарына толық сәйкес келеді.

Assessing noise and vibration mitigation in low-vibroacoustic shunt reactors

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Assessing noise and vibration mitigation in low-vibroacoustic shunt reactors

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ABSTRACT

Reactors produce noise that negatively impacts the environment during their operation. This study focused on vibration and noise reduction in shunt oil reactors through an enhanced design, aiming to mitigate these environmental consequences. Additionally, the precision of measuring vibroacoustic characteristics was enhanced by employing the finite element method. This study utilized the 110–750 kV reactor, POM-60000/525-У1. To minimize noise and vibrations from the active part to the tank, the rubber gaskets' thicknesses, dimensions, and placements were carefully chosen, considering the magnetic system's design specifics and pressing forces within the reactor frame. The reactor's design underwent improvements through modeling and optimization. In the revised design, the number of radiators in the cooling system on both sides and the stiffeners on the reactor tank's walls were increased, while the reactor's overall dimensions were preserved. The isosurfaces derived from vibroacoustic testing on the reactor tank model facilitated the processing and visualization of results, thereby validating the model's accuracy and effectiveness. The average background noise levels of the enhanced reactor were significantly lowered, with the noise difference between the reactor and its surroundings being nearly double that of its existing counterpart. Since noise from wall vibrations and the cooling system impacts reactor lifecycles, reducing these vibrations is crucial for extending the lifespan of the improved reactor.

1. Introduction

In power grids, shunt oil reactors play a crucial role in enhancing the capacities of ultra-high-voltage lines, mitigating reactive power in voltage lines, and stabilizing both reactive power and voltage levels (Belyaev et al., 2005; Meiying, 2019; Yinbiao et al., 2018). Reactive power flow within electrical networks is a dynamic process, oscillating between consumption and generation. An excess of reactive power can lead to heightened active losses and an increase in grid frequency (Bengtsson et al., 2020; Sun et al., 2017). Load variations alter the system's characteristics, modifying the flow of reactive current. This flow induces a voltage drop, lowering the system voltage below its no-load value, and results in additional network losses. To address fluctuations in reactive power demand, stemming from changes in power consumption or generation, systems often undergo adjustments or compensations. These measures ensure that operations continue within defined and acceptable parameters (Aali, 2017).

In networks characterized by predictable and stable power consumption and generation, capacitor banks or fixed-power shunt reactors are employed to manage reactive power. This compensation occurs under specific operating conditions to maintain system efficiency. Introducing mechanical switching to these units can further enhance their operational flexibility. Shunt reactors play a pivotal role in stabilizing voltage levels, ensuring fluctuations remain within a 2% threshold. Additionally, they contribute

Table 1. Main technical data related to POM-60000/525-У1.

Name	Technical specifications
Rated power, kVA	60,000
Rated voltage, kV	525/√3
Rated highest voltage, kV	550√3
Rated current, A	197.94
Rated total resistance, Ω	1531.6
Losses adjusted to an estimated temperature of 75°C	140
Connection scheme in the three-phase group	У$_0$
Frequency, Hz	50
Number of phases	1
Type of cooling	ONAN
Neutral of winding	Grounded
Winding material	Copper
Oil grade (type)	Nytro Lyra X

to a reduction in power losses, typically between 15 and 20%, thereby bolstering system stability and overall capacity (Tong et al., 2017).

During operation, transformer-reactor equipment generates noise, which in turn has adverse effects on the environment. The noise in reactors originates from the vibration of the active components and the cooling system's fans. Concurrently, the equipment's vibration, the primary source of this noise, compromises its mechanical integrity, shortening its lifespan and elevating the risk of internal damage. Notably, DC control windings, employed to maintain a constant magnetic bias flux, significantly contribute to vibration and noise by altering the core's magnetic saturation level (Shuai et al., 2015; Zhang et al., 2019).

Magnetostriction in siliceous steel, which causes deformation of the crystal lattice in magnetic materials during magnetization, along with electromagnetic forces between the discs in the active zone and dynamic forces within the windings, are primary factors contributing to reactor vibration (Chen et al., 2019; Gao et al., 2009; Yuan et al., 2022). Consequently, there is an increasing focus on processes aimed at minimizing the environmental impact of power equipment utilized in the distribution and transmission of electrical energy. The continuous vibration of the reactor core primarily accelerates the wear of insulating components, necessitating frequent maintenance and replacement of these parts in the unit (Isaac et al., 2021; Wrona et al., 2022). Presently, transformers within the 110–750 kV range emit noise levels from 79 dB(A) to just above 90 dB(A). However, health standards dictate that sustained noise exposure should not exceed 74 dB(A) during the day and 59 dB(A) at night to avoid auditory harm (Beltle & Tenbohlen, 2016; Mazur et al., 2021; Murat et al., 2020). Recent advancements have seen the finite element method applied in computer simulations to design and analyze shunt oil reactors

(Tu et al., 2021). This study aims to diminish noise and vibration in reactors of the 110–750 kV class through design enhancements of the POM-60000/525-У1 shunt oil reactor, thereby improving its noise and vibration characteristics and extending its operational lifespan.

2. Materials and methods

This study examined the POM-60000/525-У1 reactor, known for its improved vibration and noise characteristics, with the main technical data presented in Table 1. At the design stage, we used TDS, a 3D design, computer modeling, and visualization program developed by the Soft Team Group.[1] In the TDS environment, the reactor's geometric model featured a spatial shell with stiffeners (Figure 1(a)). The geometric model of the tank is depicted in Figure 1(b).

Figure 2 displays the dimensional parameters obtained in TDS and the three-dimensional (3D) model of the improved POM-60000/525 design. Using the finite element method in TDS, we simulated and optimized the tank design to lower the displacement amplitudes of its walls, consequently reducing reactor vibrations. Vibration analysis in TDS calculates the tank walls' bending amplitudes at various frequencies due to a harmonic load. The tank's geometric model included a spatial shell with stiffeners, and a 3D acoustic environment model was built inside, transmitting sound pressure to the tank walls through this oil. The tank's geometric model included a spatial shell with stiffeners, and a 3D acoustic environment model was built inside, transmitting sound pressure to the tank walls through the oil. The model focused solely on sound pressure and its transmission through the oil to the tank walls.

The target sound power level was set at 96 dB(A), with a 19.1 dB transition adjustment from the corrected to the uncorrected A-scale. To simulate the
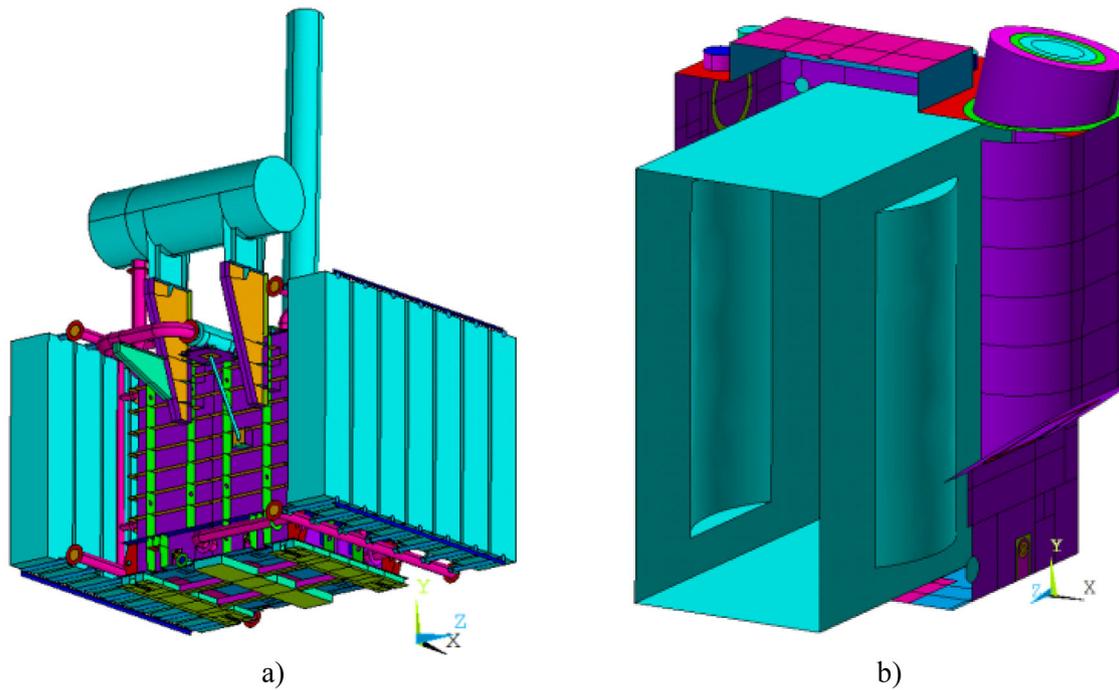
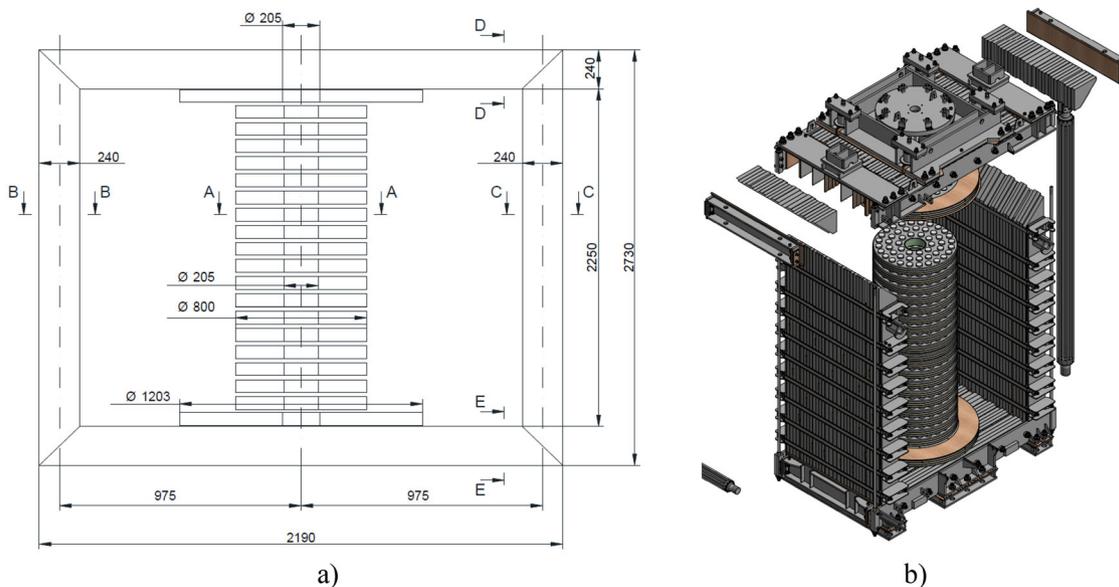**Figure 1.** 3D geometric models of the (a) reactor and (b) tank.

Figure 2. (a) Dimensional parameters of the magnetic circuit and (b) 3D model of the reactor.

active part's vibration load, acoustic pressure was applied across the tank's inner surface. The calculated sound pressure and power are listed in Table 2.

The design of the POM-60000/525 tank was improved as follows:

1. The number of 'M'-type radiators in the cooling system of the reactor was increased from six to seven on both sides.

2. The number of vertical and horizontal stiffeners on the wall of the reactor tank was increased to 15 and 7, respectively.

Laser-treated M090-27Pb HIB laser-grade electric steel with low vibroacoustic characteristics was used for manufacturing the magnetic circuit in the active part of the reactor. Laser treatment of the metal surface in the final stage of production can reduce specific magnetic losses by 8–10%. In transformer cores

Table 2. Design sound pressure and power.

Mode designation	Sound pressure at 0.3 m (dB(A))	Sound pressure at 2.0 m (dB(A))	Sound power (dB(A))
Rated voltage	92.9	73.3	71.0
Max voltage	94.0	74.5	72.6

Table 3. Design characteristics and dimensions of the POM-60000/525-U1 reactor.

Part of the magnetic core			Section	m²	%	Weight, kg
				Cross-sectional area		
Rod		Rod 1	A–A	0.4148014	100	
Side yoke	Vertical	Yoke 1	B–B	0.2693376	65	
		Yoke 2	C–C	0.2693376	65	
	Horizontal (outermost parts)	Yoke 3	D–D	0.2693376	65	
		Yoke 4	E–E	0.2693376	65	
Corners		L-type	–	–	–	
		T-type	–	–	–	–
Magnet system						24,384
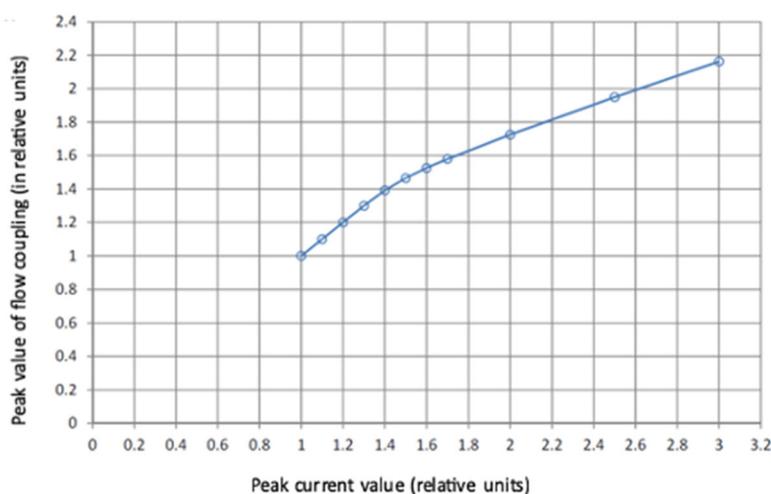
Figure 3. Saturation curve of the core material.

made of anisotropic electrical steel, eddy current losses account for up to 70% of the total remagnetization losses. Eddy current losses can be reduced via several methods, such as obtaining a material with adjustable grain size, artificially narrowing 180° domains by mechanically scratching the surface of finished sheets, and surface treatment with pulsed or continuous CO_2 laser radiations. Surface treatment of electrical steel using continuous CO_2 laser radiations does not break the insulation coating or generate additional mechanical stresses (Maharjan et al., 2019). The selected 0.27-mm-thick cold rolled grain-oriented steel possessed the following guaranteed magnetic properties: maximum specific loss at 1.7 T and 50 Hz was 0.90 W/kg and the polarization at $H = 8004/M$ was $J = 1.88$ T. The design characteristics and dimensions of the reactor are listed in Table 3.

The saturation curve of the material is shown in Figure 3. As shown in Figure 3, the dependence of the peak values of flow coupling on the peak values

of current is almost linear. Experimentally, the noise and vibration levels transmitted from the active part to the reactor tank were found to be reduced by 2–3 dB when the magnetic circuit was manufactured using M090-27Pb HIB laser electrical steel with rubber gaskets (Figure 4) and transition disks with diameters of 800 and 1205 mm in the reactor core and the central core of the magnetic circuit.

The reactor design contained a central ferromagnetic rod with nonmagnetic gaps evenly distributed along the length of the rod, which reduced the main losses owing to the reduction in the length of the magnetic field line in the non-magnetic medium. The use of adapter discs in these gaps can reduce noise levels.

According to thermal calculations, the maximum temperature of the surface of the magnetic system should be no more than 75 °C above the ambient temperature. Nitrile rubber has excellent oil resistance at high temperatures up to 300 °C and has
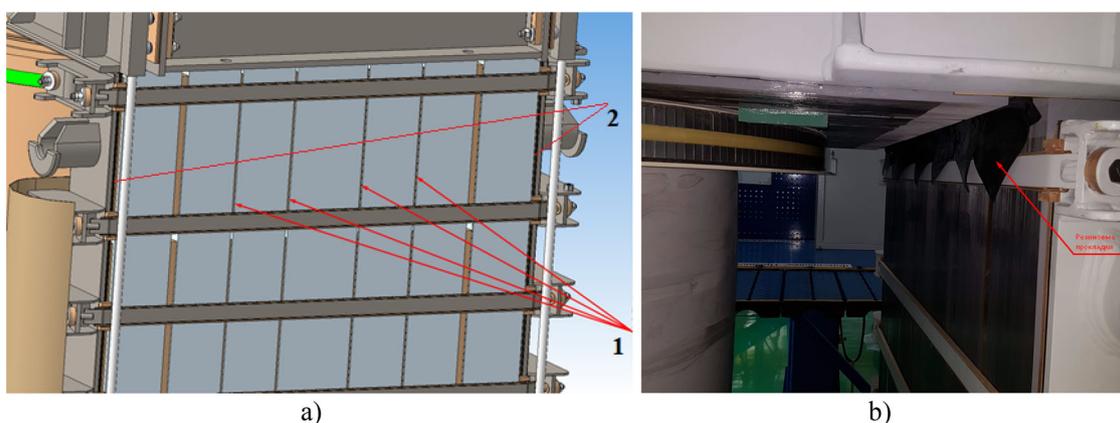
Figure 4. Installation of rubber gaskets on the 3D model of the reactor: (a) 1—between the packages of the magnetic system and (b) 2—between the beam and the yoke on the assembled reactor.
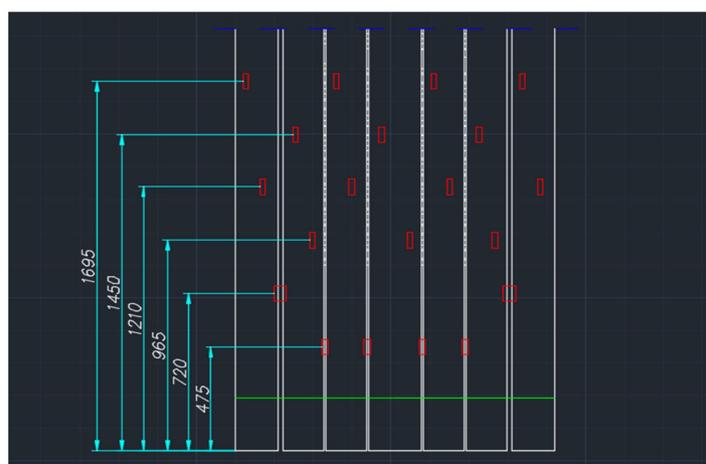

Figure 5. Grounding scheme of the magnetic system stacks.

gasoline resistance. The dimensions and position of the rubber gaskets were selected based on the design features of the reactor frame and the pressing forces of the magnetic system of this frame.

Simulations revealed that dividing the active area of steel into small areas, which increases the damping effect, can reduce noise and vibrations via the installed rubber dampers made of nitrile butadiene rubber gaskets. When nitrile rubber is used, each section of the magnetic system is grounded according to the scheme shown in Figure 5.

The following areas were included in the present study:

1. Comparative analysis of the vibration and noise characteristics of the new shunt oil reactor with an improved design and that of the operating analog, РОМБСМ-60000/500У.
2. Verification of the adequacy of the model developed using the TDS program based on the finite element method for calculating vibration displacements of reactor tank walls.

3. Results and discussion

3.1. Conducting noise tests

РОМ-60000/525-У1 has a cooling system of the 'M (ONAN)' type consisting of two groups of seven radiators each. Figure 6 shows the points at which sound levels are measured in the reactor with the cooling system.

The test reactor was installed on a stand without rollers, the nominal excitation voltage was 303.11 kV, the height of the reactor tank was 3190 mm, the total area of the test room was 891 m^2, the measuring line perimeter related to the measurement distance $L = 2.0$ m was 34 m. Sound levels were measured using a handheld analyzer (model B&K 2250 L-100) (Figure 7).

The measurement lines were placed 0.3 m from the radiating surface of the reactor at 1/3 and 2/3 of

the reactor height. A microphone was installed at each measurement point in the direction of the test objects. Before the tests, the noise meter was acoustically calibrated, and the extraneous noise levels were measured. Tables 4 and 5 summarize the measured sound data.

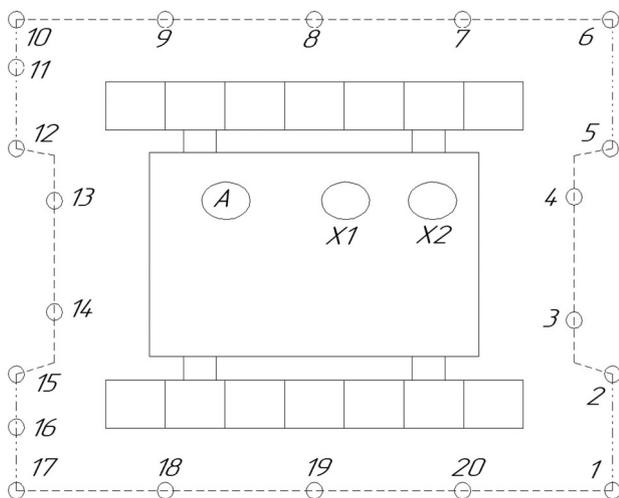The measurement results were processed, and the corrected sound power level was calculated according to IEC 60076-6-2014. The constant sound reflection coefficient K (dBA) of the room in which the tests were performed was calculated as follows:

$$K = 10 \cdot \lg \cdot \left(1 + 4 \cdot \frac{S}{A}\right), \quad (1)$$

where S is the area of the measuring surface. Additionally, A is the equivalent area over which sound is absorbed in the room and is approximately calculated using the following formula:

$$A = a \cdot S_v = 0.15 \cdot 891 = 133.65 \ m^2, \quad (2)$$

where a is the average sound absorption coefficient equal to 0.15 (IEC 60076-10-1:2016) and S_v is the total area of the test room (m²).

Figure 6. Points at which the sound levels of the reactor are measured: A—high-voltage lead and X1, X2—grounded side.

Table 5. Measured sound levels.

Measurement points	Measured sound power (2 m distance) (dB)	
	At 1/2 height of the tank	At 2/3 height of the tank
1	68.5	68.5
2	72.3	72.5
3	70.2	70.6
4	66.5	66.6
5	68.5	68.8
6	68.7	68.7
7	65.3	65.5
8	67.4	66.6
9	68.8	68.8
10	61.7	61.9
11	68.5	68.7
12	68.2	68.4
Average measured $L_{a0,3} = 68.0$ (dB)		

Figure 7. Process of measuring the sound levels of the POM-60000/525-У1 reactor.

Table 4. Measured extraneous noise levels.

Measurement points	1	2	3	4	5	6	7	8	9	10	Average background noise (dB)
	Measured extraneous noise levels (background levels)										
Before testing	39.3	38.6	38.9	39.3	39.4	38.8	38.4	38.5	38.5	38.6	38.8
After testing	38.6	38.4	39.0	39.5	39.3	38.9	38.1	38.6	38.6	38.6	

Furthermore, S is the area of the surface over which the radiation of the reactor was measured.

$$S_{0.3} = 1.25 \cdot H \cdot L = 1.25 \cdot 3.19 \cdot 34 = 135.57 \ m^2, \quad (3)$$

where H is the height of the tank and L is the length of the measuring line perimeter.

Calculated constant K, which considers the influence of the reflected sound, was

$$K_{0,3} = 10 \cdot \log \cdot \left(1 + 4 \cdot \frac{133.65}{135.57}\right) = 7.04 \ dBA.$$

The calculated average sound level L_A of the reactor with the cooling system was

$$L_{A0,3} = L_{a0,3} - \Delta L_{a0,3} - K_{0,3} = 68 - 0 - 7.04$$
$$= 60.96 \ dBA. \quad (4)$$

Corrected sound power level L_{pA} was

$$L_{pA} = L_A + 10 \cdot \log \cdot (S_{0,3}) = 60.96 + 10 \cdot \log \cdot (135.57)$$
$$= 82.2 \ dBA.$$
$$(5)$$

Therefore, the corrected sound power level of the РОМ-60000/525-У1 kV reactor was 82.2 dBA with a permissible value of 100 dBA based on IEC 60076-6-2014. Table 6 compares the calculated noise characteristics of the РОМ-60000/525-У1 reactor and those of its analog, РОМБСМ-60000/500-У1, obtained from acceptance tests https://drive.google.com/drive/folders/1pONbTSHgscVpXBTDl5BFjm8VyrWV6Vwr?usp=sharing

The analysis of the collected data shows a marked decrease in the average background noise levels for the improved reactor, РОМ-60000/525-У1, with the noise disparity between the reactor and its ambient environment being roughly double that of its predecessor, РОМБСМ-60000/500-У1. The wear on the insulating components within the reactor's magnetic system is primarily due to noise and vibration from the magnetic system's operation, a phenomenon largely attributed to magnetostriction. Specifically, the insulation between the magnetic system and the pressing yoke beams, as well as the insulation between the magnetic system and the fixing brackets, tends to degrade first. Moreover, the end beams and foot, along with the cardboard cooling rails situated between the electrical steel package layers in the magnetic system, are among the first components to show signs of wear. Consequently, these parts often require replacement during comprehensive maintenance activities. Given that reactor noise—which significantly influences its lifespan—is linked to the vibrations of the reactor walls and the cooling system, it is anticipated that the lifespan of the enhanced reactor, РОМ-60000/525-У1, will surpass that of its predecessor.

3.2. Conducting vibration tests

Vibration displacements for both the tank wall and the cooling system were assessed on a fully assembled РОМ-60000/525 shunt reactor (Figure 8). This reactor was securely positioned on a stand devoid of rollers, with an applied excitation voltage of 303.11 kV. The testing protocol adhered to the standards outlined in IEC 60068-2-80:2005. For these measurements, VIBROTEST MG-4 measuring instrument was employed. The specific locations where these vibration displacements were recorded are depicted in Figure 9. The measured vibration displacements at the designated points are detailed in Tables 7 and 8. The peak vibration displacement observed on the tank wall reached 21.9 μm, remaining within the acceptable limit of 30 μm as stipulated by IEC 60076-6-2014. In the case of the cooling system, the maximum displacement recorded was 12.15 μm, well below the allowable threshold of 60 μm. Consequently, the РОМ-60000/525-У1 reactor successfully met the vibroacoustic testing standards and complied with the criteria set forth in IEC 60068-2-80:2005.

3.3. Calculated and modeled vibration displacements of the tank walls using the finite element method

Using the finite element method within the TDS program facilitated the estimation and representation of reactor tank wall displacements through isosurfaces. Should the outcomes from the model align with those from vibroacoustic testing, it would confirm the model's accuracy.

The vibration analysis encompassed the bending amplitudes of the tank walls across various frequencies under harmonic loading. In constructing the geometrical model, intricate details, such as the active part's design—including the yoke, windings, disks, and studs—along with the positioning of the support points at the tank's base, were meticulously incorporated. The computational framework within the TDS program employed specific modules: SHELL181 for shell structures, SOLID185 for solid elements, and PIPE59 for pipe elements. The inclusion of contact elements, namely TARGE170 and CONTA174, facilitated the simulation of interactions within the model.

Inside the tank, a volumetric model of the acoustic medium, i.e. oil, through which the sound pressure was transmitted to the tank walls was constructed.

Table 6. Comparison between the calculated noise characteristics of POM-60000/525-У1 and those of POMБCM-60000/500-У1.

Type of reactor	Average noise level $L_{a0.3}$ of the transformer (dB)	Average background noise level (dB)	Difference between the transformer noise and the background noise (dB)	Background noise level $\Delta L_{a0.3}$	Surface noise level $L_{A0.3} = L_{a0.3} - \Delta L_{a0.3} - K_{0.3}$ (dB)	Corrected sound power level $L_p = L_A + 10 \cdot \log \cdot (S_{0.3})$ (dBA)
POM-60000/525-У1	68.0	38.8	29.2	0	60.96	82.2
POMБCM-60000/500-У1	69.0	54.0	15.0	0	67.0	88.0

This model was divided into two volumes. The first was directly in contact with the tank wall, and the second, the internal volume, was in contact with the active part. This calculation scheme considered only the sound pressure and the transmission of this pressure through the oil to the tank walls. The calculated sound power level was 96 dB(A). The transition correction from the corrected-A scale to the uncorrected scale was 19.1 dB. The acoustic pressure applied to the inner surface of the tank was modeled as the vibration load generated by the active part. The calculated load was 364 Pa. The frequency interval was assumed to be 50–150 Hz. The relative damping coefficient was assumed to be 0.02 (2%). The model was fixed at the locations where the bottom beams rested on the wheels.

The calculation results were presented in the form of isosurfaces on the geometric model using a given scale, depicting the mutual correspondence between color and numerical data. Figure 10 shows the calculated total vibration displacements of the entire tank at 100 Hz according to the IEC 60068-2-80:2005 test method.

The analysis revealed that the tank walls experienced their maximum displacement at the base, measuring 0.0162 mm, or 16.2 μm, as depicted in Figure 8. Displacement measurements for the tank's four sides were conducted at 100 Hz along each coordinate axis. For every side of the tank, displacement curves were plotted at points corresponding to the X and Z coordinate axis directions, within a frequency range of 50–150 Hz. Specifically, Figure 11 illustrates the HV ('−Z') side of the POM-60000/525-У1 reactor tank, where the displacement peaked at 0.01052 mm or 10.52 μm.

Figures 12(a,b) show the displacement plots (mm) in the frequency range of 50–150 Hz obtained from points 10–12 and 13–15, respectively, along the z-axis. The maximum displacement of the tank walls at a frequency of 100 Hz was observed at the center of the longitudinal walls (points 10 and 14 in Figures 6(a,b), respectively). This displacement was 0.0105 mm = 10.5 μm, and the maximum double value of displacement was 21 μm. The maximum average value of the vibration displacements of the tank walls was measured using a hand-held device (VIBROTEST MG-4) and was found to be 21.9 μm.

Thus, the model created with the TDS program, which was employed for computing the vibration displacements of the reactor tank walls using the finite element method, proved to be adequate. The discrepancy in the measured maximum displacement was found to be 4.3%.

Figure 8. Process of measuring vibration displacements of the tank wall and the cooling system of РОМ-60000/525-У1.
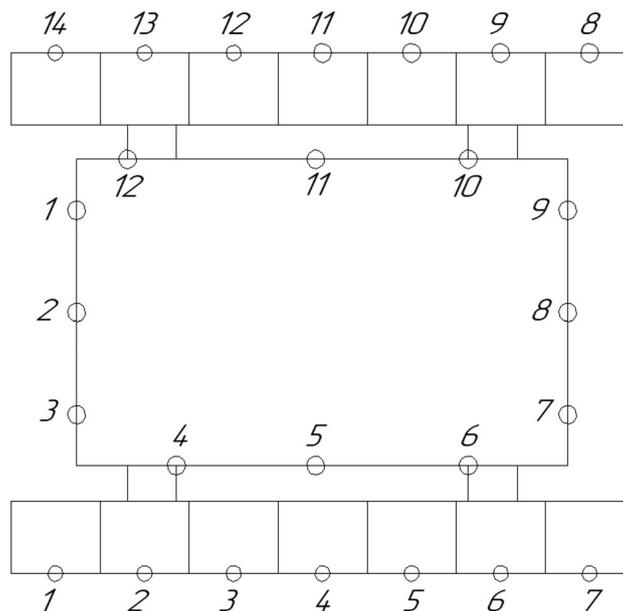

Figure 9. Points at which vibration displacements are measured on the tank wall (1–12) and the reactor cooling system (1–14).

Table 7. Measured vibration displacements of the tank wall.

Point №	1	2	3	4	5	6	7	8	9	10	11	12
Displacements (µm)	3.42	11.4	16.2	5.34	7.29	10.7	11.5	**21.9**	5.74	7.42	9.13	11.42

Note: The peak vibration displacement observed on the tank wall reached 21.9 µm (highlighted in bold), remaining within the acceptable limit of 30 µm as stipulated by IEC 60076-6-2014.

Table 8. Measured vibration displacements on the cooling system.

Point №	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Displacements (µm)	5.14	7.19	**12.15**	12.03	10.33	7.38	6.15	4.85	8.19	8.64	8.62	11.35	7.10	5.35

Note: In the case of the cooling system, the maximum displacement recorded was 12.15 µm (highlighted in bold), well below the allowable threshold of 60 µm.
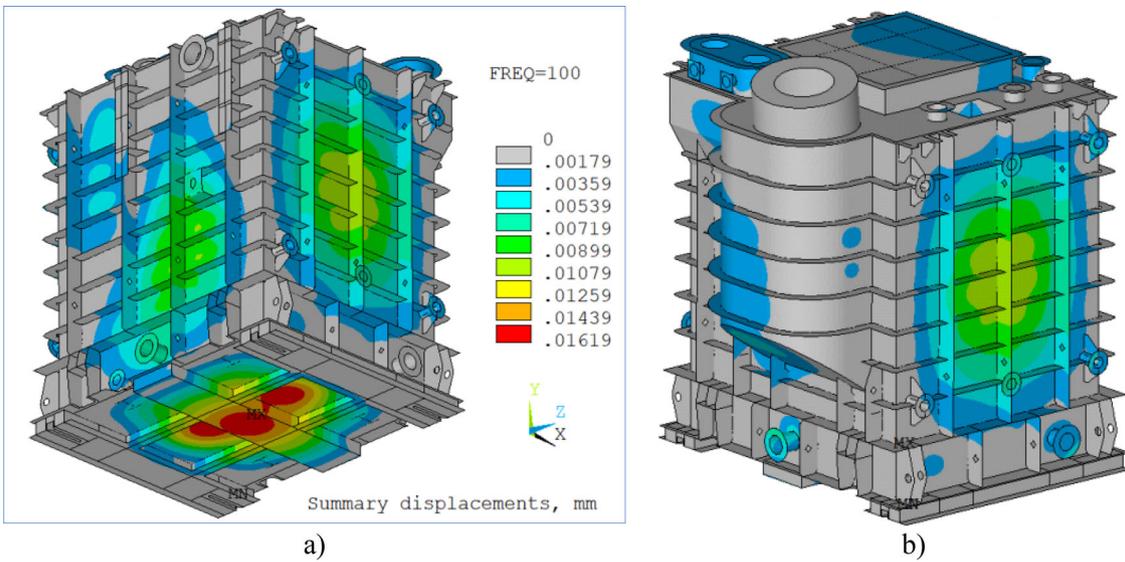
Figure 10. Vibration displacements (mm) of the tank walls at 100 Hz. (a) Calculation results and (b) 3D model of the tank.
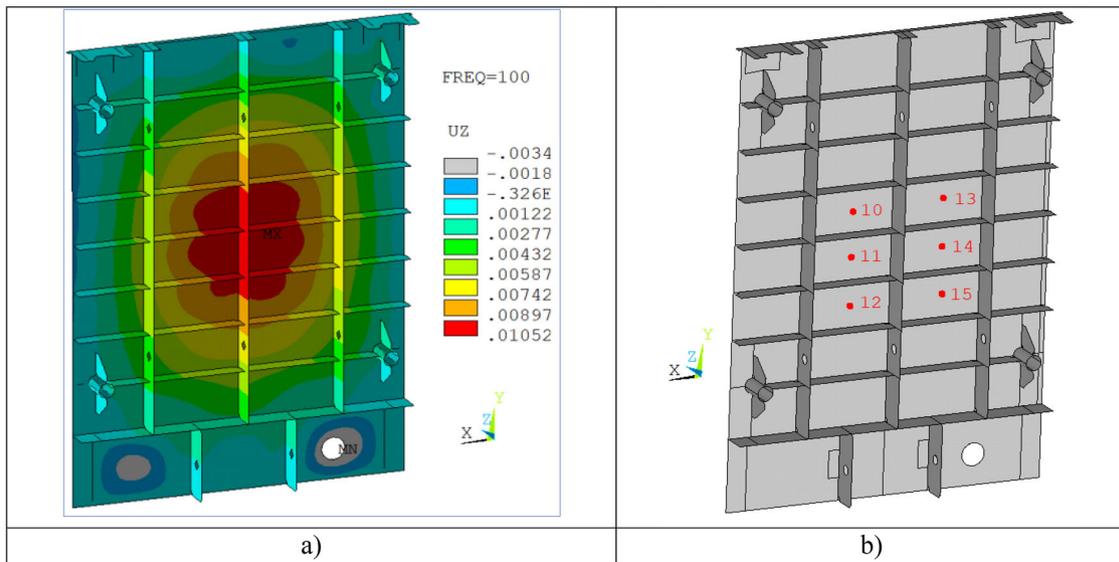

Figure 11. Vibration displacements of the tank at a frequency of 100 Hz (mm) on the HV ('−Z') side. (a) Calculation results and (b) location of selected points 10–15.
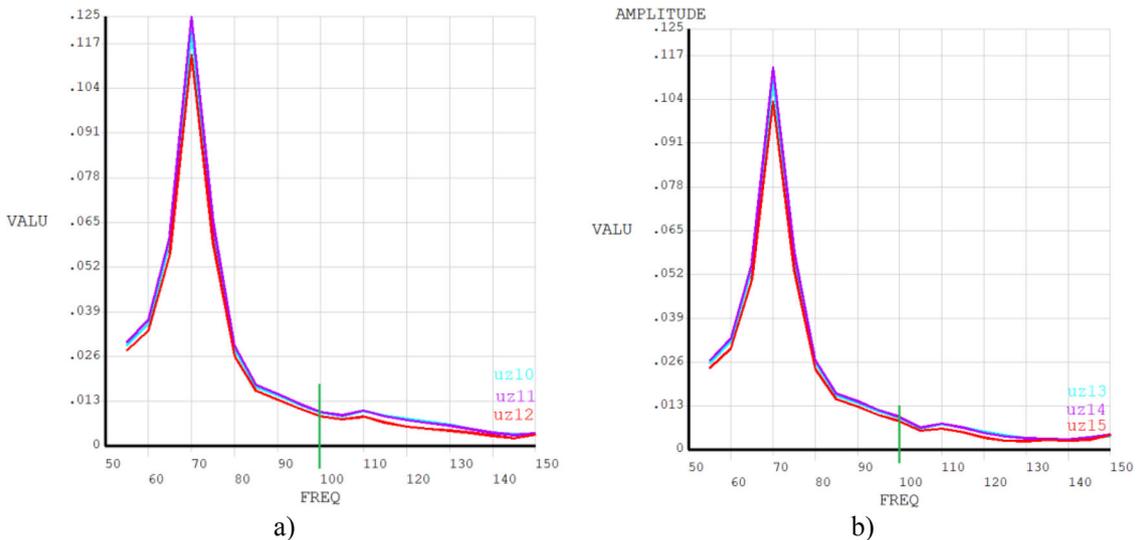

Figure 12. Displacement plots (mm) in the frequency range of 50–150 Hz were obtained from (a) points 10–12 and (b) 13–15 along the z-axis.

4. Conclusion

Using the finite element method in the TDS environment, the POM-60000/525 reactor was modeled and optimized to lower tank wall displacement amplitudes and reactor vibration levels. This led to the following reactor design improvements. The number of 'M'-type radiators in the cooling system was increased from six to seven on both sides. Additionally, the number of vertical and horizontal stiffeners on the reactor tank wall was increased to 15 and 7, respectively.

To further reduce vibration, the reactor's magnetic circuit utilized laser-treated M090-27Pb HIB laser-grade electric steel, and nitrile butadiene rubber was chosen for the damping gaskets. Furthermore, in the improved POM-60000/525-У1 reactor, transition disks of 800 and 1205 mm diameters were employed in the magnetic system's central core. The innovations halved the noise difference between the reactor and background, compared to the existing POMБCM-60000/500-У1 model. Since reactor noise from wall and cooling system vibrations significantly impacts its lifecycle, these improvements extended the lifespan of the POM-60000/525-У1 reactor.

This study's key contribution is the design enhancement of the POM-60000/525-U1 shunt oil reactor, reducing noise and vibrations for 110–750 kV reactors and extending their service life. The TDS-developed model's adequacy for calculating reactor tank wall vibration displacements was confirmed, with a maximum displacement measurement error of 4.3% by the VIBROTEST MG-4 device.

Note

1. softteamgroup.com.ua/Home/ProductInfo?id=7d13b7f9-5c4c-44cb-ad44-52694bca164e.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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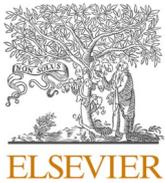
Experimental investigation and evaluation of drying methods for solid insulation in transformers: A comparative analysis

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ARTICLE INFO

ABSTRACT

Drying of transformer winding insulation has a direct impact on the dependability and durability of the transformer. The extraction of moisture from paper insulation is a crucial need in the manufacturing process of transformers. Insulation efficiency in transformers can be reduced over time due to the detrimental effects of temperature, moisture, and air, often known as aging. Heat, oxygen, and residual moisture increase the deterioration of cellulose in transformer solid insulation. This might potentially result in premature failure of the transformer. The factory's insulation drying process should ensure that the residual moisture content of bulk solid insulation remains below 0.5 %. The primary aim is to maintain a high degree of polymerization, often ranging from 1000 to 800. This article investigates the factors contributing to the degradation of cellulose insulation and analyzes various techniques that are used in manufacturing plants in Kazakhstan. In addition, this study experimentally investigates the impact of vacuum on the process of moisture evaporation and partial discharge (PD) in analysis with other methods of drying transformers.

1. Introduction

Power transformers (PT) are essential components of the power system since they provide a consistent supply of electricity. The maintenance of electricity requires the appropriate functioning of transformers. The failure rates of transformers may be represented as a "bathtub" curve, whereby the first stage is characterized by premature neonatal demise [1]. Production issues caused by faulty materials or control systems contribute to the low rate of failures. A statistical study found that 48 % of transformer failures can be linked to problems with winding insulation [2]. The study explores in Ref. [3] the use of palm kernel oil methyl esters (PKOME) as liquid bio-insulators in distribution transformers by developing and validating a heat transfer model using COMSOL Multiphysics. The model accurately predicts temperature variations, closely matching experimental data, thereby supporting the potential application of PKOME in transformers. The manufacture process of transformers significantly impacts the life expectancy and quality of the winding insulation in power transformers [4–6].

Large PT require a comprehensive manufacturing process to achieve precise specifications because of their intricate designs [7]. Be cognizant of avoiding excessive moisture from getting into solid insulation while it dries. PT solid insulators commonly utilize hygroscopic cellulose. In tropical regions, high levels of humidity lead to a significant accumulation of moisture. Before incorporating oil-liquid insulation, it is important to allow the solid insulation to undergo the drying process. Excessive moisture retention can be observed in insulation during the drying process, which may be due to various factors such as material, design, or management issues [8]. Even little amounts of moisture might cause damage to PT insulation. Chemical processes that generate increased moisture content can reduce dielectric strength and accelerate aging [9,10]. Partial discharge (PD) is an additional theoretical framework that is associated with this phenomenon. The occurrence of insulation breakdown may be attributed to the occurrence of excessive failure mode PD activity [11]. Optimal drying time is necessary to minimize remaining moisture in the production process [12].

The manufacturer plays a crucial role in determining the

dependability and longevity of distribution and power transformers. Prior to applying insulating oil, it is essential to ensure thorough drying of the cellulose solid insulation inside the transformer. The aging process is challenging, as the degradation of insulating materials may be accelerated by oxidation, hydrolysis, and pyrolysis due to the material's properties and the functioning of transformers. Hence, it is essential to minimize the presence of hygroscopic moisture throughout the production process of solid insulation to guarantee its safe and reliable performance. Insulation concerns account for 40–48 % of PT breakdowns [13]. Pyrolysis emits carbon monoxide (CO), carbon dioxide (CO2), and acids, and the insulation tends to be hot. Electricity transmission and distribution in power networks are interconnected by oil-filled PT [14]. Customers face difficulties and incur financial setbacks due to equipment damage and power supply outages resulting from transformer failure. The dielectric strength of solid insulation diminishes as the water content rises. Therefore, the process of drying transformer insulation occurs throughout the production phase, as well as during the repair of leaking tanks and subsequent wetting. Hence, solid insulation is responsible for the bulk of moisture in transformers, whereas oil has a lesser impact [15].

The drying procedure for transformer windings in Kazakhstan was established. Initially, the ambient air inside the cabinet was subjected to a specific temperature elevation. After achieving the required temperature, the winding was further subjected to heating. Subsequently, the pressure inside the vacuum-drying cabinet (VDC) was decreased, facilitating the process of vacuum drying [16,17]. The measurement of insulation temperature is not conducted, and the windings are subjected to separate pressing prior to the drying process [18]. The winding is then dried during the process of pressing. The disadvantage of this drying technology is an increased depolymerization of solid insulation due to an uncontrolled rate of rise in the temperature of the insulation, a relatively long drying time, and the need to manually adjust the axial size of the windings by removing or adding spacers. Also, increased depolymerization occurs due to the rapid extraction of moisture from the solid insulation during the pressure reduction stage. Rapid moisture extraction occurs due to a decrease in the temperature of moisture evaporation by vacuuming [19].

In order to contract the issues and comprehend the reasons behind the deterioration of cellulose insulation, it is imperative to examine the methodologies used in drying solid insulation. Based on the factors of the PT and the maintenance circumstances at on-site or manufacturing facilities, these technologies may be categorized into several classes.

The rest of the paper is organized into the following sections. Section 2 depicts the mechanisms of moisture intrusion into transformer cellulose insulation. Various methods of drying solid insulation in transformers in Section 3. Section 4 describes the experimental testbed at the Kazakhstan manufacturing plant, detailed experimental tests are elaborated, and the conclusions are summarized in Section 5.

2. Mechanisms of moisture intrusion into transformer cellulose insulation

Moisture intrusion into insulation can occur through three primary mechanisms: residual moisture left from manufacturing, from the atmosphere, and the cellulose decomposition process due to aging [7]. The residual moisture comes from either the surrounding environment or the production process. It could also be a result of cellulose deterioration due to aging. The presence of moisture in solid insulation can occur during normal operation and when the transformer tank is opened. The transformer's ability to prevent moisture from entering the external environment does not affect the degradation of cellulose molecules and the resulting production of water. Fig. 1 illustrates the breakdown of cellulose into smaller segments. The process of cellulose aging can be influenced by factors such as hydrolysis, raised temperatures, and the presence of oxygen and acid oxidation. The degree of polymerization (DP) is a useful indicator for assessing the condition of the cellulose
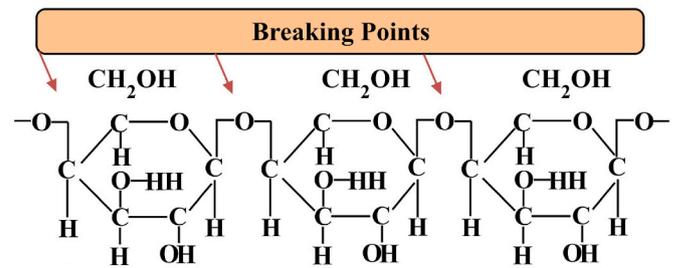

Fig. 1. Degradation processes of cellulose molecules.

insulation. The DP values in new papers typically range from 1200 to 1250. As time goes on, cellulose molecules start to break down as shown in Fig. 1, leading to a decrease in the DP value. The power density typically falls within the range of 600–800 units. When the DP falls below 200 units, the paper insulation for the windings becomes insufficient. Regularly drying the solid insulation of the transformer is crucial for minimizing the effects of moisture on the aging process and physical characteristics of cellulose. This study specifically examines the most commonly used drying processes in oil-filled transformers for practical applications.

The degree of polymerization (DP) is a measure of the number of repeating units in a polymer molecule. It can be calculated using the molecular weight of the polymer (M_w) and the molecular weight of the repeating unit (M_o) with the following formula:

$$DP = \frac{M_w}{M_o} \tag{1}$$

3. Methods of drying solid insulation in transformers

3.1. Indirect method

Drying solid insulation is the continuous drying of transformer oil using an absorbent. This approach can be considered a preventive measure as it helps to control and regulate the moisture content in the solid insulation of the transformer during its operation. However, this approach can also be considered an indirect drying method, primarily affecting the oil rather than the solid insulation. This procedure is implemented. Several adsorbers, each containing absorbent, are linked to the transformer. The absorbent has a substantial capacity for absorption. The absorbent removes the water from the oil as it passes through the adsorbers at a moderate speed of approximately 30 L per minute. When a transformer is in use, water moves from the liquid to the solid insulation. As a result, the solid insulation is effectively dried, and the circulation of oil helps remove any remaining water. Fig. 2 demonstrates the utilization of adsorbers to continuously remove moisture from oil and solid insulation within a transformer. A vacuum lowers the ambient pressure when applied to a system. This reduction in pressure decreases the boiling point of water (and other liquids), allowing moisture to evaporate at lower temperatures than it would under normal atmospheric conditions. Applying a vacuum can enhance the efficiency and speed of moisture removal in the context of drying transformer oil and solid insulation.

3.2. Vapor phase drying

The vapor phase drying (VPD) has two heating stages, in which the low-viscosity solvent vapor is used for heating. The drying chamber is where the solvent vapor undergoes condensation; subsequently, the vacuum pump eliminates it from that area. The drying process comprises many stages: preparation, heating and drying, pressure reduction, and fine vacuum. During the preliminary phase, the chamber pressure is decreased to 6 mbar by using a vacuum. The heated evaporator

(a)
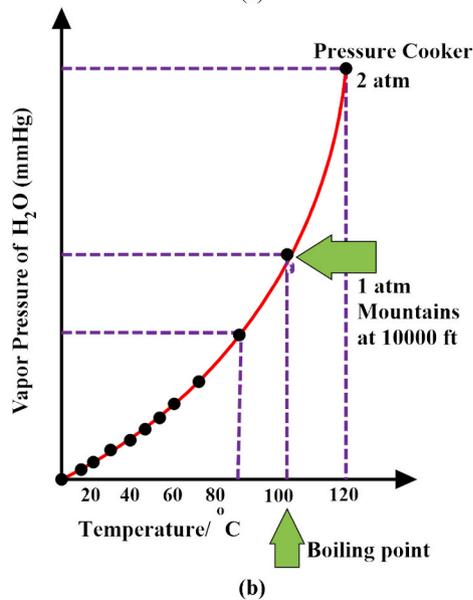
(b)

Fig. 2. (a) Continuous drying of transformer oil and solid insulation with adsorbers at the substation, and (b) relation between the vapor pressure of water and temperature.

introduces the solvent vapor into the vacuum chamber at a temperature of 403 K. During the heating and drying phase, the solvent vapor undergoes condensation as a result of variations in temperature and concentration. After the completion of this step, the drying chamber is filled with air, water vapor, and solvent vapor. A vacuum pump is used to evacuate this gas mixture for circulation. The solvent vapor is halted and then condensed in the condenser prior to being transferred to the evaporator as a component of the pressure reduction procedure. The process of decreasing the pressure is stopped once the pressure within the drying chamber reaches 26 mbar. The solvent is removed from the vacuum chamber, and the pressure is decreased to 1 mbar during the fine vacuum phase. The cycle is interrupted when the remaining moisture in the active components of the transformer drops below 0.3 %.

3.3. Hot air drying

Raising the surrounding temperature between 100 and 110 °C is a successful method for drying out transformer solid insulation, but it can

lead to uneven heat spread in the insulation. Therefore, hot air drying is only suitable for small transformers because their tanks cannot handle full vacuum conditions. Typically, it takes approximately 12–14 h to dry small transformers with a peak voltage of 6–10 kV using hot air in convection ovens. The hot air drying process is commonly used indoors, particularly in repair and production activities.

3.4. Heat and vacuum treatment chambers

Manufacturing factories and service shops utilize specialized chambers to dry cellulose insulation effectively using heat and vacuum. When the transformer core is exposed to heat in a chamber, the insulating layers experience water evaporation. Once the desired temperature is reached, a vacuum pump is employed to create a vacuum in the chamber. This helps to remove water vapor and improve the efficiency of the drying process. As illustrated in Fig. 2(b), the boiling point of water drops significantly when subjected to a vacuum. This allows for the safe extraction of water from paper without exceeding 65 °C, thus preventing any decomposition. The drying time is reduced because the chamber quickly heats up through direct heating. The heating elements are hidden behind panels within the chamber. Fans are essential for evenly distributing heat, as they circulate hot air through internal convection during the heating cycle. This ensures uniform heating of the windings, resulting in efficient and effective thermal vacuum drying. This drying method is suitable for all types of transformers.

4. Experimental testbesd at the manufacturing plant

4.1. Vapor phase dryings in manufacturing plant

In our experiments conducted on 83.3 MVA 275/160 kV power transformers, we used vapor phase drying (VPD) to remove moisture from cellulose insulation, as seen in Fig. 3 (a) and drying chamber at Fig. 3 (b)–(c). Suction and heat are used to expedite and enhance the drying process. The heat precursor used in this study was a unique organic liquid vapor with a temperature of 110 °C. The transmission of heat from the winding assembly to the solid insulating sections results in the removal of moisture from the inner layer, leading to its evaporation as water vapor on the outer layer. The production of condensed organic liquid and water vapor was achieved using vacuum pumping. The organic liquid was thereafter circulated for the purpose of drying. The evaporation of water with little thermal energy may be achieved by manipulating the heating temperature and pressure inside the VPD chamber. The pressure of the vacuum was set to 10-3 bar.

4.2. Heating and vacuum techniques for drying chambers

Heat and suction are utilized in specialized chambers within production plants and service centers to aid in the drying process of cellulose insulation. When subjected to higher temperatures within a chamber, the transformer's core undergoes the evaporation of water from its insulating layers. Once the desired temperature is reached, a vacuum pump is utilized to create a vacuum within the chamber, effectively eliminating water vapor and enhancing the efficiency of the drying process. Fig. 4 (a) shows the drying chamber and Fig. 4 (b) displays the design diagram of staged drying under isostatic compaction, which is proposed for implementation. As evident from Fig. 4(b) that, the drying time is significantly reduced in the staged drying process. In the diagram, each colored curve represents specific parameters: The temperature is indicated by the red line, while the vacuum pressure in the chamber is represented by the green line. It is also noted that varying operating conditions could potentially impact the results, including the optimal time for certain processes such as drying. Changes in operating conditions, such as temperature, humidity, and pressure, can influence the kinetics of polymerization and drying processes. The yellow line shows the percentage of shrinkage of the winding. The black line
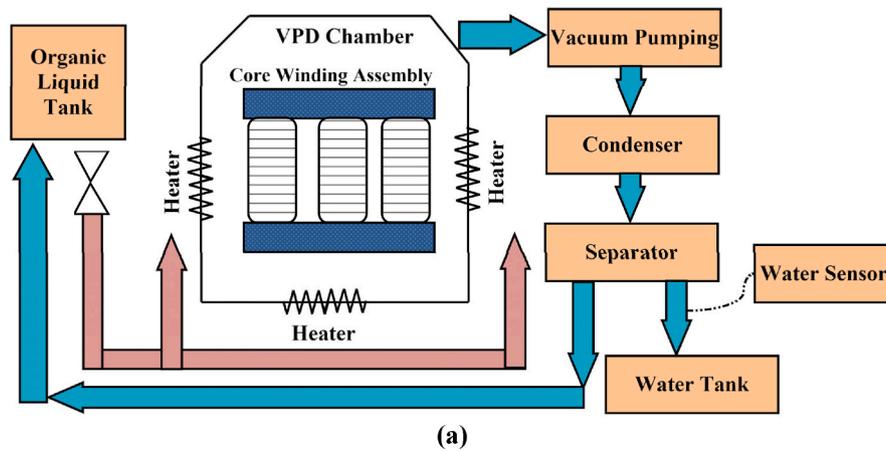
Fig. 3. (a) Block diagram of power transformers manufacture VPD chamber for drying, (b)–(c) chamber for drying the power transformer at the manufacturing plant.

indicates a significant vacuum. The blue line represents the moisture extraction from the insulation.

4.3. Implementing phased drying with an isostatic pressing system

Fig. 5 shows an isostatic press. The top and lower plates are connected to the hydraulic station of the isostatic press. One of the key advantages of implementing phased drying with an isostatic pressing system is the capability to utilize hot air for heating the transformer winding. Time has the power to regenerate the air. When the winding temperature exceeds a certain threshold, the air heating process is replaced by a phase where VDC pressure is reduced. Even in colder environments, the lower pressure within the VDC causes more moisture to evaporate from the insulation. This process leads to the heating of the transformer insulation and a subsequent decrease in depolymerization.

The heating and pressure reduction process is repeatedly carried out once the winding temperature surpasses a specific threshold. By adjusting the duration of the high vacuum phases, we can achieve a faster drying cycle while still maintaining the necessary heating phase. Furthermore, it is crucial to maintain a moderate initial pressing intensity to ensure a smooth drying process for solid insulation, without any interruptions. As the temperature reaches its peak for drying, the pressing pressure is gradually increased until it reaches the desired force. Coils are uniformly stabilized through vertical pressure. Hydraulic cylinders, pumps, and a pressure control valve are utilized to maintain a

specific pressure level. Throughout the process, the computer screen of the operator shows the force being applied and the force exerted downwards. Transformer designers can calculate the shrinkage of solid insulation and winding height by maintaining the recommended pressing force after drying. By reducing drying durations, you can lower energy expenditures and improve productivity with vacuum drying apparatus. Using isostatic pressing during the drying process improves the winding's durability against mechanical stresses.

4.4. Partial discharge assessment for transformer reliability

The PD testing and measurements were carried out following the IEC 60270 standard [20]. The PD was represented using the ABC model, which is a capacitive network that depends on apparent charge. A bushing tap coupling was used to connect the measuring impedance between the earthed transformer tank and the tap terminal. The terminal is connected to the commercially available PD measuring instrument Omicron MPD 600 using shielded coaxial cables (LiYCY) to measure and record PD. The LV winding experienced a gradual rise in AC voltage, reaching approximately 325 kV, following the IEC-60076-3 test voltage method.

The mathematical relationship for the optimal time at which the degree of polymerization (DP) starts to rise can vary depending on the specific conditions and factors affecting the polymerization process. However, a common approach is to use empirical models or experi-
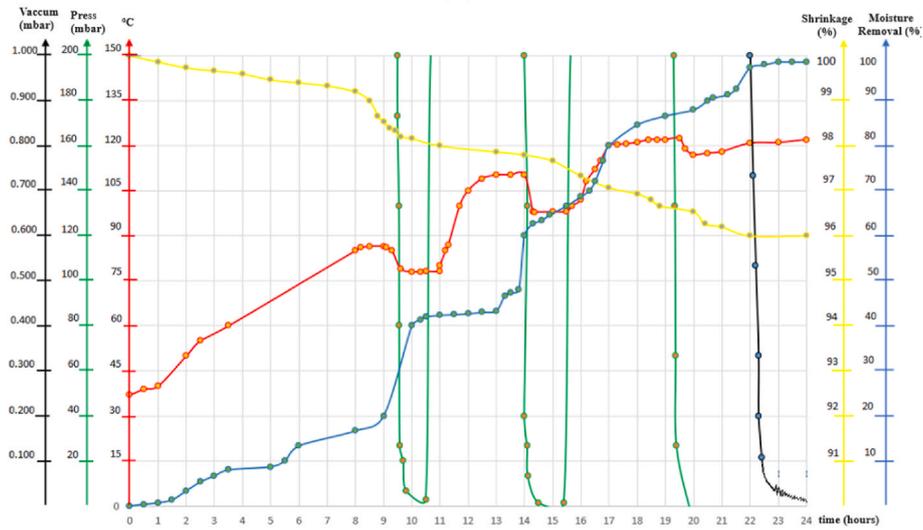
Fig. 4. (a) Drying Chambers for transformer, and (b) Staged drying diagram under isostatic pressing.

mental data to derive an equation that describes the relationship between time and DP as follow:

$$DP\,(t) = \frac{K}{1 + e^{-r(t-t_0)}} \qquad (2)$$

where K is the carrying capacity or maximum DP that can be achieved, *r* is the growth rate parameter, and t_0 is the time at which the growth rate is maximized. In this equation, the parameter t_0 represents the optimal time at which the growth rate is highest, and the degree of polymerization starts to rise most rapidly.

During the drying process, solid insulation effectively absorbs heat transfer energy. Cellulose remains unaffected by heat, which helps to minimize water contamination. Fick's law can help explain the slow movement of moisture in cellulose. The relationship between the charge's apparent magnitude and the drying time as shown in Fig. 6. It is observed from Fig. 5 that the results of the PD test indicated a tendency for extended drying times, specifically those lasting less than 68 h. Excessive heat absorption during the drying process of cellulose solid insulation can cause the polymer chain to break and the polymerization value to decrease, which may lead to structural damage. By shortening the polymer chain, the physical characteristics of cellulose insulation are

reduced, leading to a decrease in the PD inception voltage. When drying periods exceed the optimal duration, the apparent charge tests of PD show a rise due to first indications of age. A drying period of less than 68 h is insufficient to completely remove excess residue in solid insulation, leading to a higher apparent charge of PD.

4.5. Assessing the relationship between water extraction and partial discharge

Water exhibits remarkable electrical conductivity because of its minimal resistance. The highest PD test result was recorded at 150–400 g of water extraction, while the lowest result was observed at 2232 g. Based on a study conducted by Christina et al. [21], the amount of water removed during the drying process has a notable impact on the presence of residual moisture. This, in turn, is negatively correlated with the results of PD tests and can cause an increase in apparent charge conductivity. The conductivity of kraft paper insulation made from cellulose increases as the moisture content rises. This is due to the impact of dielectric response polarization and depolarization current. According to the findings of [14], the surface partial discharge of the oil-impregnated paper increased in a linear manner as the moisture
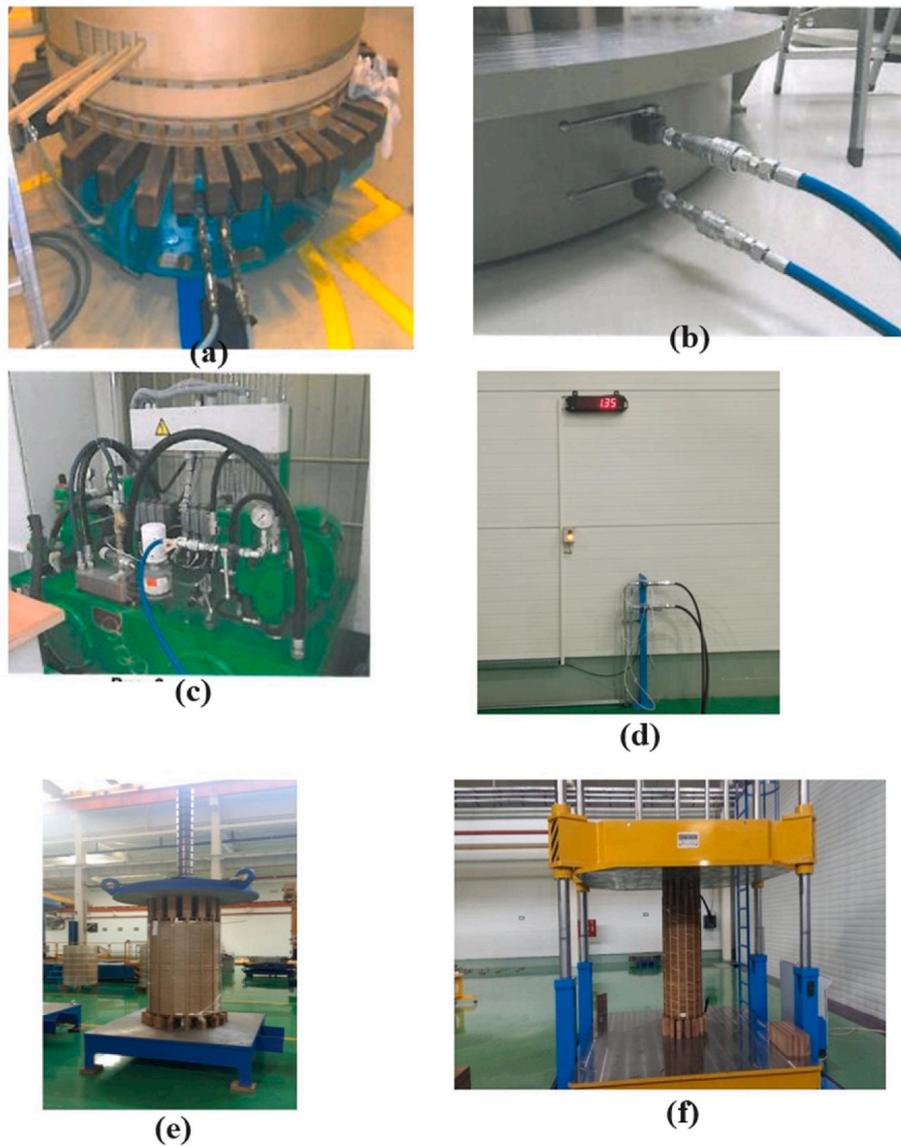
Fig. 5. (a)–(b) Connecting the hydraulic station to the stabilizing press, (c) Hydraulic unit for stabilizing press, (d) Connecting a stabilizing press to a vacuum drying cabinet, and (e)–(f) Installing the winding in a pressing device Pressing the winding in a stabilizing press.
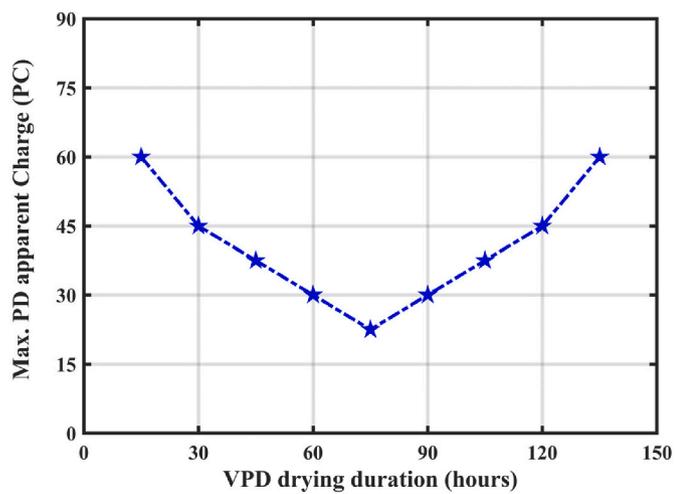

Fig. 6. Impact of drying period on partial discharge apparent charge test results.
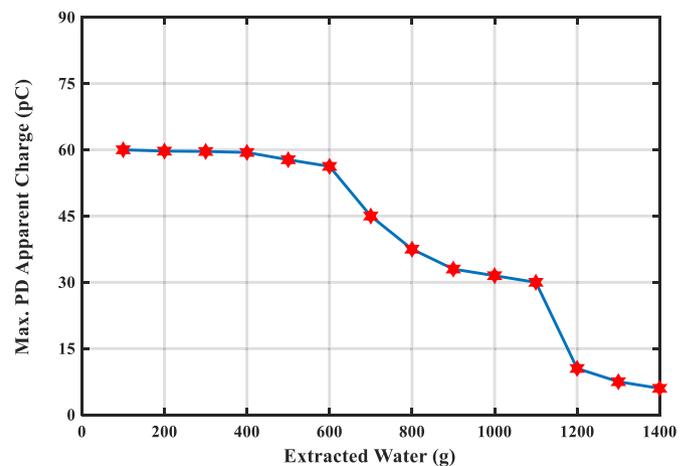

Fig. 7. Analyzing partial discharge apparent charge test results considering different levels of water extraction.

content increased during the trials. Fig. 7 shows a comparison between the extracted water content and the results of the PD apparent charge test.

5. Conclusions

An experimental investigation was carried out to examine the influence of drying duration and water extraction on the partial release encountered during the production of 83.3 MVA 275/160 kV power transformers. Various testing methods were implemented, such as vapor phase dryings in manufacturing, heating, and vacuum techniques for drying, phased drying with an isostatic pressing system, and partial discharge assessment. An investigation has been made on water extraction and partial discharge to understand the apparent partial discharge charge test results, considering different levels of water extraction. Two procedural factors were shown to have a significant impact on the outcomes of PD. Following a drying period of 68 h, we observed that the minimum partial discharge was 21 pC, while the maximum partial discharge was 60 pC after 81 h. Both values satisfied the acceptance criteria. A comprehensive investigation has discovered that the most favorable duration is 67.4 h, as established by the use of polynomial regression. While shorter drying periods may not adequately eliminate residual moisture, resulting in elevated PD values, longer drying intervals can induce cellulose degradation due to excessive heating. An essential aspect of assessing the effects of water recovery on insulating residual moisture and PD outcomes is comprehending the correlation between residual moisture content and charge conductivity. A notable rise in PT partial discharge values has been seen when exposed to drying durations of 67.4 h or more. By maintaining the residual moisture content below 0.5 %, the techniques ensure a high degree of polymerization (1000–800), which is crucial for prolonging transformer lifespan and reliability.

CRediT authorship contribution statement

Adilbek Tazhibayev: Writing – review & editing, Writing – original draft, Software, Project administration, Formal analysis, Data curation, Conceptualization. **Yernar Amitov:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Nurbol Arynov:** Visualization, Validation, Software, Methodology, Data curation, Conceptualization. **Nursultan Shingissov:** Writing – review & editing, Visualization, Validation, Resources, Formal analysis, Data curation, Conceptualization. **Askat Kural:** Writing – review & editing, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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REVIEW

BON VIEW PUBLISHING

Development of Customer-Focused Automated Systems for Transformer Design and Manufacturing: A Comprehensive Review

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Abstract: This study examined significant progress in intelligent manufacturing (IM) technologies in collaboration with a prominent producer of electric power transformers. The study particularly focused on the role of intelligent supply chain management (SCM) technologies in optimizing the manufacturing process. The intelligent SCM modules incorporated in the intelligent machine demonstration utilize an ontology to establish linguistic linkages across key aspects such as intelligent supplier selection, component ordering, and intelligent product quality prediction. These modules are essential in synchronizing orders with analytic hierarchy process analysis and multi-objective integer optimization, thereby improving both the efficiency and quality of the manufacturing process. One of the key challenges faced by decision-makers is identifying multiple feasible solutions while adhering to stringent operational constraints. To provide further insights, this study also includes a comprehensive literature review of the transformer manufacturing process, covering advanced technologies, intelligent SCM, optimization techniques in transformer design, and various IM methods. This review critically examines the advantages and limitations of existing solutions, identifying areas where further advancements are needed. By integrating intelligent supply chain technologies with manufacturing processes, this study highlights potential improvements that can enhance operational performance and decision-making in transformer production.

Keywords: intelligent manufacturing, optimization, power transformers, supply chain management techniques

1. Introduction

Modern industrial systems utilize the Internet of Things (IoT), cloud computing, and big data analytics to apply artificial intelligence (AI) techniques that facilitate smart decision-making and adjust to changing market demands [1, 2]. Many companies are improving their supply chain operations and processes to better decision-making in inventory management, production scheduling, predicting machine failures, preventing equipment breakdowns, and ensuring product quality [3]. Research is actively underway in smart manufacturing, focusing on prediction-driven product quality control and optimization. This work uses advanced predictive modeling techniques grounded in data, mainly when complex end-product characteristics are crucial and constantly changing. Predictive models are created and assessed using paired data whenever possible to quantify the critical component features that influence the final quality attributes. Predicting product quality accurately is essential for enhancing manufacturing processes and operational factors [4]. The Industry 4.0 effort is prepared to impact supply chains, strengthen the efficiency of workers and machines, boost communication, optimize data management, and raise standards among environmental and market stakeholders [5]. Entities and people are using the advantages of sophisticated technology, digital transformation, and cloud-based solutions. Market dynamics compel corporations to adapt to variable labor markets, varied product demands, and increasing material costs. The fourth industrial revolution integrates physical and digital elements to optimize processes, manage data, and automate functions to minimize costs, enhance quality, and boost efficiency and productivity [6].

Advanced manufacturing systems are designed to meet specific requirements for automation control, facility configuration, and production capacity. Information management design comprises three distinct levels: workshop logistics and production, field control networks, sensor configurations, and manufacturing execution systems (MES) [7, 8]; dynamic operations, concerning the movement of equipment and work-in-process (WIP) [9]; and static physical configuration, encompassing production line layout and equipment planning. Transformations are driven by escalating rivalry within the industry to optimize production and delivery schedules, reduce manufacturing expenses, and augment operational efficiency. These modifications are implemented to cater to the varied requirements of customers seeking more personalized, tailored, and smaller quantities of items [10].

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To maintain global competitiveness, organizations must prioritize robust manufacturing quality to consistently provide high-quality final goods, particularly for intricate items requiring substantial customization [11]. Overseeing intricate production processes in conventional manufacturing systems presents difficulties due to supply chain deficiencies, restricted data sets, and inadequate data digitization [12]. Numerous companies and institutions have transitioned from traditional paper-based operations to integrated information systems to tackle the issues they encounter. Integrating IoT and cloud computing facilitates the rapid collection and organization of in-process data inside production systems while concurrently assimilating information from an expanding network of suppliers [13]. This capability enhances the forecasting of final product attributes, significantly influencing their functioning, structural integrity, and longevity [14]. Figure 1 shows the transformer manufacturing unit with supply chain management (SCM). It is essential for intelligent manufacturing (IM) firms to promptly implement a traceable process and a dynamic control system that incorporates intelligent quality decision support [15]. This research is undertaken in collaboration with a leading power transformer producer that caters to a worldwide clientele with varied requirements [16]. Industrial power transformers are intricate, expensive, and engineered for specific applications. To thrive in the global market, the organization must enhance its digital connection, facilitate information exchange across the supply chain, and use intelligent decision-making in production, including predicting final product quality [17]. The firm is executing a digital transformation plan aligned with the tenets of Industry 4.0. This approach integrates sophisticated business processes with cutting-edge methodologies and digital technology to generate value for intelligent businesses, particularly within smart manufacturing value chains. Digitizing industrial operations and associated methods and making educated management choices, such as anticipating end-product quality in a supply chain, may enhance productivity, maximize resource use, minimize waste, and increase profitability [18]. Digital transformation may enhance creative communities, streamline industrial processes, and swiftly address market demands [19]. This research will use material data to forecast the product's attributes, notably focusing on power transformer iron core losses. Organizations tested samples from each batch to verify compliance with client expectations [20]. The corporation incurred significant waste in labor and raw materials when completed items failed to fulfill customer quality criteria. Manufacturers and their supply chain collaborators use sophisticated IoT apps to digitize product lifetime data [21]. Data on fundamental components may be used to forecast product quality using precise predictive models. This work presents a model that uses numerical values for iron and copper cores to forecast the quality of transformer products, including iron and copper losses that significantly influence transformer performance. The predictive model is evaluated using supervised, semi-supervised, and integrated machine learning techniques to forecast transformer quality precisely [22, 23].

1.2. Key contributions

The article primarily focuses on optimizing transformer design by integrating advanced manufacturing techniques, AI, and predictive modeling. However, transformer design is inherently linked to the broader industry supply chain, as improvements in

Figure 1
Transformer manufacturing unit with supply chain management
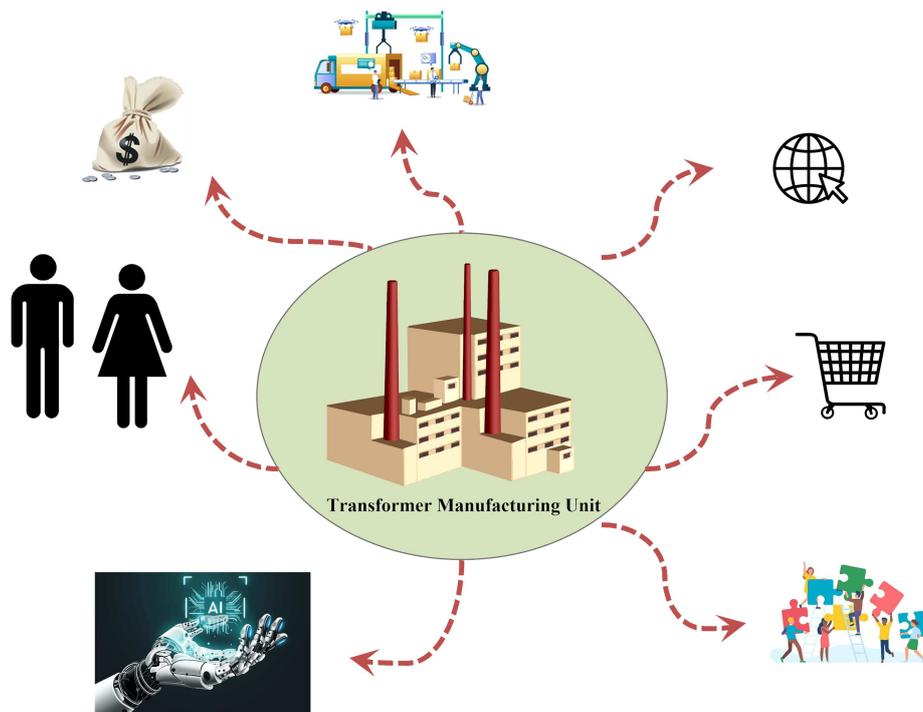
design influence material selection, production efficiency, cost-effectiveness, and overall SCM. Likewise, advancements in the supply chain—such as the adoption of smart logistics, real-time monitoring, and automated quality control—support the development of high-performance transformers by ensuring the availability of high-quality materials, minimizing delays, and reducing costs.

By addressing the limitations of conventional quality prediction methods, this study contributes to the advancement of IM within the Industry 4.0 paradigm. Studies emphasize how these technologies enhance operational efficiency through predictive maintenance, real-time monitoring, and smart decision-making, particularly in Industry 4.0 frameworks. Despite the opportunities, challenges remain, especially for small and medium-sized enterprises in adopting complex systems like MES. Sustainability is also a growing focus, with e-commerce and energy-efficient models becoming central to smart manufacturing. AI and machine learning continue to play a critical role in improving diagnostics and decision-making in industrial maintenance. This study serves as a step toward a more integrated, data-driven approach to predictive quality control, facilitating the broader adoption of digital transformation in manufacturing industries.

The article is structured into the following sections: Section 2 presents the manufacturing process at the industry level. Section 3 depicts a comprehensive literature survey on SCM in the power industry and optimizing transformer design using AI techniques. Section 4 elaborates on advanced technologies and systems in smart manufacturing, followed by conclusions in Section 5.

2. Power Transformer Manufacturing

The design and development of transformers in the latter half of the 19th century were pivotal to the operation of modern electricity networks. These devices efficiently convert electrical energy to the required voltage or current levels, enabling the practical use of electricity across various applications. While low voltages are advantageous for power generation and consumption due to reduced energy loss, high voltages are more effective for long-distance electricity transmission, minimizing losses over vast distances [24]. The foundation for transformer technology was laid in 1831 by British scientist Michael Faraday, who demonstrated the principles of electromagnetic induction, highlighting the essential role of transformers [25]. Over the following five decades, the application of alternating current (AC) systems solidified the importance of transformers, with the "power transformer" emerging as a vital component for electricity transmission and distribution [26]. Today, transformers play a crucial role in ensuring the reliability and efficiency of electrical systems. Power transformers, typically immersed in oil, rely on this oil for both cooling and insulating their windings and cores [27]. In some cases, additional cooling fluids are necessary to maintain optimal performance. Transformers operate by adjusting the impedance, current, and voltage of an AC source, which is achieved through the interaction of primary and secondary coils wound around an iron core [28]. A magnetic saturation transformer, in particular, regulates and isolates the primary coil by controlling these key parameters. When voltage is applied to the secondary coil, the AC in the primary coil induces an alternating magnetic flux in the iron core, allowing the transformer to convert electrical energy effectively [29].

Figure 2 illustrates the industrial manufacturing process at Asia Trafo LLP in Shymkent, Kazakhstan, where transformers are

Figure 2
**Manufacturing process of power transformer at Asia Trafo LLP in Shymkent, Kazakhstan**
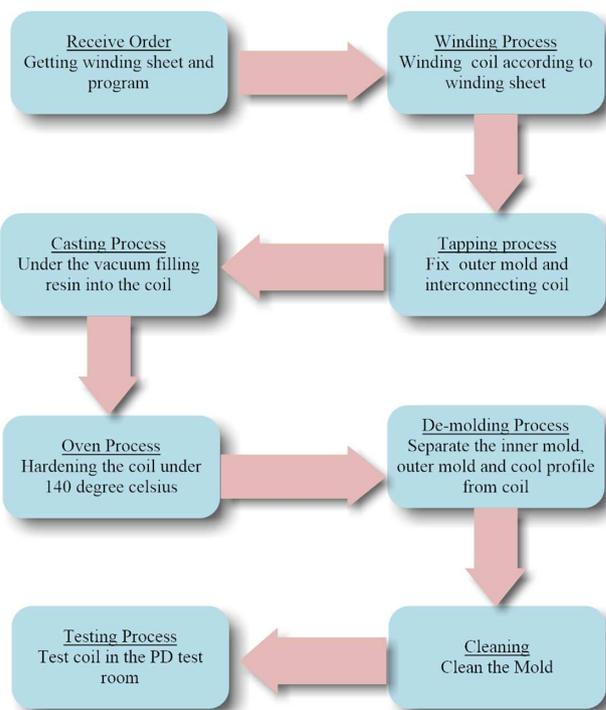
produced [30]. These devices typically feature coils with two or more windings, enabling them to perform their essential functions. In essence, transformers are designed to regulate voltage, current, and impedance reliably through electromagnetic mutual inductance. The iron cores within transformers enhance magnetic coupling between the coils. They are constructed from silicon steel sheets welded together to minimize hysteresis losses and reduce eddy currents. The copper coils are insulated from the electrical system to minimize eddy currents further, and the wires or aluminum components may be encased and laminated. Eddy currents occur when ACs interact with the fluctuating magnetic field of the primary coil. Keeping these currents low is critical to preventing disruptions in the core current flow between the primary and secondary coils. The iron core plays a central role in this process, converting electrical energy from the primary circuit into magnetic energy and then back into electrical energy in the secondary circuit. This study aims to achieve better voltage regulation, reduce losses, improve efficiency, and reduce raw material costs [31].

3. Comprehensive Literature Analysis

Manufacturing high-quality products and items is essential to guarantee sustainable business operations and foster client trust. This section comprehensively reviews the transformer manufacturing process, addresses quality prediction, and summarizes ensemble learning and machine learning studies.

The key research areas covered in this section are categorized as follows: SCM (30%), optimizing transformer design using AI techniques (25%), advanced technologies and smart manufacturing

Figure 3
Focus areas (a) transformer manufacturing literature, (b) number publications in the area

(a)

Focus Areas in Transformetr Manufacturing Literature

(b)

% Publications
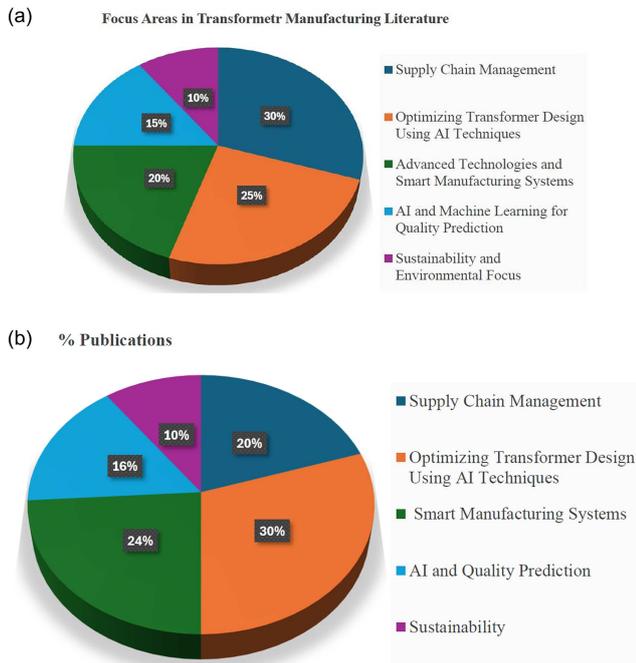
systems (20%), AI and machine learning for quality prediction (15%), and sustainability and environmental focus (10%) as shown in Figure 3. This classification provides a structured approach to understanding the key research areas and their relative significance. Furthermore, this review highlights advancements in model-based manufacturing quality inspection, offering insights into the role of digital transformation in modern manufacturing.

3.1. Supply chain management in power industry

The power transformer sector has undergone significant changes in the past decade, reflecting broader trends in SCM. Smart transformers have been introduced to improve grid reliability, aligning with the global shift toward outsourcing raw materials and reducing costs [32]. However, during this time frame, there was an increase in the costs of raw materials, specifically steel and copper, which presented difficulties for major companies such as ABB, Siemens, and GE [33]. In the next year, the launch of environmentally friendly transformers, including ester-filled options, was in line with the sector's emphasis on sustainable supply chains and cutting carbon footprints amid stricter environmental rules. The rise of renewable energy led to a greater need for high-voltage transformers, as blockchain technology also started enhancing transparency in supply chains.

However, disruptions in the supply chain were caused by geopolitical tensions. There was a growth in digital transformers using IoT-based monitoring, encouraging manufacturers to adopt lean production methods to shorten lead times, even with the increasing cybersecurity threats in SCM [35]. The efforts were made to streamline installation processes through standardization and

modularization initiatives, utilizing AI-driven demand forecasting to enhance supply chain efficiency. Yet, difficulties were encountered in obtaining global transformer components due to tariffs and trade barriers. The hybrid transformers integrating traditional and renewable energy capabilities emerged, with advanced analytics improving inventory management and supplier connections. However, the industry continued to be affected by economic uncertainties, which caused fluctuations in demand [36]. The COVID-19 pandemic in 2020 heavily impacted the sector, resulting in delays in projects, shortages in supplies, and a move toward more robust and adaptable supply chains focusing on local sourcing. This was followed by a surge in electrification and urbanization, leading to upgrades in transformers and the use of digital twins and AI-based tools for SCM to enable predictive maintenance despite ongoing raw material shortages and shipping delays [37]. The sector was concentrating on creating energy-saving transformers to achieve decarbonization goals, as visibility technologies in the supply chain, such as IoT and blockchain, were becoming more popular due to sustainability demands. The HVDC transformer technology was introduced to transmit power over long distances and implement circular economy strategies for recycling and reusing transformer components [38]. However, production was impacted by worldwide semiconductor shortages. The combination of smart grids and progress in digitalization will continue to improve supply chains, fueled by the use of AI and machine learning [39]. It will also tackle issues surrounding energy transition and grid modernization. Major companies such as GE, Schneider Electric, and Siemens are important figures in the changing environment of the power transformer industry as they work to manage the challenges of supply chain dynamics [40]. A comprehensive study on SCM in the power industry in manufacturing power transformers is tabulated in Table 1.

3.2. Optimizing transformer design using AI techniques

AI has played a pivotal role in optimizing transformer design, addressing challenges such as efficiency improvement, material cost reduction, and enhanced reliability. This section explores various AI-based methodologies, including genetic algorithms (GAs), artificial neural networks (ANN), and multi-objective evolutionary optimization techniques. Researchers use several AI techniques to tackle issues in improving transformer design [41, 42].

3.2.1. Genetic algorithms

J.H. Holland invented GAs in 1975, while David Goldberg and L.B. Booker demonstrated their efficacy in addressing complicated issues in 1989 and 1975 [43]. GAs are efficient instruments for optimization across several domains, including engineering, research, and industry [44]. Their comprehensive perspective, accessible design, and vast application have significantly increased their appeal. Gas-insulated systems have shown reduced costs related to the building, operation, and maintenance of transformers. Using these GAs enhances the design of the cooling system for distribution transformers. A GA-based evolutionary computational model was developed by Wong et al. [45], including identifying power transformer characteristics. GAs have enhanced toroidal core transformers and cast-resin distribution transformers. An improved

Table 1
A comprehensive survey on supply chain management in the power industry

Key manufacturing company	Key trends in power transformers	Developments in supply chain management	Challenges
ABB, Siemens, GE	Adoption of smart transformers for improved grid reliability	Global outsourcing of raw materials; increased focus on cost optimization	Rising costs of raw materials (steel, copper)
Schneider Electric, Hitachi	Introduction of eco-friendly transformers (e.g., ester-filled transformers)	Focus on sustainable supply chains, reducing carbon footprints	Environmental regulations tightening on manufacturing processes
Toshiba, Alstom Grid	Increased demand for high-voltage transformers due to renewable energy integration	Blockchain in supply chains for better transparency	Supply chain disruptions due to geopolitical tensions
Mitsubishi Electric, Hyundai Electric	Rise of digital transformers with IoT-based monitoring	Push toward lean manufacturing to reduce lead times	Cybersecurity risks in supply chain management
ABB, Siemens	Standardization and modularization of transformers for easier installation	AI-driven demand forecasting in supply chains	Tariffs and trade barriers affecting global transformer component sourcing
Schneider Electric, GE	Emergence of hybrid transformers combining traditional and renewable energy compatibility	Advanced analytics for inventory management and supplier relationship optimization	Fluctuations in demand due to economic uncertainties
Toshiba, CG Power	Impact of the COVID-19 pandemic: Delayed projects, shortages in supply	Shift toward resilient and flexible supply chains; emphasis on local sourcing	Logistics disruptions, factory closures, labor shortages
Siemens Energy, Hitachi Energy	Increased electrification and urbanization driving transformer upgrades	Digital twins and AI-powered SCM for predictive maintenance of transformers	Raw material shortages, shipping delays due to pandemic recovery
ABB, Hyundai	Development of energy-efficient transformers to meet decarbonization targets	Supply chain visibility technologies (e.g., IoT, blockchain) gaining ground	Sustainability pressures on transformer production processes
Siemens, Mitsubishi Electric	High-voltage direct current (HVDC) transformer technology for long-distance power transmission	Circular economy practices emerging in the supply chain (recycling, reusing transformer parts)	Global semiconductor shortages affecting production
GE, Schneider Electric	Smart grid integration with transformers, further advancements in digitalization	AI and machine learning fully integrated into supply chain optimization	Energy transition challenges and grid modernization demands

design for a rectifier power transformer was attained by using a GA and simulated annealing, as outlined in Wang et al. [46]. GA effectively enhanced the designs of rectifier power transformers. Georgilakis tackled the issue of decreasing transformer expenses using evolutionary algorithms and external elitism. The distribution transformer design used a hybrid optimal technique that integrated deterministic approaches, GAs, and two-dimensional finite elements to get the most efficient solution. A penalty function technique for assessing objective functions with weighted coefficients and a basic evolutionary algorithm was used in Koutsoukis et al. [47] to illustrate the ideal transformer design based on the total cost of ownership.

3.2.2. Advanced techniques in artificial neural networks

ANN provide a computational framework inspired by biological neural networks and are widely applied in transformer design and fault diagnosis. ANN models have been used to predict transformer prices, forecast magnetic core properties, and minimize iron losses during manufacturing [48]. In Cantillo-Luna et al. [49], it was suggested that ANN could be used to forecast transformer prices during the design phase. On the other hand, Santamargarita et al. [50] used ANN to forecast the properties of magnetic transformer cores and related core losses to minimize iron losses in produced transformers. Applying neural networks and evolutionary programming improved the performance of wound core distribution transformers. Hajiaghapour-Moghimi et al. [51] effectively predicted losses in distribution transformers by utilizing daily load curve data with neural networks. This eliminated the need for the utility to evaluate the load profile for each client type. In a situation with supply imbalances, neural networks were used to evaluate iron losses, and Taguchi techniques were applied to improve core manufacturing processes to minimize iron losses [52]. Kaminski et al. [53] used a neural network to assess how long transformer oil would remain effective. The

model was applied to ten transformers with known transformer oil breakdown voltages. The modeling of nonlinear power transformers was accomplished using complex, valued open recurrent neural networks. Additionally, ANN often play an important role in identifying malfunctions in transformers. Wavelet signals were used in a real-time detection method described by Silva et al. [54]. This system was created to detect transformer inrush and fault currents using ANN. Sharma et al. [55] and Ekojono et al. [56] have shown how dissolved gas analysis can be used in training neural networks to identify early flaws in transformers. Meanwhile, other researchers, Elagoun and Seghier [57] and Mharakurwa [58], have demonstrated the effectiveness of an ANN in diagnosing problems with bushings. A specific neural network model was used in Torres-Huitzil and Girau [59] to identify each type of issue, showcasing the capability of ANN to classify errors.

Recent advancements in AI, particularly deep learning and large-scale models, have significantly improved transformer design optimization. Deep learning techniques like convolutional and recurrent neural networks enhance fault detection, lifetime estimation, and performance forecasting by extracting complex features and recognizing patterns. Large AI models, such as vision transformers and generative models, enable predictive analysis and automated design exploration, optimizing efficiency and reducing material costs. Additionally, integrating AI with digital twin technology allows real-time simulation of transformer behavior, enabling predictive maintenance and design adjustments to improve reliability and minimize downtime [60, 61].

### 3.2.3. Optimizing transformer design with multi-objective evolutionary algorithms

Multi-objective optimization effectively identifies one or more optimum solutions for complicated problems with many goals. Numerous real-world search and optimization tasks include numerous goals. Evolutionary multi-objective optimization methods use an iterative process to assess increasing solutions, enhancing their significance in the domain. Consequently, evolutionary algorithms are advantageous for maximizing several goals [62]. The research [63] enhanced transformer design by integrating an evolutionary multi-objective optimization approach with an unbounded population size and chaotic sequences. The methodology for developing the differential algorithm using the truncated gamma probability distribution function was shown in Coelho et al. [64]. Particle swarm optimization enhanced efficiency and reduced costs [65], while GAs effectively optimized the multi-objective design of high-frequency transformers. During the design phase of transformers, a multi-objective evolutionary optimization technique was used to determine the necessary parameters accurately [66]. A bacterial foraging method was proposed by Abou El-Ela et al. [67] to achieve optimum multi-objective transformer design. The objective of this strategy was to elevate expenses while concurrently diminishing the efficiency of a 500 kVA transformer. The authors assert that advancements in the design of multi-objective optimum transformers are ongoing.

4. Advanced Technologies and Systems in Smart Manufacturing

Clients in the industrial sector have diverse needs regarding mechanical and electrical engineering products, particularly as many larger pieces of equipment are highly specialized [68]. This specialization creates a significant challenge for manufacturers, as they must meet market demand while striving to improve production efficiency, maintain product quality, and control manufacturing costs. Digital transformation plays a crucial role in addressing these challenges, yet it is a complex endeavor [69, 70]. The situation is further complicated by rapid changes in global demand and the expectation of shorter delivery times. Manufacturers of high-quality

Figure 4
Supply chain management knowledge framework
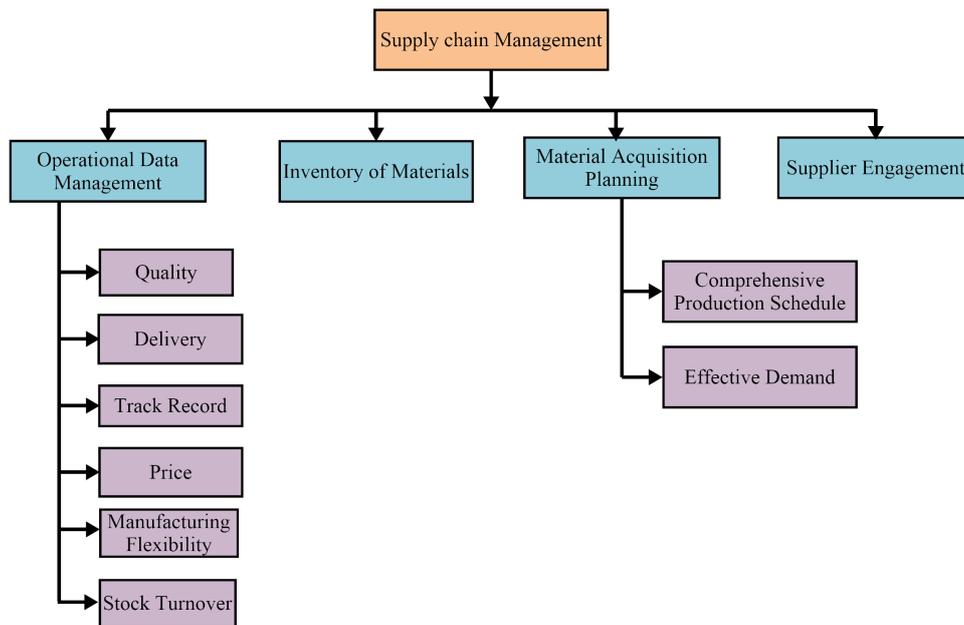
electrical power transformers, for instance, must ensure quality at every stage of operations—from procurement and production to distribution [71, 72]. Stability in production processes is crucial to avoid disruptions that could impact customer satisfaction. This section explores the essential role of SCM, machine learning, and IoT in driving digital transformation. By leveraging these technologies, manufacturers can optimize operations, swiftly respond to market demands, and enhance product quality, leading to greater customer satisfaction [73–75].

4.1. Supply chain management knowledge framework

The SCM knowledge framework is illustrated in Figure 4. Historically, vertical integration was a dominant strategy among electromechanical engineering manufacturers. However, in today's digital economy, companies increasingly rely on digital integration with global suppliers to enhance operational efficiency [76]. Advanced information technology is crucial in this shift, as it can significantly improve SCM by gathering accurate, real-time data from upstream suppliers and downstream consumers. This data-driven approach enables manufacturers to optimize their resources, ensuring they can effectively meet customer needs regarding products and services. One of the primary benefits of this digital integration is improved communication with customers, which, in turn, boosts company revenue [77]. Manufacturers can personalize their production systems by utilizing data for real-time planning and control, ensuring that products meet specific customer specifications. This capability also facilitates seamless order relaying to reliable suppliers, further enhancing efficiency. The first step in effective SCM is procuring raw materials essential for producing and selling finished goods to end users. Successful SCM involves managing key components such as inventory, demand, quality, and delivery time while integrating all suppliers into the company's internal and external product and service value chain. Supplier management encompasses the organization of the entire supply chain, including merchants, logistics providers, and manufacturers. Key steps in this process include acquiring raw materials, developing efficient production methods, and distributing products to customers. Organizations must consider multiple factors, including quality, cost, delivery time, and service when selecting suppliers to ensure they meet ISO standards. Supplier selection is a critical process involving weighing various criteria impacting customer satisfaction. Factors such as delivery time, product quality, service levels, and pricing are vital. The weighted average method is often employed to evaluate and prioritize these criteria during the supplier selection process. For example, Supplier A might offer fast delivery at a lower price but provide lower-quality goods. In contrast, Supplier B may deliver higher-quality products at a higher cost but with slower delivery. A weighted average can help businesses balance these trade-offs, enabling them to meet specific goals in a highly competitive market. Companies can enhance their competitiveness and ensure market sustainability by focusing on high-quality products. In the supplier evaluation process, opportunity costs, risks, and other quantitative factors are translated into cost measures, facilitating informed decision-making [78]. A matrix is frequently employed to outline key stages and priorities in the supplier evaluation process, using ratio and nominal scales for supplier comparison [79]. Various SCM methods are available to identify and evaluate suppliers effectively. One notable method is the Delphi technique, which anonymously gathers expert feedback through iterative questionnaires to reach a consensus. The total cost method evaluates cost ratios before selecting suppliers, while mathematical models, such as multi-objective linear or non-linear programming, consider constraints and multiple objectives. The data envelopment analysis model assesses supplier performance across market segments. Additionally, the fuzzy analytic hierarchy process (AHP) is beneficial when information is ambiguous, and the multi-objective AHP effectively combines qualitative and quantitative factors for decision-making in commercial situations [80, 81]. Overall, AHP plays a critical role in the backdrop of business priorities and strategies, and research indicates that it effectively fosters long-term supplier relationships. By adopting these methodologies, organizations can make more informed decisions that enhance their supply chain efficiency and contribute to their overall business success [82].

4.2. Manufacturing operations management (MOM)

Manufacturers today face mounting pressure from global competition, shifting labor markets, increasing material costs, trade disputes, and regulatory constraints [83, 84]. Industry 4.0 technologies, particularly IoT, AI, and cloud computing, are critical in overcoming these challenges by enhancing efficiency, reducing costs, and increasing productivity. In this context, advancing Industry 4.0 technologies is crucial for reducing costs, enhancing quality, and significantly increasing productivity and efficiency. The IoT plays a pivotal role in this transformation by connecting the entire value chain through digitalization, AI, and automation. This integration facilitates the straightforward

Figure 5
Manufacturing execution knowledge framework
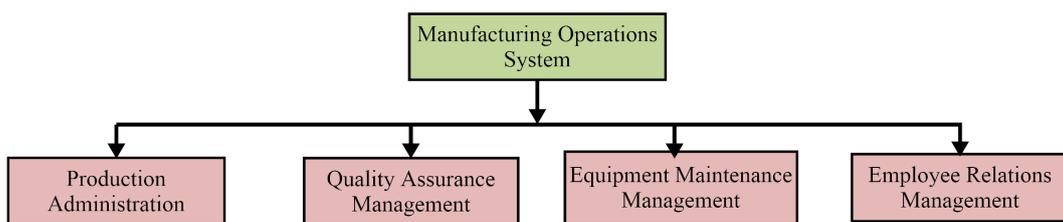
acquisition of physical equipment, efficient communication, collaborative development efforts, and real-time management of components for the bill of materials [85]. The combination of cloud computing with application systems enables the creation of intelligent industrial systems at a more affordable price, allowing organizations to remain agile and responsive in a fiercely competitive global marketplace. It is essential for buyers and sellers to collaborate effectively in customizing high-value items that are offered in limited quantities. To improve competitiveness and foster brand loyalty, businesses must enhance customer service by increasing process efficiency and lowering product manufacturing costs [86, 87]. In the typical manufacturing sector, three strategies have emerged as particularly effective for improving productivity: enhancing output, reducing labor costs, and acquiring new equipment. Analyzing current manufacturing operations can uncover opportunities to meet changing customer order demands and enhance the supply chain's equipment, workforce, and production capacity. Figure 5 illustrates how manufacturing operations management (MOM) contributes to the advancement of information-driven IM. MOM systems assist managers in reallocating human resources and optimizing production capacity to meet performance targets and objectives. This optimization is achieved through a comprehensive analysis of several critical areas, including operator and production management, quality management, machine and equipment production rates, human resource management, material loss status, and work-in-process quality. To enhance overall performance and delivery, it is essential to optimize production management, quality management, machine and equipment production rates, and human resource management. These components are defined within the manufacturing systems, and the ontology is illustrated in Figure 6. By focusing on these key areas, organizations can achieve a more efficient and effective manufacturing process, ultimately leading to improved competitiveness and customer satisfaction [88, 89].

This study by Torres et al. [90] examines error-proofing strategies to document industrial quality issues and reduce variability through human error analysis. To reduce the reliability problems stemming from equipment design in the workplace, it is essential to have a clear understanding of the root causes of faults [91]. Effective supply management, analysis of equipment production rates, monitoring of manufacturing history, and the implementation of enterprise resource planning (ERP) systems are essential elements that need to be established to collect management data prior to the commencement of production for client orders [92]. Managers can meet customer requirements by optimizing machine operations, effectively managing material demand, and utilizing real-time quality management data from various sources. Twelve essential functions of MES have been defined to address the needs of the manufacturing industry.

The functions encompass resource allocation and control, production scheduling, data collection and acquisition, quality management, management of production processes, material batch management, production traceability, performance analysis, operational and detailed planning, document management, human resource management, maintenance management, and material transportation, storage, and tracking [93, 94]. Further, the MOM of top manufacturing companies is summarized in Table 2.

4.3. Material flow mechanisms in key operational units

Specialized part suppliers can improve process efficiency and minimize setup and changeover times on production lines by allocating low and irregular-volume components to additive manufacturing (AM). This process programming, which supports the idea that AM and traditional manufacturing (TM) function together, is referred to as "combinational," and this term defines it [95].

Figure 6
Hierarchical model of transformer casing components
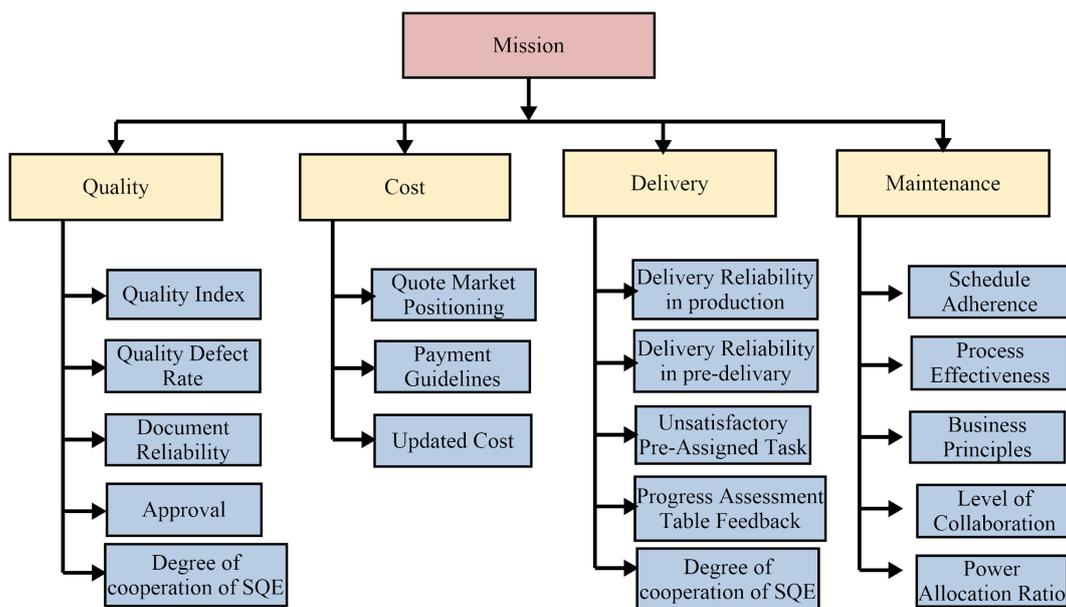
AM simplifies the stages of TM, enhances material transportation, reduces waste, lowers work-in-process inventory, and minimizes errors. This makes it especially advantageous for companies concentrating on batching and job work [96]. Two different machining methods and components that were produced for inventory were incorporated into the TM process before the finishing, testing, and packaging stages. AM has led to a notable decrease in work-in-progress and finished product inventories [97]. The achievement arose from printing being the main production method, and there was no need for client design involvement. Producing in smaller batches can lower costs, allowing for delays in production, local-

ization, and adjustments directly at the distribution point [98]. The order decoupling point needs to be moved to the customer's site to improve timeliness. This gives supply chain companies, usually smaller than specialized suppliers, an additional incentive to utilize technology to produce different components on their manufacturing lines. Bringing component fabrication closer to assembly facilities and delivering spare parts nearer to clients could improve the efficiency of original equipment manufacturers (OEMs). This will result in lower costs for material handling, transportation, component shortages, and inventory management. Possible areas for improvement are bottlenecks, capacity management, and line

Table 2
A comprehensive survey on MOM

Main manufacturing companies	Key trends in power transformer manufacturing	Manufacturing operations management (MOM) innovations	Challenges in MOM
ABB, Siemens	Shift toward energy-efficient transformers and high-capacity units	Introduction of basic digital dashboards to track production in real time	Limited integration of production systems, siloed data management
Schneider Electric, Hitachi	Increasing demand for compact, high-performance transformers	Early adoption of manufacturing execution systems (MES) for production scheduling and quality control	Fragmented data systems impacting operational efficiency
Toshiba, Alstom Grid	Focus on automation and optimization of production processes	Use of automated assembly lines and quality control testing using SCADA systems	High costs of implementing advanced MOM solutions
Mitsubishi Electric, Hyundai Electric	Implementation of lean manufacturing principles to reduce waste	Introduction of IIoT sensors to collect real-time data on production floor operations	Data overload due to multiple sources; managing predictive analytics
ABB, Siemens	Rise of digital twins to simulate manufacturing processes	Adoption of integrated MOM systems combining MES, ERP, and PLM for better decision-making	Cybersecurity vulnerabilities in interconnected MOM systems **AQ1**
Schneider Electric, GE	Standardization of transformer manufacturing processes across global facilities	Data-driven MOM systems leveraging AI and machine learning for predictive maintenance	Integration challenges with legacy equipment and systems
Toshiba, CG Power	COVID-19 pandemic leads to remote monitoring and automation upgrades	Virtual commissioning tools adopted to simulate production and reduce on-site workforce	Production delays and labor shortages impacting manufacturing schedules
Siemens Energy, Hitachi Energy	Recovery from pandemic impacts leads to increased automation investments	AI-driven process optimization for improved yield and reduced downtime	Shortages of skilled workers to manage complex MOM systems
ABB, Hyundai	Greater emphasis on sustainability in transformer manufacturing processes	Cloud-based MOM platforms enabling global collaboration and real-time data access	Supply chain disruptions affecting raw materials procurement
Siemens, Mitsubishi Electric	Use of additive manufacturing (3D printing) for customized transformer parts	Real-time visibility into all stages of production through advanced MOM dashboards	Complex compliance requirements and evolving regulations
GE, Schneider Electric	Integration of green energy in manufacturing operations for carbon-neutral production	Full-scale integration of AI/ML in MOM for predictive analytics and resource optimization	Increasing need for cybersecurity and data protection in MOM environments

balancing. Implementing AM at the factory level reduces reliance on just-in-time supplier coordination, leading to significant transportation cost savings. Additionally, minimizing material waste enhances operational efficiency. However, studies indicate that AM systems generally have lower throughput compared to TM methods, making it essential to evaluate demand rates when assessing production speed and efficiency [99, 100].

4.4. Communication flow and collaborations among essential partners

AM can significantly reduce demand planning and forecasting errors by minimizing the distance between supply chains and producing components on-site with fewer supply chain entities [101]. This results in greater collaboration among supply chain

Table 3
Comprehensive survey

Author(s)	Key findings	Drawbacks	Main decisions	Role of data enabler	Algorithms used
Wang et al. [103]	Emphasizes collaboration across the supply chain.	Lack of standardized frameworks for collaboration.	Enhance partnerships and integrate data sharing protocols.	Facilitates real-time data exchange for decision-making.	N/A
Lee et al. [104]	Identifies benefits such as improved visibility and responsiveness.	Challenges in technology adoption and workforce skills.	Invest in training and technology integration.	Provides analytics for demand forecasting and inventory control.	Regression Analysis
Gupta et al. [105]	Highlights opportunities in automation and data analytics.	High implementation costs and cyber-security risks.	Develop a phased approach to technology adoption.	Supports automation through data insights and analytics.	Decision Trees, Simulation Models
Khan et al. [104]	Demonstrates potential for transparency and traceability.	Complexity in implementation and integration with legacy systems.	Implement blockchain in phases, starting with critical suppliers.	Ensures data integrity and security in transactions.	Hash Algorithms, Smart Contracts
Ivanov and Dolgui [107]	Discusses the importance of resilience and adaptability.	Lack of a comprehensive model for measuring resilience.	Build resilience strategies into supply chain designs.	Enables real-time risk assessment through data collection.	Machine Learning Algorithms
Akbari and Hopkins [108]	Links sustainability with digital technologies for efficiency.	Difficulties in balancing sustainability and cost.	Create sustainability metrics aligned with supply chain goals.	Provides data analytics for sustainable practices.	Multi-Criteria Decision-Making
Kar and Kushwaha [109]	AI improves decision-making and reduces operational costs.	Dependence on data quality and algorithm biases.	Incorporate AI tools for data analysis and forecasting.	Acts as a facilitator for big data analytics.	Neural Networks, Genetic Algorithms
Awotunde et al. [110]	IoT enhances real-time monitoring and tracking capabilities.	Data security and privacy concerns.	Adopt IoT technologies gradually, ensuring data protection measures.	Provides continuous data flow for operational insights.	IoT Protocols, Data Fusion Techniques

Table 4
Quantitative analysis of technical methods and outcomes in transformer manufacturing

Reference	Technical method	Application context	Quantitative outcome	Key metric
Koutsoukis et al. [47]	Hybrid GA + finite element analysis	Transformer cost optimization	15% reduction in ownership costs	Cost efficiency
Kaminski et al. [53]	Artificial neural networks (ANN)	Oil breakdown prediction	94.2% accuracy in predicting oil lifespan	Predictive accuracy
Coelho et al. [64]	Gamma Differential Evolution	Multi-objective transformer design	20% cost reduction, 10% efficiency gain	Cost and efficiency
Khan et al. [106]	Blockchain traceability	Supply chain fraud prevention	22% reduction in supply chain fraud	Risk mitigation
Lee et al. [104]	IoT-enabled logistics	Production throughput improvement	18% increase in throughput	Operational speed
Rasiya et al. [97]	Additive manufacturing (AM)	Material waste reduction	28% reduction in material waste	Sustainability
Pereira et al. [98]	AM vs. traditional manufacturing (TM)	Lead time reduction	25% faster production for low-volume parts	Lead time efficiency
Santamargarita et al. [50]	ANN-based real-time monitoring	Core loss minimization	8.5% reduction in core losses	Energy efficiency
Hashemi and Kilic [66]	NSGA-III optimization	Harmonic distortion reduction	18% decrease in harmonic distortion	Power quality
Wang et al. [103]	Blockchain integration	Supply chain transparency	40% reduction in transaction delays	Operational transparency
Kar and Kushwaha [109]	AI-driven decision-making	Operational cost reduction	25% reduction in operational costs	Cost efficiency
Mika and Goudz [34]	Material recycling initiatives	CO_2 emissions reduction	25% reduction in carbon footprint	Environmental impact

organizations, particularly in the design capabilities employed by OEMs and AM providers. Incorporating information about component management in digital design enables assemblers to reduce the number of decisions they need to make regarding scheduling and planning. Improving demand visibility can be accomplished by eliminating supply chain intermediaries through electronic commerce solutions for asset management [102]. This will improve production scheduling and optimize capacity. Co-creation improves the relationship between customers and their suppliers by enhancing the customer's membership in the supply chain. This enables more precise local decision-making based on data. Bringing manufacturing operations closer to customers enables this transformation. A comprehensive survey is enumerated in Table 3. A detailed quantitative analysis of technical methods and outcomes in transformer manufacturing is summarized in Table 4.

5. Conclusions

This article has examined the advancements in innovative manufacturing technologies and their impact on power transformers' manufacturing and design processes. Integrating Industry 4.0 technologies, particularly IoT, cloud computing, and AI, is essential for enhancing SCM and optimizing manufacturing processes. Employing current data allows producers to make informed decisions, improve manufacturing processes, and maintain quality standards across the supply chain. The study highlights the importance of collaboration among supply chain participants, emphasizing the preference for digital integration over conventional vertical integration. This modification allows organizations to more effectively respond to changing market demands and save operational costs. The findings indicate

that, despite obstacles such as cybersecurity threats, technological implementation expenses, and supply chain interruptions, the strategic use of predictive analytics and machine learning may effectively mitigate these issues. The study also examines several methodologies, including GAs, neural networks, and multi-objective optimization, to enhance the performance and efficacy of transformers. The significance of data as a facilitator in this context is paramount; it is essential for forecasting, guaranteeing quality, and optimizing production levels. Manufacturers may improve their competitiveness and advocate for sustainable practices in the industry by focusing on intelligent SCM and using new technology. This research contributes to the ongoing discourse on digital transformation in manufacturing, offering insights to bolster future efforts to enhance productivity, quality, and customer satisfaction within the power transformer sector. However, the study is limited by the scope of available data, which may not fully capture the complexities and variances across different manufacturing environments. Future research could explore case studies across diverse regions and industries, considering additional challenges such as the scalability of technologies, the adaptability of workforce skills, and the long-term economic impacts of digital transformation in manufacturing. Additionally, further investigations into the integration of emerging technologies, such as 5G and blockchain, in enhancing supply chain resilience and performance could provide valuable insight.

Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data are available on request from the corresponding author upon reasonable request.

Author Contribution Statement

Adilbek Tazhibayev: Conceptualization, Methodology, Software, Validation, Formal analysis, Resources, Data curation, Writing – original draft, Writing – review & editing. **Irbulat Utepbergenov:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – review & editing, Supervision, Project administration. **Iouliia Skliarova:** Conceptualization, Methodology, Software, Validation, Formal analysis, Resources, Data curation, Writing – review & editing.

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A: PLM is Product Lifecycle Management)

В Е С Т Н И К

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ЭНЕРГЕТИКА И ЭНЕРГЕТИЧЕСКОЕ МАШИНОСТРОЕНИЕ

ПОДХОД К СНИЖЕНИЮ ШУМА И ВИБРАЦИИ ШУНТИРУЮЩИХ РЕАКТОРОВ НА ОСНОВЕ УСОВЕРШЕНСТВОВАНИЯ КОНСТРУКЦИИ И ПРИМЕНЯЕМЫХ МАТЕРИАЛОВ

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Аннотация. Актуальность исследования связана с тем, что вибрация, являющаяся источником шума реактора, влияет на его собственную механическую прочность, снижая срок службы. Целью настоящих прикладных исследований является уменьшение вибрации и шума в шунтирующих масляных реакторах с использованием предложенных инновационных решений на основе усовершенствования конструкции и применяемых материалов для увеличения жизненного цикла. Научная новизна предлагаемого комплексного подхода состоит в снижении амплитуды перемещений стенок бака и соответственно уменьшения уровня вибрации реактора с использованием компьютерного моделирования и оптимизации конструкции бака проектируемого реактора и в применении для активной части реактора материалов с низкими виброакустическими характеристиками. Сравнение шумовых характеристик нового реактора РОМ-60000/525-У1 с результатами обязательных приемо-сдаточных виброакустических испытаний подобных реакторов данного класса, производимых в Казахстане, подтвердили снижение корректированного уровня звуковой мощности нового реактора. Результаты исследования имеют большую практическую значимость для отечественного трансформаторостроения.

Ключевые слова: шунтирующий реактор, вибрация активной части, усовершенствование конструкции реактора, виброакустические характеристики, испытание, испытание реактора на нагрев, реактивная мощность, напряжение.

Введение

Шунтирующие масляные реакторы используются на объектах электрических сетей для повышения пропускной способности линий сверхвысокого напряжения, разгружая их по реактивной мощности, а также регулирования реактивной мощности и напряжения. Поток реактивной мощности в электрических сетях является следствием переменного потребления и генерирования реактивной мощности. Чрезмерная реактивная мощность вызывает увеличение активных потерь и повышение частоты сети [1-5]. При изменении характера по нагрузке меняется и реактивный ток, поступающий из системы. При протекании реактивного тока происходит падение напряжения, и напряжение в системе будет снижаться по отношению к напряжению холостого хода. Кроме того, протекание реактивного тока вызовет дополнительные потери в сети.

Применительно к системам, в которых требования по переменной реактивной мощности, обусловленной изменениями в потреблении и/или генерировании энергии, не могут быть удовлетворены, общепринятой практикой является использование средств коррекции или компенсации с целью обеспечить работу системы в заданных и приемлемых условиях.

В сетях, где потребление и генерирование хорошо предсказуемы и стабильны, используются конденсаторные батареи или шунтирующие реакторы фиксированной мощности. Однако в этом случае компенсация реактивной мощности выполняется только для определенных рабочих условий. Большая гибкость может быть достигнута, если предусмотрено механическое переключение этих

агрегатов. Шунтирующий реактор помогает нормализовать уровень напряжения таким образом, что его колебания не выходят за пределы 2%. Результатом его установки является значительное сокращение активных потерь: снижение потерь электроэнергии на 15–20%, что, в свою очередь, приведет к улучшению стабильности и пропускной способности системы [6, 7].

В процессе эксплуатации трансформаторно-реакторное оборудование производит шум, причиной которого является вибрация оборудования. Анализ показывает, что источниками сильной вибрации и шума являются управляющие обмотки постоянного тока, используемые для обеспечения постоянного магнитного потока смещения, который изменяет степень уровня магнитного насыщения сердечника [8, 9]. Также к основным причинам вибрации реакторов относятся магнитострикция кремнистой стали, приводящая к деформации кристаллической решетки магнитного материала при его намагничивании, и электромагнитная сила между дисками активной зоны, и динамические силы в обмотках [10-13].

На сегодняшний момент средний уровень шума, производимый трансформаторами, мощностью реактора 110–750 кВ составляет от 79 дБ(А) до чуть более 90 дБ(А) [14,15]. Вибрация влияет на его собственную механическую прочность реактора, снижая срок службы и повышая возможность возникновения внутренних повреждений. Из-за постоянной вибрации активной части в первую очередь происходит износ изоляционных деталей, что приводит к частым капитальным ремонтам и заменам изоляционных деталей. Поэтому снижение шума и вибрации на настоящий момент остается одной из актуальных задач современного трансформаторостроения.

 Предлагаемый комплексный подход основан в использовании возможности снижения амплитуды перемещений стенок бака и соответственно уменьшения уровня вибрации реактора с применением компьютерного моделирования и оптимизации конструкции бака проектируемого реактора и материалов с низкими виброакустическими характеристиками для активной части реактора. Работа посвящена исследованию уменьшения шума и вибрации в реакторах на класс напряжения 110–750 кВ с целью увеличения жизненного цикла на примере усовершенствования конструкции шунтирующего масляного реактора РОМ-60000/525-У1 с улучшенными вибрационными и шумовыми характеристиками, рассчитанного на более длительный срок службы по сравнению с аналогами.

Методология
Для исследований был использован реактор РОМ-60000/525-У1 с улучшенными вибрационными и шумовыми характеристиками, основные технические данные которого представлены в таблице 1.

Таблица 1 - Основные технические данные реактора РОМ-60000/525-У1

Наименование	Технические характеристики
Номинальная мощность, кВА	60000
Номинальное напряжение, кВ	525/√3
Линейное напряжение кВ	525
Номинальное наибольшее напряжение, кВ	550√3
Номинальный ток, А	197,94
Номинальное полное сопротивление, Ом	1531,6
Потери, приведенные к расчетной температуре 75°С кВт	140
Схема и группа соединения	Y-заземление глухое или через реактор
Частота, Гц	50
Число фаз	1
Вид охлаждения	ONAN
Нейтраль обмотки	Заземляется
Материал обмотки	Медь (Cu)
Марка (тип) масла	Nytro Lyra X

Расчет на вибрацию предполагает расчет амплитуд изгиба стенок бака при разных частотах на действие гармонической нагрузки. При построении геометрической модели учитывается конструкция активной части с ярмом, обмоткой, дисками, шпильками, а также расположение мест опирания на дно бака. К тому же при проектировании бака реактора методом конечных элементов эффективным подходом для снижения амплитуды перемещении стенок и увеличения механической жесткости конструкции является увеличение горизонтальных и вертикальных ребер и применение локальных масс для формирования частотных характеристик [16-18]

На этапе проектирования конструкции данного реактора использована программа 3D-дизайна, компьютерного моделирования и визуализации TDS компании Soft Team Group [19]. Полученная в программе TDS геометрическая модель реактора представляет собой пространственную оболочку с ребрами жесткости (рисунок 1а).

а)   б)
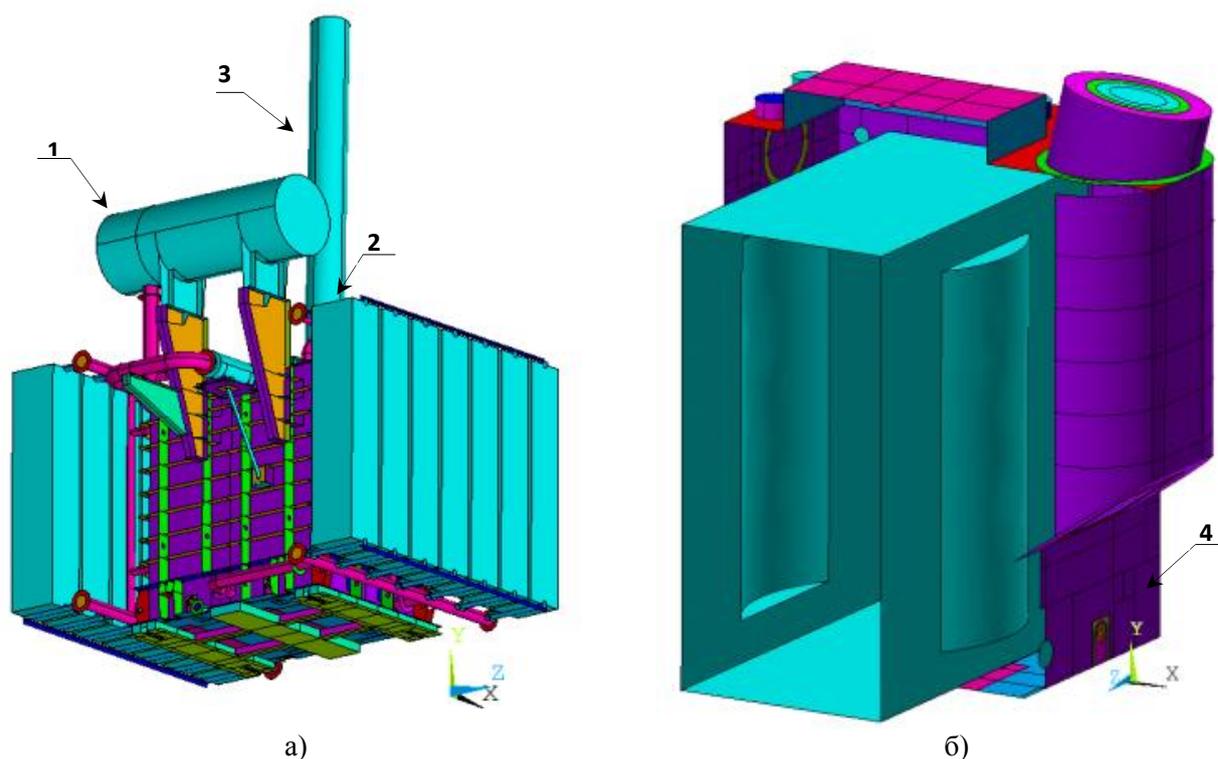
Рисунок 1 – 3D – модели: геометрическая модель реактора (а) и геометрическая модель бака (б):
1 – расширительный бак (а); 2 – радиатор (а); 3 – высоковольтный ввод (а);
4 – бак реактора (б)

Общий вид геометрической модели бака показан на рисунке 1б.

В качестве материала с низкими виброакустическими характеристиками для изготовления магнитопровода активной части реактора выбрана электротехническая сталь марки М090-27Pb HIB Laser с лазерной обработкой и в качестве резиновых прокладок – бутадиен-нитрильный каучук.

Для снижения амплитуды перемещений для стенок бака и соответственно уменьшению уровня вибрации реактора применено компьютерное моделирование и оптимизация конструкции бака на основе метода конечных элементов в среде TDS. В расчетной схеме применялись типы конечных элементов: SHELL181, SOLID185, PIPE59; контактные элементы: TARGE170 и CONTA174.

В результате усовершенствована конструкции бака РОМ-60000/525-У1:

       1)   увеличилось количество радиаторов в системе охлаждения реактора вида «М» с 6 до 7 с обеих сторон;

   2) увеличилось количество вертикальных и горизонтальных ребер жесткости на стенке бака реактора.

Опытным путем было определено снижение уровня шума и вибрации, передаваемой от активной части к баку реактора, на 2–3 дБ при изготовлении магнитопровода из электротехнической стали марки М090-27Pb HIB Laser с использованием резиновых прокладок (рисунок 2) и переходных дисков диаметром 800 и 1205 мм в центральном стержне магнитопровода, а также в конструкции остова реактора


а)

б)

Рисунок 2 – Установка резиновых прокладок на 3D-модели реактора (а): 1 – *между пакетами магнитной системы (между пакетами магнитной системы 0,5мм резиновые прокладки); 2 – между балкой и ярмом (между балкой и ярмом 4 мм резиновые прокладки);* на собранном реакторе (б)

Усилия прессовки магнитной системы остова – усилия затяжки ярмовых шпилек составляет 26кН, бандажей 12кН.

Кроме того, бутадиен-нитрильная каучуковая резина обладает отличной маслостойкостью при температуре 110 °С. Толщина, размеры и положение резиновых прокладок выбираются в зависимости от конструктивных особенностей остова реактора, а также усилий прессовки магнитной системы остова.

На рисунке 3 представлены полученные в TDS размерные параметры и 3D-модель усовершенствованного реактора РОМ-60000/525-У1.
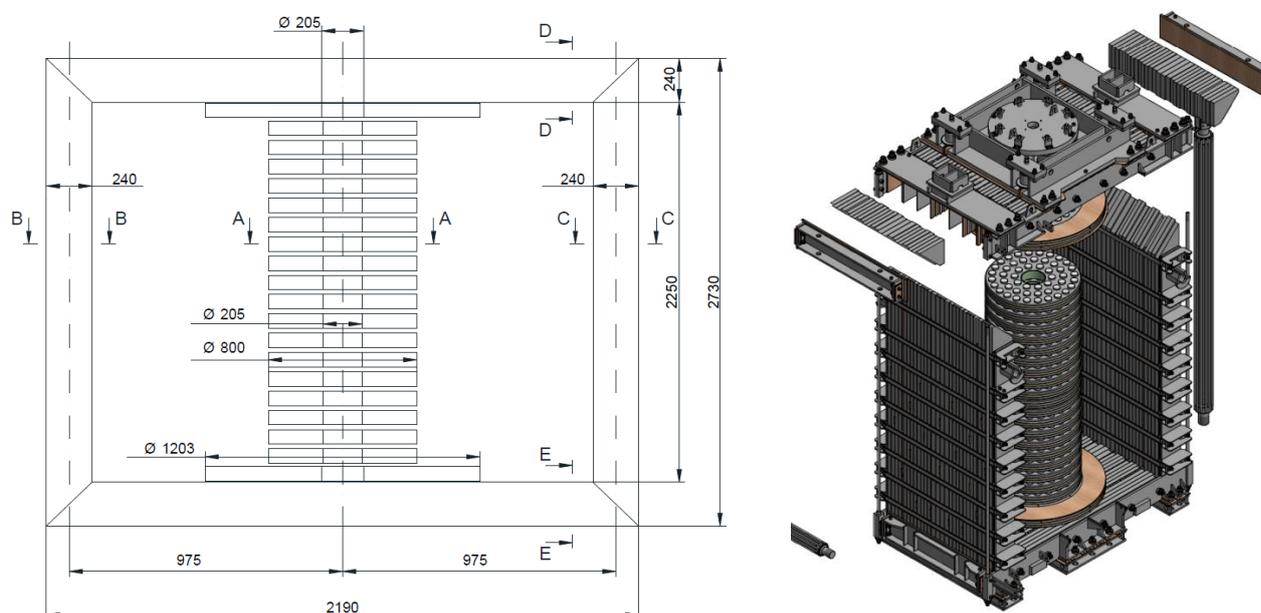
а)   б)
Рисунок 3 – Размерные параметры магнитопровода (а) и 3D-модель реактора (б):
1 – центральный стержень реактора (а); 2 – верхнее ярмо (а); 3 – нижнее ярмо (а);
4 – боковой стержень (а); 5 – верхний диск (а); 6 – нижний диск (а); 7 – фиксирующий кронштейн
(б); 8 – электротехническая сталь (б); 9 – торцевая балка (б)

Моделирование показало, что эффект снижения уровня шума и вибрации от установки резиновых демпферов в качестве прокладок из бутадиен-нитрильного каучука (NBR) в активном сечении получен, благодаря делению активной площади на более мелкие участки.

Настоящие исследования включают:

1) сравнение шумовых характеристик усовершенствованного реактора РОМ-60000/525-У1 с результатами обязательных приемо-сдаточных испытаний подобных реакторов данного класса, производимых в Казахстане;

2) проверку соответствия характеристик усовершенствованного реактора требованиям действующих отечественных и международных стандартов при применении рассмотренных инновационных решений для снижения уровня шума и вибрации реактора путем реализации полного цикла испытаний: виброакустические испытания; импульсные испытания; испытания на нагрев.

2. Результаты и обсуждение

2.1 Шумовые и вибрационные испытания
2.1.1 Проведение шумовых испытаний
Испытуемый новый реактор типа РОМ-60000/525-У1, как отмечалось выше, имеет систему охлаждения вида «М (ONAN)», состоящую из 2 групп по 7 радиаторов. На рисунке 4 показано расположение точек измерения уровней звука реактора с системой охлаждения.
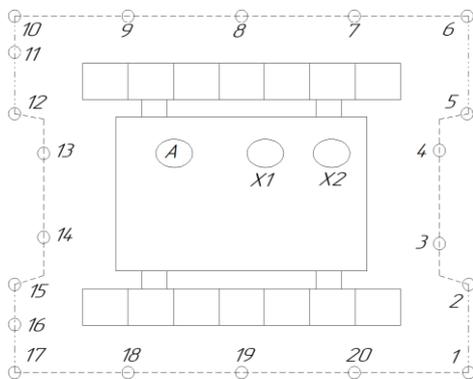

Рисунок 4 – Расположения точек измерения уровней звука реактора: А – высоковольтный вывод; Х1, Х2 – заземленная сторона

Испытуемый реактор устанавливался на подставку, без катков; номинальное напряжение возбуждения составляет 303,11 кВ; высота бака реактора 3190 мм; общая площадь испытательного помещения 891 м^2; длина периметра измерительной линии для расстояния измерения L=2,0 м составляет 34 м. Измерение уровня звука осуществлялось с помощью ручного анализатора модели B&K 2250L-100 (рис. 5).

Рисунок 5 – Процесс измерения уровней звука реактора РОМ-60000/525-У1

Измерительные линии располагались на расстоянии 0,3 м от излучающей поверхности реактора на высоте, равной 1/3 и 2/3 высоты реактора. Микрофон устанавливался в каждой точке измерения в направлении объекта испытания.

Перед испытаниями была проведена акустическая калибровка шумомера и были измерены уровни посторонних шумов. В таблицах 2 и 3 приведены полученные данные по измерению звука.

Таблица 2 - Результаты измерений уровня посторонних шумов

Точки измерений	Измеренные значения уровня посторонних шумов (уровень фона)										Среднее значение фонового шума (dB)
	1	2	3	4	5	6	7	8	9	10	
Перед испытанием	39,3	38,6	38,9	39,3	39,4	38,8	38,4	38,5	38,5	38,6	38,8
После испытаний	38,6	38,4	39,0	39,5	39,3	38,9	38,1	38,6	38,6	38,6	

Таблица 3 - Результаты измерений уровней звука

Измеренные значения звуковой мощности (расстояние 2м), (dB)		
Точки измерений	На высоте 1/2 Н бака	На высоте 2/3 Н бака
1	68,5	68,5
2	72,3	72,5
3	70,2	70,6
4	66,5	66,6
5	68,5	68,8
6	68,7	68,7
7	65,3	65,5
8	67,4	66,6
9	68,8	68,8
10	61,7	61,9
11	68,5	68,7
12	68,2	68,4
Среднее измеренное значение	67,88	67,97
Среднее измеренное значение, $L_{a0,3} = 67,93$ (dB)		

Обработки результатов измерений и расчет корректированного уровня звуковой мощности выполнены по ГОСТ 51401–99.

Постоянная коэффициента звукоотражения К (дБА) для помещения, в котором проводились испытания, рассчитывается:

$$K = 10 \cdot \lg \cdot \left(1 + 4 \cdot \frac{S}{A}\right), \tag{1}$$

где: S – площадь измерительной поверхности;

A – эквивалентная площадь звукопоглощения в помещении, которая рассчитывается приближенно по формуле:

$$A = \mathrm{a} \cdot S_v = 0{,}15 \cdot 891 = 133{,}65 \text{ м}^2 \tag{2},$$

где: a – средний коэффициент звукопоглощения, равный 0,15 (ГОСТ 51401–99),

S_v – общая площадь испытательного помещения, м^2

Площадь измерительной поверхности излучения реактора:

$$S_{0.3} = 1{,}25 \cdot \mathrm{H} \cdot \mathrm{L} = 1{,}25 \cdot 3{,}19 \cdot 34 = 135{,}57 \text{ м}^2, \tag{3}$$

где: H – высота бака;

L – длина периметра измерительной линии.

Расчётное значение постоянной K, учитывающей влияние отраженного звука:

$$K_{0,3} = 10 \cdot \lg \cdot \left(1 + 4 \cdot \frac{133{,}65}{135{,}57}\right) = 7{,}04 \text{ дБА},$$

Результаты вычисления среднего уровня звука L_A реактора с системой охлаждения:

$$L_{A0,3} = L_{a0,3} - \Delta L_{a0,3} - K_{0,3} = 68 - 0 - 7{,}04 = 60{,}96 \text{ дБА} \tag{4}$$

Корректированный уровень звуковой мощности:

$$L_{pA} = L_A + 10 \cdot lg \cdot \left(S_{0,3}\right) = 60{,}96 + 10 \cdot lg \cdot (135{,}57) = 82{,}2 \text{ дБА} \tag{5}$$

Таким образом, корректированный уровень звуковой мощности реактора типа РОМ-60000/525 кВ составил 82,2 дБА при допустимом значении 100 дБА установленных норм стандарта IEC 60076-6-2014. Кроме того, как отмечалось выше на сегодняшний момент средний уровень шума, производимый трансформаторами, мощностью реактора 110–750 кВ составляет от 79 дБ(А) до чуть более 90 дБ(А), поэтому полученное значение корректированного уровня звуковой мощности 82,2 дБА находится ближе нижнему порогу, что соответствует малому уровню шума. Для сравнения – аналог нового реактора РОМБСМ-60000/500-У1, производимый в Казахстане, по данным приемо-сдаточных испытаний имеет значение корректированного уровня звуковой мощности L_{pA}= 88.0 дБА [20].

2.1.2 Проведение вибрационных испытаний

Измерение виброперемещения стенки бака и охладительной системы проводилось на полностью собранном шунтирующем реакторе РОМ-60000/525-У1 (рис. 6). Реактор установлен на подставке, без катков; напряжение возбуждения 303,11 кВ; методика испытаний по ГОСТ 12.1.012–90. Измерительный прибор SVAN-958.

Рисунок 6 – Процесс измерения вибрационных перемещений стенки бака и системы охлаждения реактора РОМ-60000/525-У1

Расположение точек измерения вибрационных перемещений показано на рисунке 7.
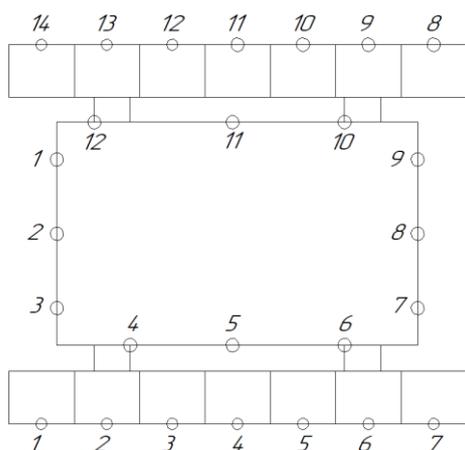

Рисунок 7 – Расположение точек измерения вибрационных перемещений стенки бака (1–12) и на системе охлаждения реактора (1–14)

Результаты измерений вибрационных перемещений в указанных точках приведены в таблицах 4 и 5.

Таблица 4 – Измеренные вибрационные перемещения стенки бака, мкм

№ точки	1	2	3	4	5	6	7	8	9	10	11	12
мкм	3,42	11,4	16,2	5,34	7,29	10,7	11,5	**21,9**	5,74	7,42	9,13	11,42

Таблица 5 – Измеренные вибрационные перемещения на системе охлаждения, мкм

№ точки	1	2	3	4	5	6	7	8	9	10	11	12	13	14
мкм	5,14	7,19	**12,15**	12,03	10,33	7,38	6,15	4,85	8,19	8,64	8,62	11,35	7,10	5,35

Максимальная величина вибрационных перемещений реактора типа РОМ-60000/525-У1 с системой охлаждения составила: на стенке бака – 21,9 мкм при допустимом значении по IEC 60076-6-2014 – не более 30 мкм; на системе охлаждения – 12,15 мкм при допустимом значении – 60 мкм. Шунтирующий реактор типа РОМ-60000/525-У1 виброакустические испытания выдержал и удовлетворяет требованиям ГОСТ 12.1.012–90.

2.2 Результаты импульсных испытаний реактора

Проверка соответствия электрической прочности изоляции при воздействии напряжений грозовых импульсов полного (ПГИ), срезанного (СГИ) и коммутационного импульса (КИ) проводились по методике ГОСТ 1516.2–97, ГОСТ 1516.3-96 и IEC 60076–3:2013, трехударным методом приложения импульсов отрицательной полярности со стороны линейного вывода. Схема испытаний представлена на рисунке 8.
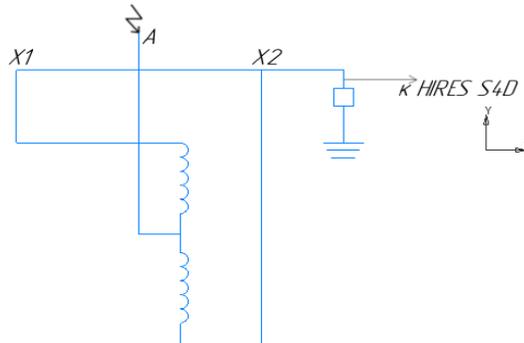
Рисунок 8 – Схема испытаний изоляции реактора воздействии напряжений ПГИ, СГИ и КИ

Для обнаружения недопустимых повреждений изоляции в качестве основного метода применялся метод, основанный на изменении формы колебаний напряжений и токов в обмотке в случае повреждения изоляции при приложении к испытуемой обмотке импульса напряжения.

Полный грозовой импульс – 1425 кВ; длительность фронта $T_ф$=1,2±0,36мкс, длительность импульса $T_и$=50±10 мкс. Срезанный грозовой импульс – 1550 кВ; предразрядное время $T_с$=2,5-5 мкс. Коммутационный грозовой импульс – 1050 кВ; время подъёма импульса – не менее 20 мкс, длительность импульса – не менее 500 мкс. Испытательное оборудование: генератор импульсного напряжения IG 240/2400G; емкостный делитель импульсного напряжения SMC 1000/2200; устройство регистрации переходных процессов HiRES-S4D.

Изоляция реактора выдержала приложения напряжений ПГИ амплитудой 1425 кВ отрицательной полярности (рисунок 9).
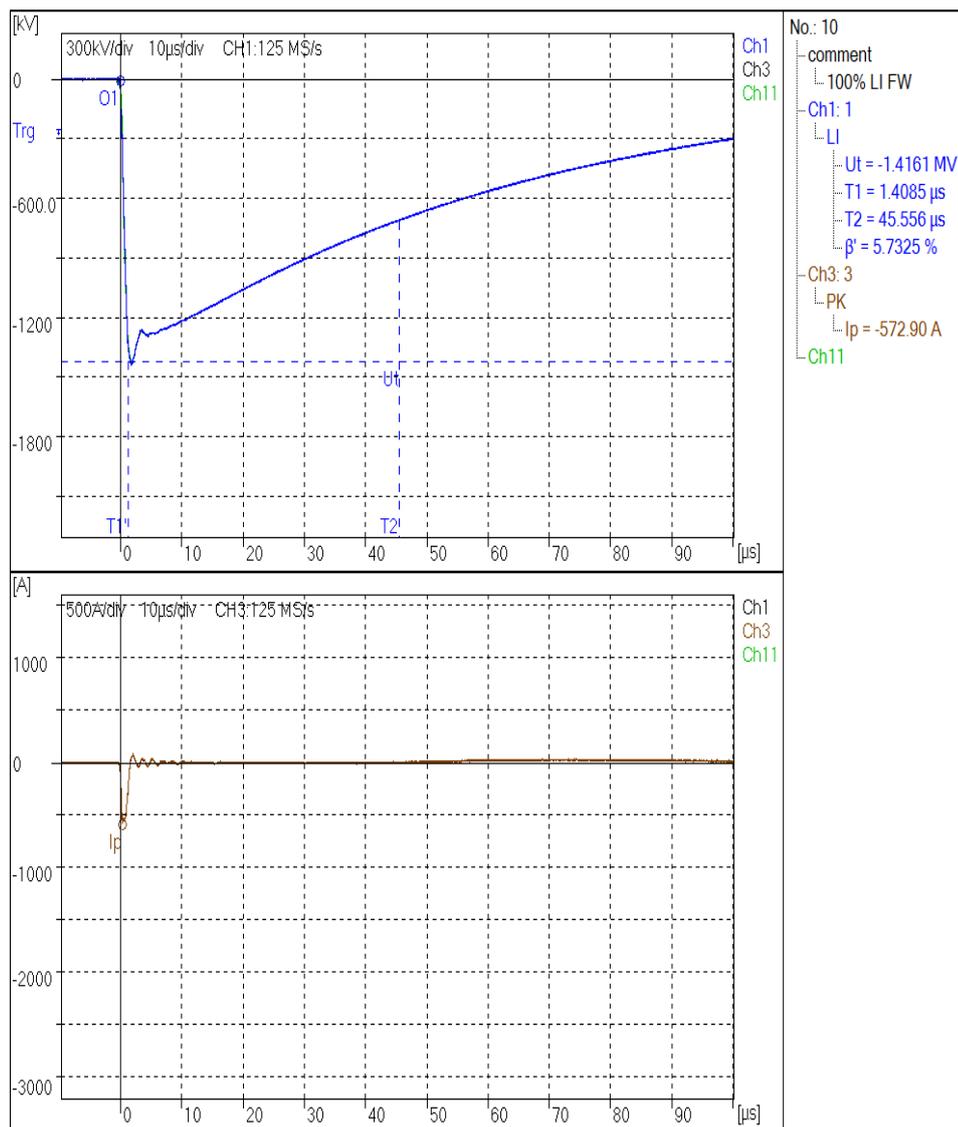
Рисунок 9 – Осциллограммы испытания изоляции обмотки реактора полным грозовым импульсом 1425 кВ

Изоляция реактора выдержала приложения напряжений СГИ амплитудой 1550 кВ отрицательной полярности (рисунок 10).
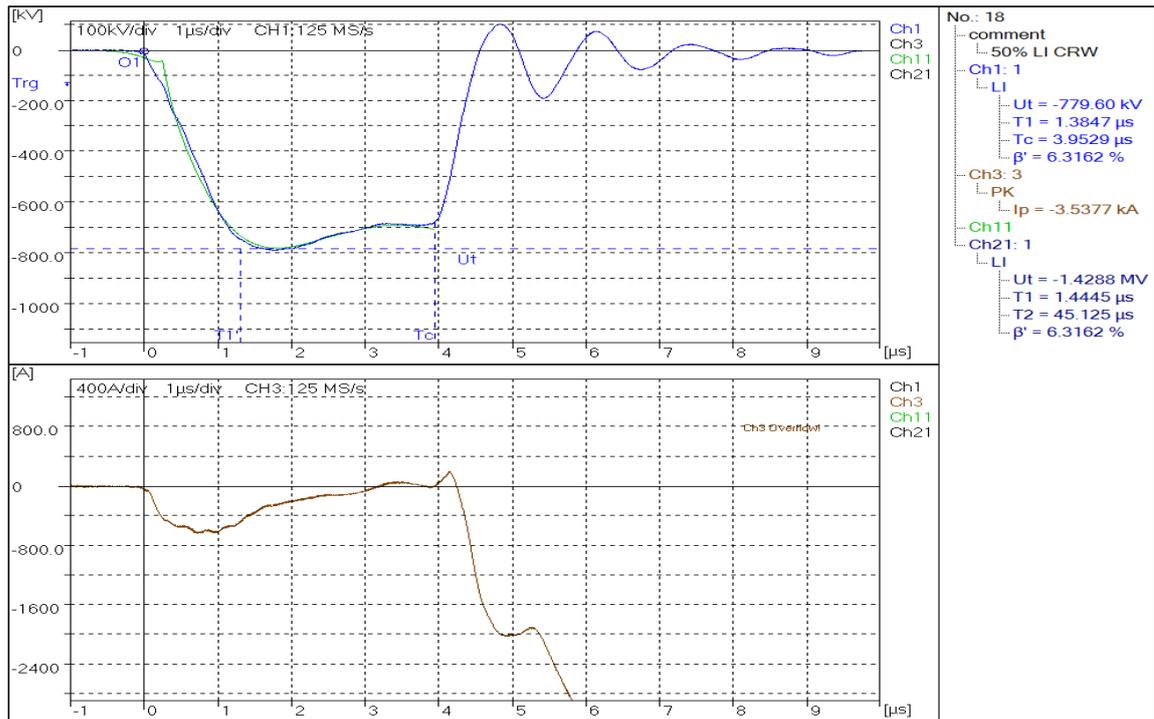
Рисунок 10 – Осциллограммы испытания изоляции обмотки реактора срезанным грозовым импульсом 1550 кВ

Изоляция реактора выдержала испытания напряжением КИ амплитудой 1050 кВ отрицательной полярности (рисунок 11).
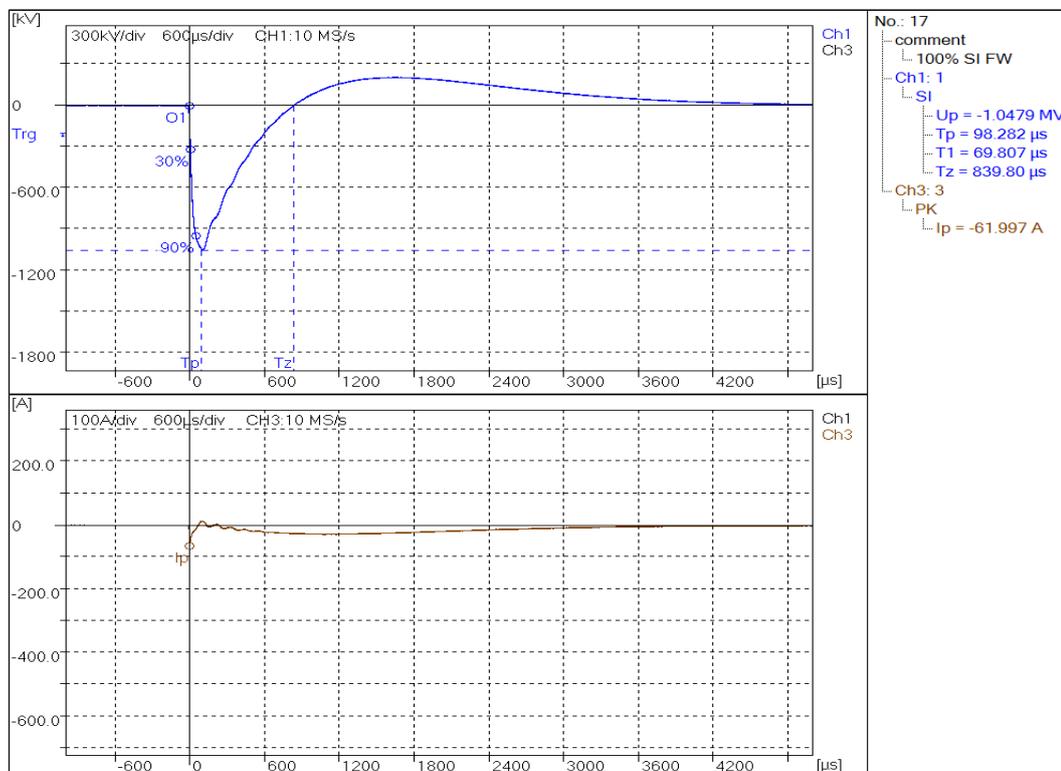

Рисунок 11 – Осциллограммы испытания изоляции обмотки реактора коммутационным импульсом 1050 кВ

Во время испытаний недопустимых повреждений изоляции реактора не обнаружено. Искажений формы осциллограмм, полученных при испытательных напряжениях 100% $U_{ИСП}$, по сравнению с осциллограммами при сниженном напряжении (50) % $U_{ИСП}$, не отмечено. Реактор выдержал испытание электрической прочности изоляции импульсными напряжениями. Электрическая прочность изоляции реактора типа РОМ-60000/525-У1 соответствует требованиям IEC 60076.3–2013–10 при воздействии импульсных напряжений.

2.3 Результаты испытания реактора на нагрев

Испытание на нагрев производилось на полностью собранном шунтирующем реакторе с системой охлаждения «М». Испытание проводилось по методике ГОСТ 3484.2–88 при номинальном напряжении 303,11 кВ и токе 197,9 А до установившейся температуры. Измерение температуры масла в патрубках производилось с помощью термопар. Температура обмотки определялась по изменению сопротивления обмотки постоянному току. Вовремя испытаний полностью отсутствовали воздействия ветра, солнечной или другой тепловой радиации. Полученные результаты измерения приведены на рисунке 12 и таблицах 6 и 7.

$$y = 0{,}0002x^2 - 0{,}0091x - 0{,}2839$$
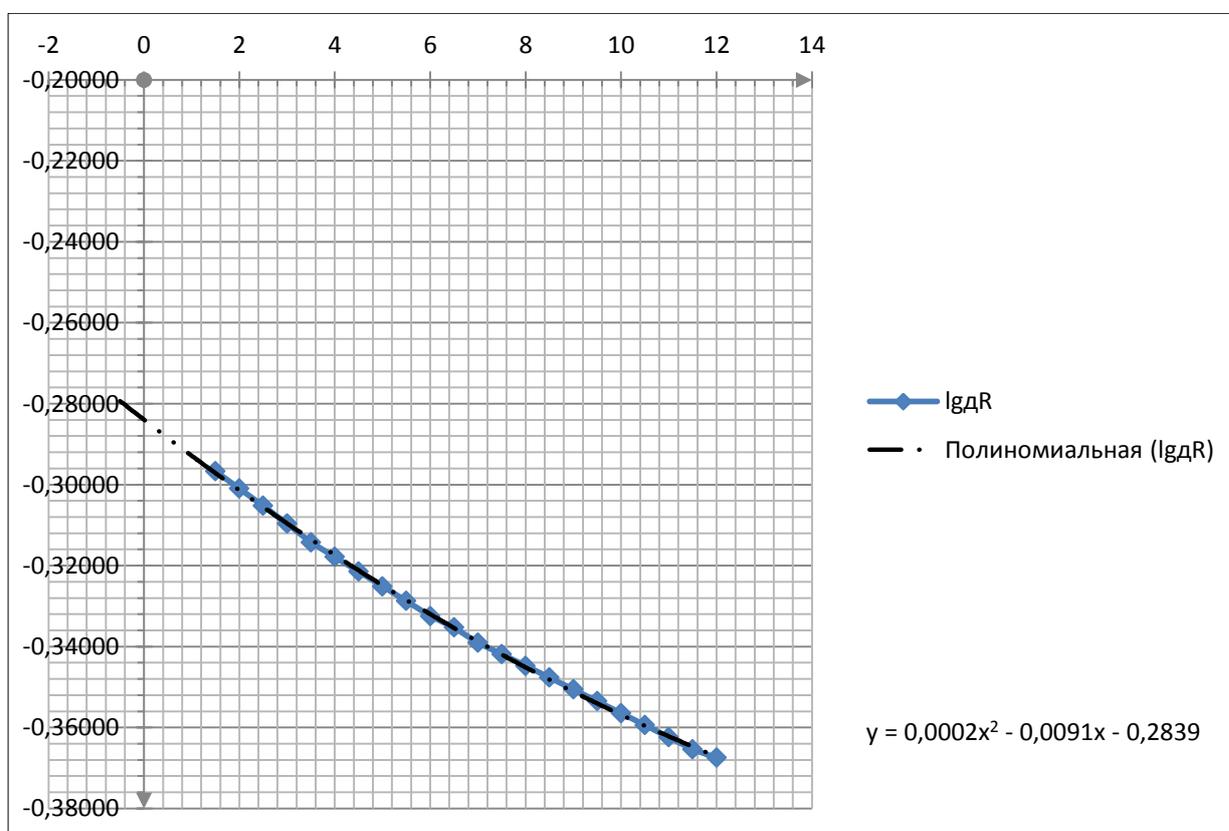
Рисунок 12 – Логарифмы разностей сопротивлений А (высоковольтный вывод) и (Х1+Х2)-заземленная сторона

Таблица 6. Результаты измерения температуры при нагреве до установившейся температур

Время, час	Температура окружающей среды, ºС				θ в/с,ºС верхних слоев мала	$\Delta\theta$в/с,ºС Превышение темп. масла над θср	Превышение темп. масла у входа в охладитель $\Delta\theta$в/с,ºС	Превышение темп. масла у выхода из охладителя $\Delta\theta$в/с,ºС
	θ_1	θ_2	θ_3	$\theta_{ср}$				
1:00	33,1	32,7	32,8	32,9	70,0	37,1	70,0	38,5
2:00	34,2	33,2	33,8	33,7	72,0	38,3	72,0	41,7

3:00	35,2	34,7	34,9	34,9	76,5	41,8	76,5	43,9
4:00	35,3	34,6	34,8	34,9	79,0	44,0	79,0	44,3
5:00	35,4	34,6	35,0	35,0	81,0	46,3	81,0	46,8
6:00	35,0	34,2	34,7	34,6	83,1	48,5	83,1	48,6
7:00	34,9	34,1	34,6	34,5	85,0	50,5	85,0	51,4
8:00	34,5	34,0	34,2	34,2	85,9	51,7	85,9	51,5
9:00	34,4	34,0	34,3	34,2	86,4	52,2	86,4	52,0
10:00	34,4	34,0	34,3	34,2	86,7	52,5	86,7	52,3

Таблица 7. Измерение сопротивления обмоток трансформатора в горячем состоянии

Время, мин	Сопротивление обмотки А (Х1+Х2)			
	R (Ом)	дR (Ом)	T (мин)	lgдR
1′30″	2,9100	0,505	1,5	-0,29671
2′	2,9051	0,500	2	-0,30094
2′30″	2,9002	0,495	2,5	-0,30522
3′	2,8952	0,490	3	-0,30963
3′30″	2,8900	0,485	3,5	-0,31426
4′	2,8860	0,481	4	-0,31785
4′30″	2,8820	0,477	4,5	-0,32148
5′	2,8780	0,473	5	-0,32514
5′30″	2,8741	0,469	5,5	-0,32873
6′	2,8701	0,465	6	-0,33245
6′30″	2,8671	0,462	6,5	-0,33526
7′	2,8631	0,458	7	-0,33904
7′30″	2,8601	0,455	7,5	-0,34189
8′	2,8571	0,452	8	-0,34477
8′30″	2,8541	0,449	8,5	-0,34766
9′	2,8511	0,446	9	-0,35057
9′30″	2,8481	0,443	9,5	-0,35350
10′	2,8451	0,440	10	-0,35645
10′30″	2,8421	0,437	10,5	-0,35942
11′	2,8391	0,434	11	-0,36241
11′30″	2,8361	0,431	11,5	-0,36542
12′	2,8341	0,429	12	-0,36744
22′	последний отчет Rn - 2,4050 Ом			

По сопротивлению R_o в момент отключения нагрузки определяем температуру обмоток $\theta_{обм.}$ по формуле:

$$\theta_{обм.} = \frac{R_0}{R_x} \cdot (T + \theta_x) - T, \tag{6}$$

где: T – коэффициент, равный 235 ºC для обмоток из меди.
Соответственно превышение температуры обмоток равно

$$\theta'_{обм.} = \theta_{обм.} - \theta_{охл.}; \tag{7}$$

Результаты испытаний на нагрев представлены в таблица 8.

Таблица 8. Результаты испытаний на нагрев

Наименование элементов конструкции трансформатора	Превышение температуры, ºС	
	Результаты испытаний	Нормированные значения
Верхние слои масла	52,5	Не более 60
Обмотки	58,6	Не более 65
Наиболее нагретые точки обмотки (ННТ)	65,7	Не более 75
Магнитная система	55,6	Не более 75
Поверхность бака	20,13	Не более 70

Превышение температуры конструктивных элементов реактора над температурой окружающего воздуха не превышает допустимых значений. Реактор РОМ-60000/525-У1 испытание на нагрев выдержал и удовлетворяет требованиям IEC 60076-6-2014.

Заключение

Увеличение вертикальных и горизонтальных ребер жесткости на стенке бака в реакторе РОМ-60000/525-У1 привело к снижению амплитуды перемещений для стенок бака и соответственно к снижению уровня вибрации реактора. Также эффект снижения уровня шума и вибрации от установки резиновых демпферов в качестве прокладок из бутадиен-нитрильного каучука (NBR) в активном сечении получен, благодаря делению активной площади на более мелкие участки.

Сравнение измеренных и рассчитанных шумовых характеристик усовершенствованного реактора РОМ-60000/525-У1 с результатами обязательных приемо-сдаточных испытаний подобных реакторов данного класса, производимых в Казахстане, подтверждает снижение значение корректированного уровня звуковой мощности нового реактора.

Испытание на нагрев и проверка электрической прочности изоляции при воздействии напряжений грозовых импульсов полного, срезанного и коммутационного импульса собранного реактора с использованием предложенных инновационных решений показал соответствие предельных характеристик усовершенствованного реактора требованиям действующих отечественных и международных стандартов.

Вкладом авторов является разработанный подход уменьшения вибрации и шума в шунтирующих масляных реакторах с использованием предложенных инновационных решений на основе усовершенствования конструкции на этапе проектирования моделирования методом конечных элементов и применения для активной части реактора материалов с низкими виброакустическими характеристиками. Таким образом, впервые изготовленный в Казахстане реактор с улучшенными вибрационными и шумовыми характеристиками рассчитан на более длительный срок службы по сравнению с действующими аналогами и соответственно определяет практическую значимость предложенного подхода.

Благодарности

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ҚҰРЫЛЫМДЫ ЖӘНЕ ҚОЛДАНЫЛАТЫН МАТЕРИАЛДАРДЫ ЖЕТІЛДІРУ НЕГІЗІНДЕ АЙНАЛМАЛЫ РЕАКТОРЛАРДЫҢ ШУЫ МЕН ДІРІЛІН АЗАЙТУ ТӘСІЛІ

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Аңдатпа. Зерттеудің өзектілігі реактор шуының көзі болып табылатын діріл өзінің механикалық беріктігіне әсер етіп, оның қызмет ету мерзімін қысқартуымен түсіндіріледі. Бұл қолданбалы зерттеудің мақсаты – шунттық мұнай реакторларындағы діріл мен шуды азайту, жақсартылған дизайн мен өмірлік циклді ұлғайту үшін қолданылатын материалдар негізінде ұсынылған инновациялық шешімдерді қолдану. Ұсынылып отырған кешенді тәсілдің ғылыми жаңалығы компьютерлік модельдеуді жобаланған реактордың резервуарының құрылымын оңтайландырудан және тиісінше резервуар қабырғаларының қозғалу амплитудасын азайтудан және реактордың белсенді бөлігі үшін төмен виброакустикалық сипаттамалары

бар материалдар пайдалану арқылы реактордың діріл деңгейін төмендетуден тұрады. Жаңа ROM-60000/525-У1 реакторының шу сипаттамаларын Қазақстанда шығарылған осы сыныптағы ұқсас реакторлардың міндетті қабылдау виброакустикалық сынақтарының нәтижелерімен салыстыру жаңа реактордың реттелетін дыбыс қуаты деңгейінің төмендеуін растады. Зерттеу нәтижелерінің отандық трансформатор өнеркәсібі үшін үлкен практикалық маңызы бар.

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AN APPROACH TO REDUCING NOISE AND VIBRATION OF SHUNT REACTORS BASED ON IMPROVING THE DESIGN AND MATERIALS APPLIED

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__Abstract.__ The relevance of the research is related to the fact that vibration, which is a source of reactor noise, affects its own mechanical strength, reducing its service life. The purpose of the present applied research is to reduce vibration and noise in shunt oil reactors using the proposed innovative solutions based on the improvement of the design and materials used to increase the life cycle. The scientific novelty of the proposed integrated approach consists in reducing the amplitude of tank wall displacements and, accordingly, reducing the level of reactor vibration using computer modeling and optimization of the designed reactor tank design and application of materials with low vibroacoustic characteristics for the reactor core. Comparison of noise characteristics of the new reactor ROM-60000/525-U1 with the results of mandatory acceptance vibroacoustic tests of similar reactors of this class produced in Kazakhstan confirmed the reduction of the corrected sound power level of the new reactor. The results of the research are of great practical significance for the domestic transformer industry.

__Keywords:__ shunt reactor, vibration of the active part, reactor design improvement, vibroacoustic characteristics, test, reactor heating test, reactive power, voltage.

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ANALYSIS OF AUTOMATION STRATEGY FOR INTEGRATED CUSTOMER-ORIENTED SYSTEM VIA SMART DIGITAL NODES IN DISTRIBUTION TRANSFORMERS

Abstract. There are many compelling justifications for the significance of MV/LV distribution transformers in facilitating customer-centric services in the next years. The integration of transformer-level intelligence has the potential to strengthen the characteristics of the low voltage (LV) grid management system, which is often lacking in automation. The transformer enables the use of advanced technologies such as local private networks and EDGE computing. The transformer plays a vital role in connecting the appliances of end consumers with the medium voltage grid. Typically, the location of the facility is in close proximity to the client inside a neighboring energy village. Transformer stations are thus ideal locations for the placement of batteries that facilitate the sustenance of the local energy community, bigger photovoltaic panel systems, and expedited charging apparatus. This article presents, use of Smart Digital Nodes (SDNs) as central nodes within the energy community, replacing the conventional MV/LV distribution transformers. This research is intended to provide a new digital service model at the distribution transformer level. A real-life scenario is presented. Hence, the transformer station presents a very advantageous site for the integration of batteries, substantial photovoltaic (PV) panel sets, or rapid charging devices within the local energy community.

Keywords. Smart Digital Nodes, distribution transformers, photovoltaic, medium voltage grid, Community Services and Resilience

Introduction.
The Implementation of digital grid layers for enhancing community services and resilience modern digitalization. This is now in the process of establishing a digital service at the distribution transformer level with the aim of accelerating the energy transition and fostering public participation. The proposed approach involves the use of Smart Digital Nodes (SDNs) as central nodes within the energy community, replacing the conventional MV/LV distribution transformers [1]. SDN enhances the adaptability and market robustness of the distribution grid by including additional services. The concept is supported by contemporary power electronics and digital coordination. In order to cultivate client engagement, user interfaces in close proximity to Smart Transformers use local communication. Smart Transformers (ST) have been the subject of literature for a decade. However, in a broad sense, it has been defined as anything that does not function as a power transformer. As a proficient authority in the field of energy conservation, it possesses the capability to demonstrate the monitoring and troubleshooting of Smart Transformers. A multitude of attractive characteristics were identified in [2] subsequent to the examination of several topologies. Despite its benefits, the absence of a step-down transformer led to increased energy losses due to the activation of the MV by the IGBT. SDN efficiency may be enhanced by using modular components or a step-down transformer. A Smart Grid Design Model (SGAM) has been used to solve the challenges of interoperability

requirements and the increasing complexity associated with supporting many system solutions. According to the SGAM study [3], improving energy flow routing may enhance the efficiency and reliability of ST. SGAM offered a frequency management solution by using a meticulous model of the Irish transmission system [4]. Research has shown that STs have the capability to sustain transient stability even when subjected to a 10% increase in wind power from non-synchronous output, without necessitating the use of inertia modeling. Despite significant advancements in technology, the economic viability of this approach remains uncertain [5-6]. End user participation and pilot programs are crucial as well. SDN facilitates the integration of advanced technologies, including DC grids, solar panels, batteries, electric car charging, and smart houses, into hybrid grid technology. While the significance of grid-level and customer-level limitations is similar, priority is given to community-level services. This is crucial for doing control hierarchy analysis [7-8].

Key research inquiries encompass the integration of community services at the distribution transformer level, the prerequisites for the SDN, approaches to empower energy communities and encourage active engagement, business models centered around the node, and the responsibilities of different stakeholders in this configuration. The project will consist of both a pilot phase and a prototype phase. Finally, the research will assess the social implications and economic feasibility of the study.

A complete architecture of the SDN is shown in Figure 1. This research utilizes the SDN, a sophisticated alternative to MV/LV transformers. This new technology facilitates the expansion of distribution transformer services and enhances control capabilities [9].
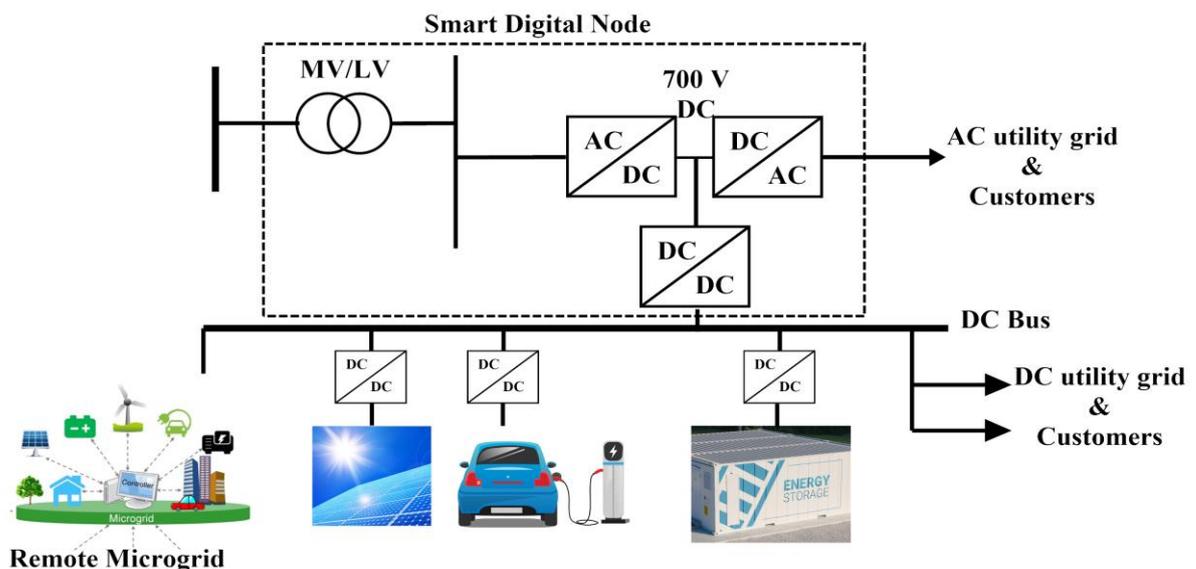
Figure 1 - Architecture of Digital Smart Digital Node

SDN produces LVAC and LVDC outputs while receiving MV grid input. LVDC may be implemented as either an LVDC grid for customer connection or as a DC bus in close proximity to the SDN for local resource integration. In the demonstration process, it is customary to transmit the MV voltage input to electronic components either directly or via an MV/LV block transformer. In order to facilitate direct MVAC application, it is essential that MVAC voltage-compatible components be readily available and cost-effective. SDNs establish connections with their clients' locations using cost-effective and uncomplicated wireless networking. The innovation provides LoRaWAN Terminals and integrates SDN with a LoRaWAN Gateway [10].

The inquiry will start by examining a network located in a suburban or rural area. Customers within a one-kilometer radius of the transformer are situated on this elevated network.

The low voltage (LV) grid is characterized by the configuration and operation of radial networks. The first study will include the participation of 5-10 consumers who are linked to transformers. These conditions enable the establishment of energy communities in geographically isolated, rural, and other constrained settings.

The main goal of the company is to provide cutting-edge services to stakeholders via the use of SDN's communication and technological capabilities. Our technological proficiency encompasses as follows:

1) PLC converter control for AC/DC/AC converter drivers.

2) For higher-level control and optimization, the 4Stage Decision Engine (4SDE) may combine. Establish a connection between converter control and PLC to supervise the local battery control system of SDN and the communication system as shown in Figure 2 for managing customer demand response resources. Collaboration for SDN in the context of MV grid services.
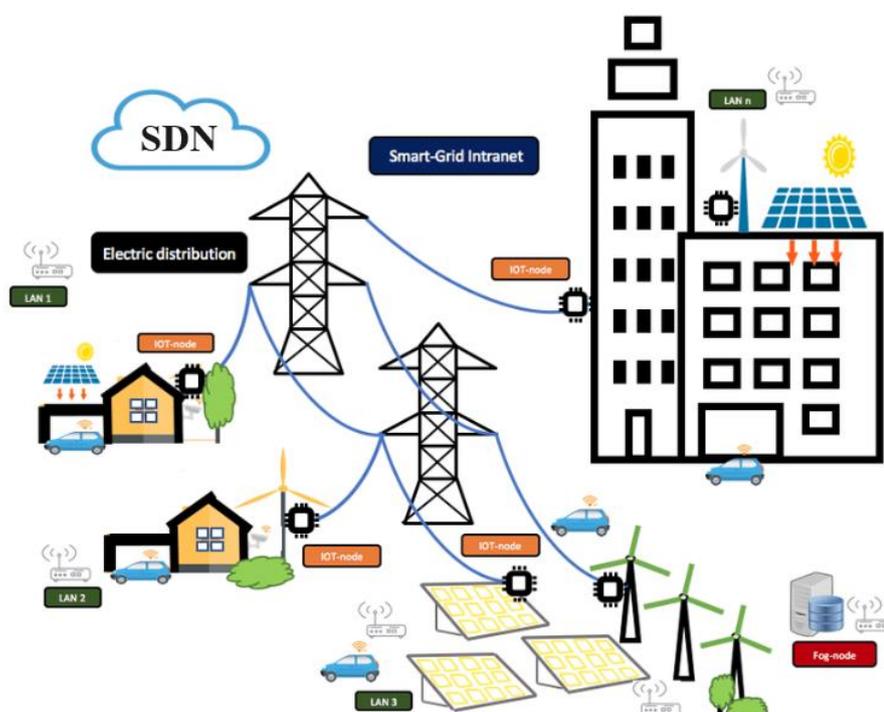
Figure 2 - Architectural Insights into Smart Digital Node-Powered Energy Communities

Materials and Methods.

SDN is being developed in the form of seven use cases [11-12] as shown in Figure 3. Despite the diverse control functions, all use cases are facilitated by a unified control and communication architecture. Table 1 presents a comprehensive list of the prominent attributes associated with each use case. The standards pertaining to the Smart Digital Node units were developed after an examination of several use cases. This includes the converters, technical tools, control system, and communication mechanisms that provide interaction between the DSO and client systems. Use cases are used in the development of test cases and success criteria for the first prototypes of a project. The smart transformer, functioning as a service node, has the capability to directly deliver electricity to an electric car charging station. An approach to facilitate electric vehicle charging during periods of increased power consumption involves connecting nearby batteries to the direct current (DC) connection of the intelligent transformer.
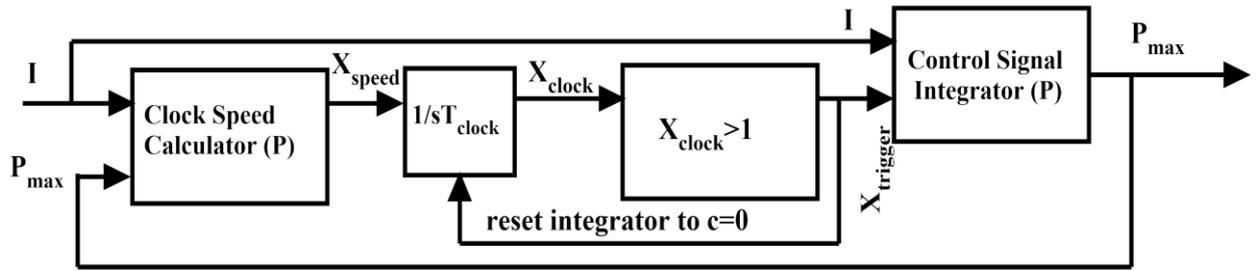
Figure 3 - SDN Control architecture
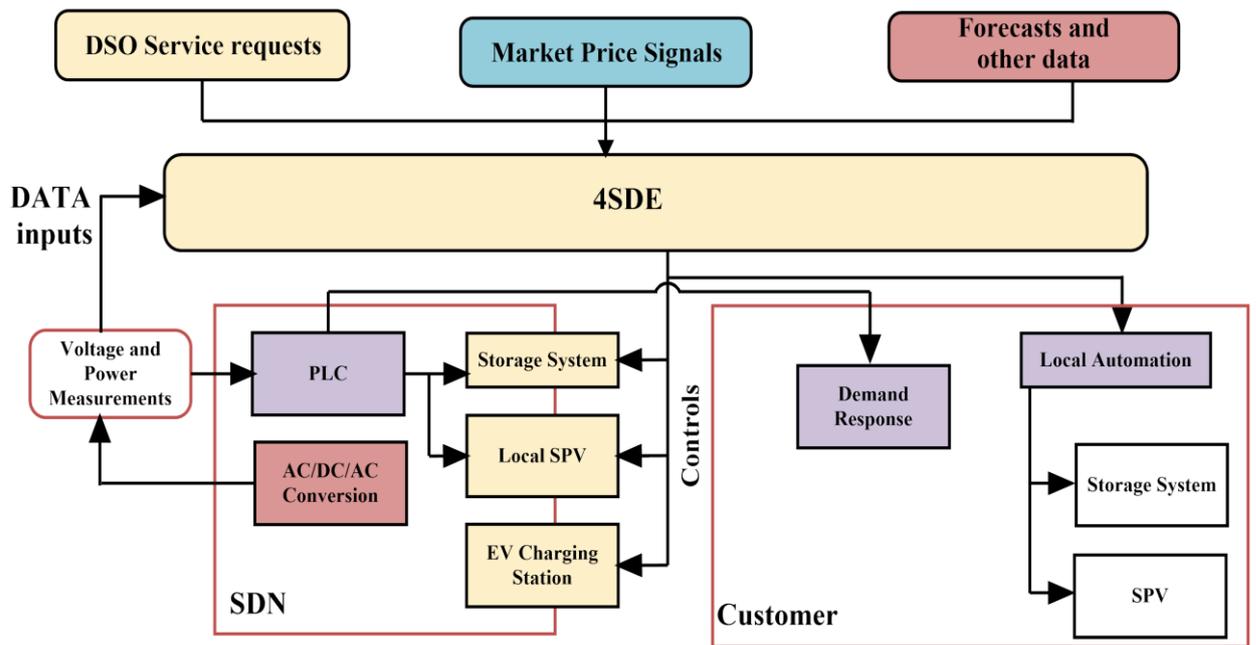
Figure 4 - Enhancing Efficiency in Finland Smart Homes with a Strategic Control Framework

Table 1 - The Implementation of Digital Grid Layers for Enhancing Community Services and Resilience

Use case	Description	Objective
Scenario 1: Managing the grid involves overseeing voltage levels, frequency, power quality, and protection measures.	The supply for the LVAC and LVDC sides must fulfill voltage, frequency, and power quality requirements. The harmonics and electromagnetic compatibility are considered. It's important to prioritize protective measures according to national safety laws, including the likelihood of simultaneous AC and DC failures.	Providing high-quality items to all customers, regardless of their circumstances.
Scenario 2: Resilience necessitates the presence of stability and prompt recovery in the face of brief power outages and disruptions.	SDNs have the capability to effectively handle disruptions and fluctuations in the input supply voltage, hence enhancing dependability. The SDN facilitates extended events via the use of demand response or energy storage.	SDN enhances the quality and dependability of the supply.

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Scenario 3: The primary objectives of local optimization are to maximize operational efficiency while taking into account various elements such as emissions, self-sufficiency, and economic considerations.	Objectives can act as guiding principles for SDN management. Optimization may be linked to economic optimization by using dynamic tariffs, local generation for self-sufficiency, and grid side emission intensity to decrease emissions. Users have the ability to develop supplementary standards.	SDN power flow optimization customized to individual requirements.
Scenario 4: The objective is to enhance the provision of HVAC, EV charging, distributed producing, and other related services within the local area.	Controllable resources have the potential to be dynamically adjusted in order to enhance local generation and consumption while minimizing the effect on grid connections. Utilize the demand response and charging/discharging capabilities of an SDN battery or the voltage management and reactive power control operations of power electronics in order to regulate energy usage. By integrating these procedures, the ability to accommodate HVAC and electric car needs is enhanced.	In order to enhance the grid, it is important to include resources that possess the capacity to generate substantial quantities of power.
Scenario 5: The provision of services to the local grid, including voltage regulation, power quality management, power peak avoidance, and temporary backup power, is undertaken.	SDN has the potential to provide several advantages to DSO, including voltage control, power peak management, backup support, and enhanced power quality. DSOs have the option to use fixed contracts or make service requests on an as-needed basis.	Enhance the grid by including more services.
Scenario 6: Facilitate the functioning of spot markets, responsible parties, and reserve markets such as FCR and FFR.	SDN has the potential to enhance market-led services, especially in reserve markets and other immediate prospects. The use of SDN flexibility by an aggregator or balancing actor is contingent upon the prevailing market circumstances.	SDN optimizes financial profits in several business sectors.
Scenario 7: The local energy community offers peer-to-peer markets, shared electric vehicle charging, solar and storage systems, and many services.	SDN can serve as a central hub for local energy services. Examples of community services include peer-to-peer exchanges, electric car sharing, the placement of solar panels next to sustainable development zones, battery systems, and several other services. The neighborhood has the potential to greatly benefit from grid and market services. The control possibilities available to the community include self-sufficiency and economic efficiency.	Provide adaptable services to the energy community.

Results.

The SDN methodology is developed and implemented in two application scenarios such as Germany and Finland. The control architecture is applied to each development case, as well

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as to prototypes and test setups. Despite the unique features of each case, a shared structure enables the creation of services and business models that are compatible with each other. Besides creating a prototype of the SDN concept, it was also tested and confirmed in a controlled laboratory and testing environment.

Discussion.
1. Intelligent Home Automation and Sustainable Solutions in Germany.
The SDN in Germany has developed a reactive power controller and an active power controller to regulate transformer loads [13]. Figure 5 depicts the replication of the operational controller on a compact grid including five loads.
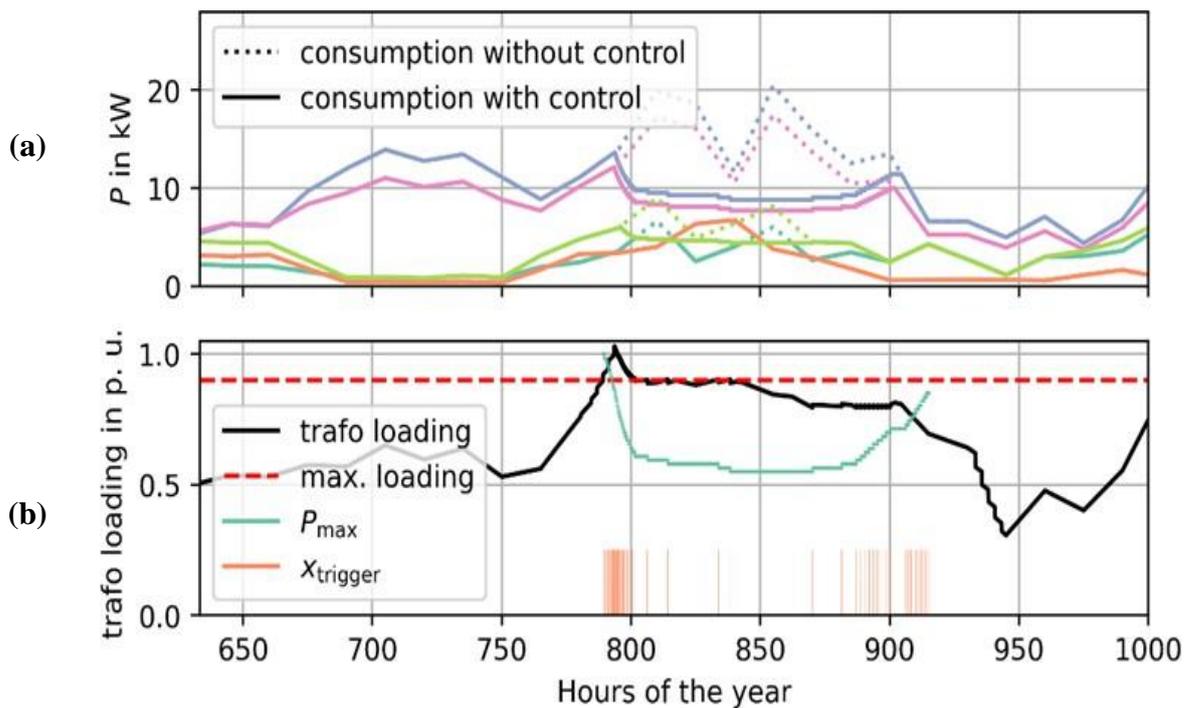

Figure 5 - Power Distribution (a) Household power usage data and (b) transformer load active power controller control signals

The maximum power consumption of dispersed loads is determined by Pmax. The trigger frequency is adjusted by the Clock Speed Calculator as the transformer loading approaches its maximum value. Following the activation of triggers, the Control Signal Integrator systematically decreases power. Once the load on the transformer decreases to less than 0.8 per unit (p. u.), the power limit is progressively raised once again. The power constraint is eliminated if the loading falls below a second threshold of 0.7 per unit (p. u.). The transformer load was decreased to a level below its maximum capacity, as seen in the accompanying graphic.
2. Smart Home Automation and Sustainable Solutions in Finland.
Finish academics are doing an investigation of the network of suburban or rural areas [14]. Customers are linked to this network within a radius of one kilometer, and it is equipped with an above-ground transformer. Low voltage (LV) networks have a radial configuration. Initially, a transformer-connected community of 10 people would be subjected to testing. These conditions are ideal for community efforts in distant, rural, and other areas with inadequate energy resources. The THT Control 4 Stage Decision Engine (4SDE) offers advanced control and optimization capabilities inside the control architecture. 4SDE is responsible for managing client demand response controls and controlling the drive of the SDN prototype using PLC-based

converters. Lora WAN wireless technology and direct control signals will be used for client connection. The 4SDE system collects external signals and adjusts its performance based on the specific application scenario. The control structure is shown in Figure 4. The 4SDE control system optimizes power supply and energy load via a simple control platform. The 4SDE has four distinct stages, namely: 1. Constantly active; 2. Activated at ideal times; 3. Activated as required; and 4. Adaptable storage unit. The components of the power supply and load are grouped into four phases. The dynamic power request of each customer load is determined by a four-stage process of demand response classification. In the context of decision-making, power needs may be classified into four distinct categories: ideal, required, and urgent. The 4SDE employs 24-hour, historical, and current predictions for optimization purposes. Subsequently, the system implements thresholds and parameters that are tailored to certain classes of components and clientele.

Conclusions.

This research facilitated the advancement of SDN and its associated applications in MV/LV transformers. While the technological architecture has been mostly established, our investigation will include an examination of cost-benefit analysis, social implications, and commercial strategies. SDN will establish a connection between the MV and LV levels. To provide more perspective, a more thorough examination of the relationship between the top and lower layers will be conducted. The flexible architecture enables the use of diverse control logics and implementations across a range of circumstances. The technical and interoperability needs of smart transformer technology may be more effectively met by standardizing the presentation of use cases and matching their characteristics with the SGAM reference framework. The presence of homogeneity facilitates the objective comparison and contrast of different circumstances. This facilitates the identification of regulatory gaps by regulators and assists network operators in devising viable solutions. The use of energy market services encompasses several services such as multi-market optimization, day-ahead optimization, and frequency control. Local grid services include a range of activities, including voltage regulation, bottleneck management, investment optimization, and power quality enhancement. The application cases emphasize various energy community services, including peer-to-peer transactions, shared rapid charging, local optimization, resilience, and local flexibility markets. Ultimately, they include indigenous resources such as photovoltaic panels, battery stations, and rapid electric vehicle charging. Simultaneously addressing these use cases would enhance the financial feasibility of the proposition.

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ТАРАТУ ТРАНСФОРМАТОРЛАРЫНДАҒЫ АҚЫЛДЫ ЦИФРЛЫҚ ТҮЙІНДЕР АРҚЫЛЫ ИНТЕГРАЦИЯЛАНҒАН КЛИЕНТКЕ БАҒЫТТАЛҒАН ЖҮЙЕНІҢ АВТОМАТТАНДЫРУ СТРАТЕГИЯСЫН ТАЛДАУ

Аңдатпа. Келесі жылдарда тұтынушыға бағытталған қызметтерді жеңілдетудегі MV/LV тарату трансформаторларының маңыздылығына көптеген дәлелді негіздемелер бар. Трансформатор деңгейіндегі интеллектті біріктіру автоматтандыруда жиі жетіспейтін төмен кернеу (LV) желісін басқару жүйесінің сипаттамаларын күшейту мүмкіндігіне ие. Трансформатор жергілікті жеке желілер мен EDGE есептеулері сияқты озық технологияларды пайдалануға мүмкіндік береді. Трансформатор соңғы тұтынушылардың

құрылғыларын орташа кернеулі желіге қосуда маңызды рөл атқарады. Әдетте, нысанның орналасқан жері көрші энергетикалық ауылдың ішіндегі клиентке жақын орналасқан. Трансформатор станциялары жергілікті энергетикалық қауымдастықтың, үлкен фотоэлектрлік панельдік жүйелердің және жылдам зарядтау құрылғыларының қамтамасыз етілуін жеңілдететін аккумуляторларды орналастыру үшін тамаша орын болып табылады. Бұл мақалада кәдімгі MV/LV тарату трансформаторларын алмастыратын Smart Digital Nodes (SDNs) энергетикалық қоғамдастықтың орталық түйіндері ретінде пайдалану ұсынылады. Бұл зерттеу тарату трансформаторы деңгейінде жаңа цифрлық қызмет моделін ұсынуға арналған. Шынайы өмірден алынған сценарийлер ұсынылған. Осылайша, трансформаторлық станция жергілікті энергетикалық қоғамдастықта аккумуляторларды, айтарлықтай фотоэлектрлік (PV) панельдік жинақтарды немесе жылдам зарядтау құрылғыларын біріктіру үшін өте тиімді алаңды ұсынады.

Түйінді сөздер. Ақылды цифрлық түйіндер, тарату трансформаторлары, фотоэлектрлік, орташа кернеулі желі, Қоғамдық қызметтер және төзімділік.

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АНАЛИЗ СТРАТЕГИИ АВТОМАТИЗАЦИИ ИНТЕГРИРОВАННОЙ КЛИЕНТООРИЕНТИРОВАННОЙ СИСТЕМЫ С ПОМОЩЬЮ ИНТЕЛЛЕКТУАЛЬНЫХ ЦИФРОВЫХ УЗЛОВ В РАСПРЕДЕЛИТЕЛЬНЫХ ТРАНСФОРМАТОРАХ

Аннотация. Существует множество убедительных обоснований важности распределительных трансформаторов среднего/низкого напряжения для облегчения предоставления услуг, ориентированных на клиента, в ближайшие годы. Интеграция интеллекта на уровне трансформатора может улучшить характеристики системы управления сетью низкого напряжения (НН), которой часто не хватает автоматизации. Трансформатор позволяет использовать передовые технологии, такие как локальные частные сети и вычисления EDGE. Трансформатор играет жизненно важную роль в подключении приборов конечных потребителей к сети среднего напряжения. Как правило, объект располагается в непосредственной близости от клиента на территории соседнего энергетического поселка. Трансформаторные станции, таким образом, являются идеальными местами для размещения батарей, которые облегчают жизнь местному энергетическому сообществу, более крупных систем фотоэлектрических панелей и устройств для ускоренной зарядки. В этой статье представлено использование интеллектуальных цифровых узлов (SDN) в качестве центральных узлов в энергетическом сообществе, заменяющих традиционные распределительные трансформаторы среднего/низкого напряжения. Целью данного исследования является создание новой модели цифровых услуг на уровне распределительного трансформатора. Представлены

реальные сценарии жизни. Следовательно, трансформаторная подстанция представляет собой очень выгодное место для интеграции батарей, крупных комплектов фотоэлектрических (PV) панелей или устройств быстрой зарядки в местное энергетическое сообщество.

ЭНЕРГЕТИКА
ENERGY
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ИССЛЕДОВАНИЕ МЕТОДОВ СУШКИ С ПРЕССОВАНИЕМ ТВЕРДОЙ ИЗОЛЯЦИИ СИЛОВЫХ ТРАНСФОРМАТОРОВ С ЦЕЛЬЮ УВЕЛИЧЕНИЯ ЖИЗНЕННОГО ЦИКЛА

Аннотация. Наличие влаги может нанести вред силовым трансформаторам, ускоряя процессы старения, уменьшая диэлектрический запас, начальное напряжение частичного разряда, что в свою очередь повышает риск неожиданных сбоев. Современные электротехнические предприятия используют различные методы сушки, зачастую многие из них менее эффективны. Для решения этих проблем в данной статье предлагается применять синтетический эфир в сухом распределительном трансформаторе. Для исследования была использована усовершенствованная экспериментальная модель изоляции трансформатора. С помощью этой модели осуществлялась сушка сложного эфира с помощью молекулярного фильтра и тщательно отбиралась адсорбированная масса. Содержание воды в полосах прессованного картона до и после сушки анализировали для определения эффективности сушки целлюлозной изоляции. Содержание воды определялась методом титрования Карла Фишера. При уровне влажности эфира 105-120 ppm и температуре системы изоляции 70 градусов образцы, прошедшие сушку в течение 5 дней, показали потерю воды выше 1%. Эксперименты исследования были проверены на силовых распределительных трансформаторах.

Ключевые слова. Техника сушки, распределительные трансформаторы, влага, синтетический эфир.

Введение.

Силовые трансформаторы часто выходят из строя из-за разрушения изоляции. Влага является значимым фактором старения электротехнической бумаги, поскольку она является одновременно катализатором и следствием этих процессов [1-2]. Обычно удвоение содержания воды в изоляционной бумаге сокращает срок ее службы. Так, трансформатор с влажностью 4% стареет за 10 лет, а трансформатор с влажностью 2% стареет за два десятилетия [3]. Трансформаторы обычно имеют срок службы от 30 до 50 лет, что в основном определяется состоянием изоляционной системы, которая естественным образом ухудшается с течением времени. Температура является ключевым фактором, влияющим на скорость реакций в минеральном масле. Повышение температуры масла примерно на 10 градусов Цельсия ускоряет процессы старения в два раза в диапазоне от 60 до 100 градусов Цельсия [4]. По истечении 30 лет изоляция герметичных сетевых трансформаторов обычно содержит около 2% воды, а в распределительных трансформаторах со свободно дышащими расширителями может содержаться до 3% воды [5]. Трансформаторы с мембранными системами, заполненный минеральным маслом, подвергаются ежегодному повышению влажности целлюлозной

изоляции в диапазоне от 0,05% до 0,06%. Однако у трансформаторов, оснащенных расширителями, обеспечивающими циркуляцию воздуха, может наблюдаться повышение на 0,2% [6]. Для трансформатора, находящегося в эксплуатации около 20 лет, изоляция может быть классифицирована как «мокрая» в соответствии с тремя стадиями, определенными в стандарте IEEE Std 62-1995 [7]. Это может снизить нагрузочную способность и потребовать просушки изоляции. По мере разложения масла в ней меняются вязкость, кислотность, содержание воды и электрические свойства. Состаренная целлюлозная изоляция подвергается окислению, гидролизу и термолизу [8]. Различные реакции, такие как температура, уровень кислорода, наличие воды и катализаторы, могут влиять на скорость реакции. На скорость движения влияют уровень кислорода и высокая температура изолирующей системы. Целлюлозная бумага разлагается гораздо быстрее при влажности 3% по сравнению с 1% воды [9]. Повышенный уровень влажности может быть результатом процесса старения и попадания воды снаружи в систему изоляции. Это явление вызвано изменениями относительной влажности и периодическими колебаниями давления [10].

Современные камеры для сушки трансформаторов используют тепло для нагрева изоляции и создания вакуума за счет вытягивания воздуха из бака. Нагрев обеих обмоток низкочастотным нагревом (НЧН) в вакууме в настоящее время является наиболее эффективным методом. Однако спрос на распределительные трансформаторы ВН/СН низкий. Проблемы с утечками и компрессией резервуаров часто возникают из-за недостаточного поддержания вакуума [11-12].

В литературе используются различные изоляционные бумаги, такие как целлюлоза, крафт-бумага, термически улучшенная крафт-бумага (ТУК) и т. д. [13]. Кроме того, недавнее исследование было проведено с целью изучения возможности использования листов целлюлозы вместо бумаги ТУК [14]. Целлюлозные изоляционные материалы содержат арамидное волокно, которое обеспечивает исключительную прочность и термостойкость до 220°С. Существует вероятность того, что целлюлозная изоляционная бумага может иметь лучшую термостойкость, чем бумага ТУК. Однако важно учитывать и другие важные факторы. Исследование охватывает различные факторы, такие как механические характеристики, содержание влаги, электрическая стабильность, побочные продукты старения и прочность на разрыв [15].

Целлюлозная изоляция состоит из 70% целлюлозы, 30% термически улучшенной крафт-целлюлозы и 30% метаарамидных волокон. В результате три слоя сжимаются в один слой. Самый верхний слой состоит из ТУК. Использование целлюлозных волокон для изготовления основы бумаги является общепринятой практикой [16]. Арамидные волокна служат для стабилизации и укрепления целлюлозных волокон. Эта структура повышает механическую прочность бумаги на случай, если целлюлоза ослабнет в результате процессов старения. Арамидные материалы демонстрируют выдающиеся тепловые характеристики при испытаниях на воздухе, их класс термической стойкости позволяет выдерживать температуру до 220 градусов Цельсия. Важно отметить, что арамидные материалы значительно дороже целлюлозных. Целлюлоза имеет разумную цену и обладает характеристиками, находящимися между арамидом и целлюлозой [17].

В этой статье представлено экспериментальное исследование процесса сушки целлюлозной бумаги синтетическим эфиром. Изучение влияния температуры на отдельные характеристики синтетических эфиров, исследование того, как термическое старение и влажность окружающей среды влияют на изоляцию из целлюлозы.

Материалы и методы.

Исследование взаимосвязи между влажностью, кислородом и температурой, и продолжительностью жизни.

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Влияния температуры в горячих точках, содержания влаги и концентрации кислорода в изоляционной бумаге из целлюлозы и TUK является целью данного экспериментального исследования. Имитационная модель разработана для понимания свойств изоляционной бумаги в вышеупомянутых условиях.
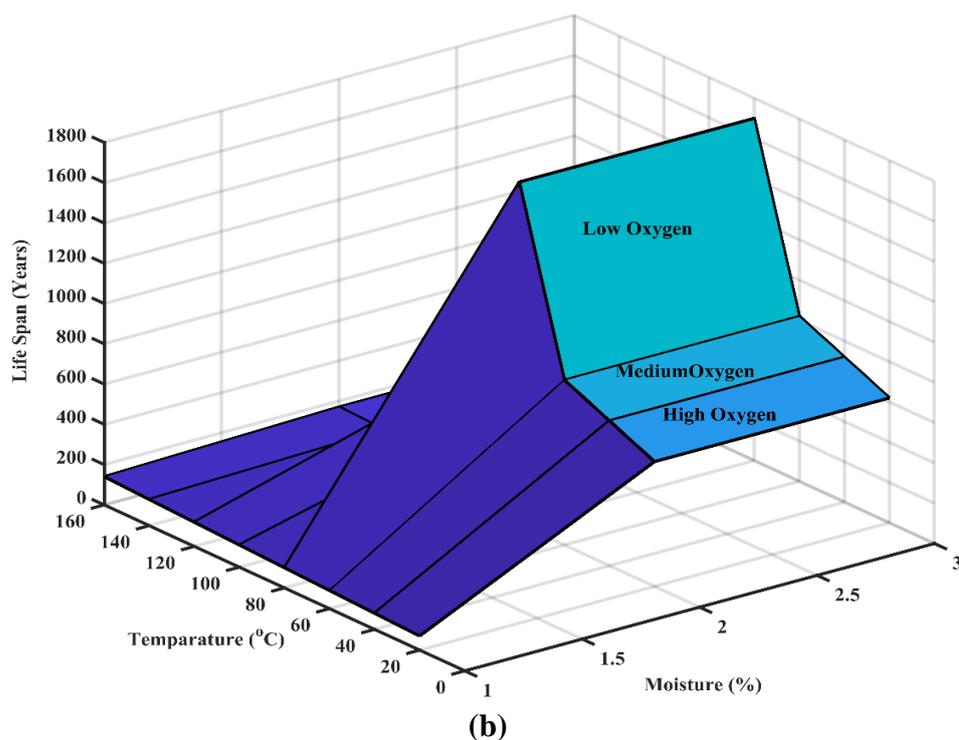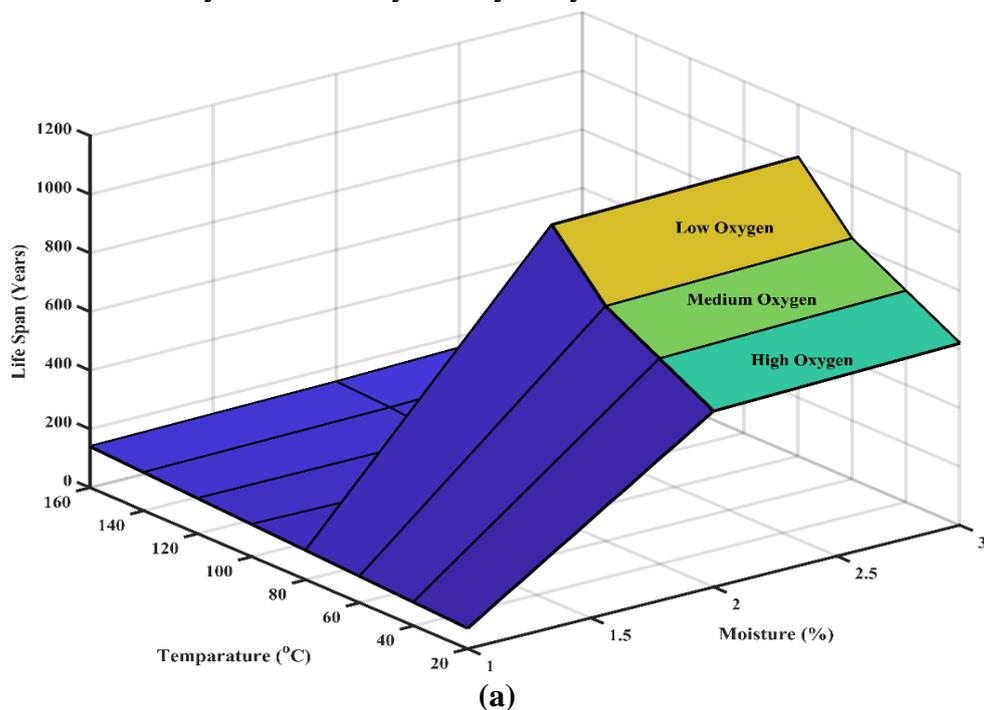

Рисунок 1 - Сравнение срока службы изоляции при трех уровнях кислорода в зависимости от температуры и влажности: *(а) бумага ТУК; (б) целлюлозная бумага*

Срок службы трансформатора, использующего целлюлозную бумагу и листы ТУК при температурах горячих точек в диапазоне от 50 до 160 °C, показан на рисунках 1(а) и 1(b). Считается, что изоляционная бумага обычно имеет уровень влажности от 0,5% до

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3%. Важно понимать, что температура, влажность и уровень кислорода должны оставаться постоянными на протяжении всей жизни. Моделирование показывает, что существует корреляция между низким и высоким уровнем кислорода и наличием трехслойных поверхностей. На рисунке 1 продемонстрирован как низкий уровень кислорода продлевает жизнь, в отличие от двух других уровней кислорода. По мере увеличения концентрации кислорода разница в продолжительности жизни уменьшается. Срок службы целлюлозной бумаги вдвое больше, чем у бумаги ТУК, как видно из сравнения рисунков 1(a) и 1(b).

Экспериментальный стенд.

Блок-схема испытательной модели показана на рисунке 2, а лабораторная модель, показанная на рисунке 3, с точностью воспроизводит и улучшает процесс сушки целлюлозной изоляции с использованием эфирных растворителей. Первое прессовка обмотки осуществляется с силой, указанной в сушке (1 цикл -100%) с тремя циклами нагрузки-разгрузки, выдерживая обмотку под давлением в течение 2-3 минут после достижения силы, как показано на рисунке 4. Для регулирования процесса сушки целлюлозный утеплитель хранится внутри термоизолированного контейнера. У входа в камеру находится перистальтический насос (ПН), который обеспечивает циркуляцию эфирной жидкости по всей системе. Целлюлозная изоляция способствует равномерному нагреву и сушке при циркуляции. На выходе был установлен расходомер (FM) с клапаном (CV) для регулирования потока эфира. Оптимизация скорости потока жидкости имела решающее значение для согласования производительности вакуумной сушильной установки с желаемой эффективностью, которую затем можно было бы интегрировать в портативную систему.
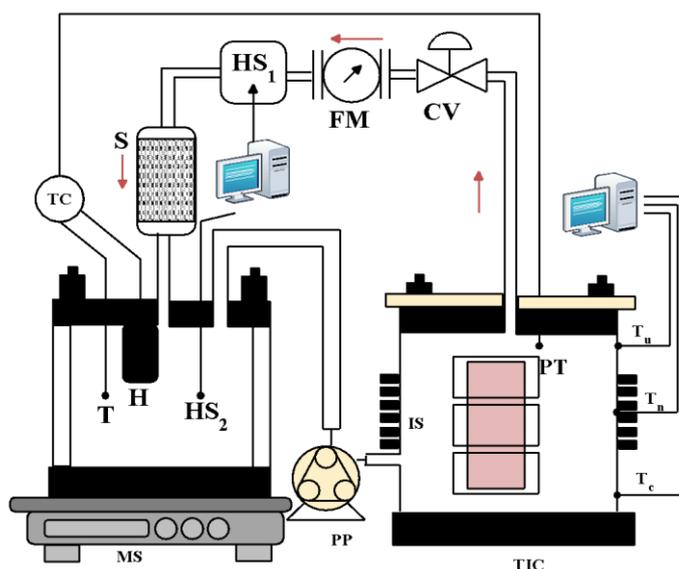

Рисунок 2 - Установка прототипа для сушки изоляционной системы в лаборатории

В практическом применении сложный эфир должен пройти процесс сушки с использованием вакуумной системы. Однако в лабораторных условиях для этой цели использовали молекулярный фильтр 3А. Вес фильтра был отрегулирован таким образом, чтобы поддерживать содержание влаги в сложном эфире ниже 130 частей на миллион в термоизолированном контейнере, оборудованном изоляционной системой (испытуемый объект). Температуру и содержание влаги в эфире контролировали с помощью датчика влажности (HS1), установленного на входе молекулярного фильтра (S). Датчик влажности HS2 предназначен для определения температуры и уровня влажности окружающей среды.

Затем эфир помещают в камеру, предназначенную для защиты испытуемого объекта от высоких температур. Внутри этой камеры находится гибкий сильфон, в котором заключена модель обмоток трансформатора. Датчик сопротивления PT100 используется для измерения температуры эфира в верхней части камеры, а термопары (Tu, Tn и Tc) используются для отслеживания температуры на внешней стенке камеры в трех разных точках. Была проведена оценка при изготовлении маслопроводов между слоями с использованием модели послойной намотки, состоящей из профилированного медного провода с бумажной изоляцией и полосок прессованного картона размером 2,2 миллиметра. Проверка уровня влажности целлюлозы включает проверку полосок до и после процесса сушки. После тщательного тестирования изделие точно воспроизводит цилиндрическую форму изоляции силового трансформатора. Этот подход эффективно отслеживает и количественно оценивает процесс сушки целлюлозной изоляции в контролируемой лабораторной среде. Это дает ценную информацию о практических приложениях, таких как управление изоляцией силовых трансформаторов.
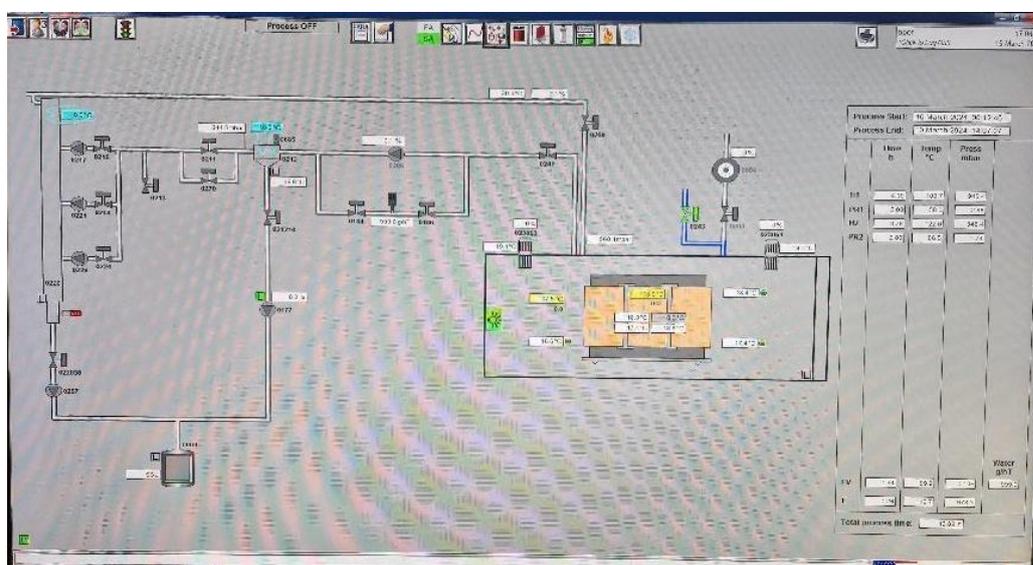
(a)

(b)

(c)

Рисунок 3 - Испытание системы изоляции:
моделирование многослойной обмотки в системе изоляции (a); объект испытания системы изоляции (b) и система лабораторных испытаний (c)
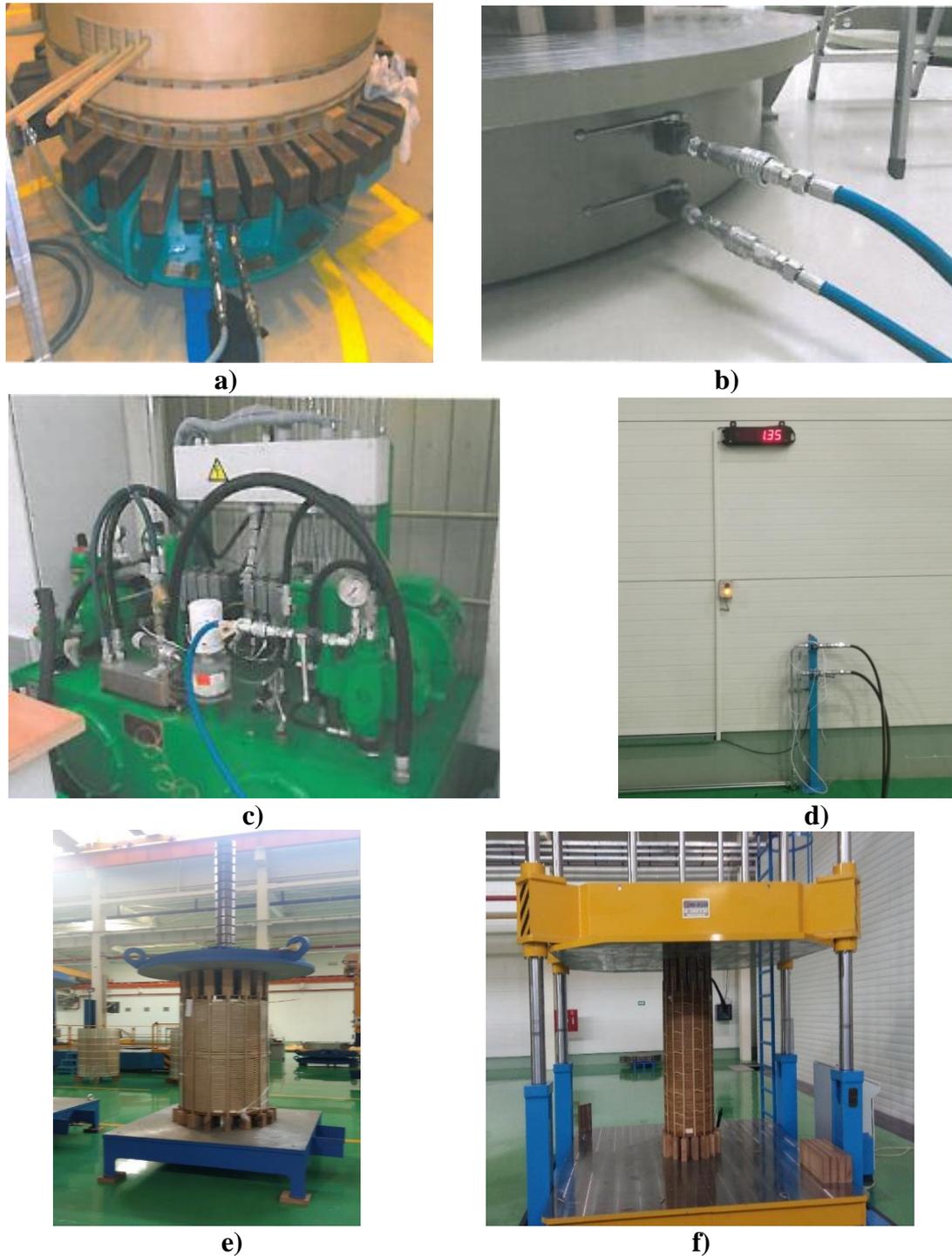
a)

b)

c)

d)

e)

f)

Рисунок 4 – Прессование обмотки в стабилизирующем прессе:
*подсоединение гидравлической станции к стабилизирующему прессу (а) и (b),
гидравлический агрегат стабилизирующего пресса (с), подключение стабилизирующего
пресса к вакуумсушильному шкафу (d); установка намотка в прессующем устройстве (e);
прессовка обмотки в стабилизирующем прессе (f)*

Результаты и обсуждения.

Процедура сушки включала использование синтетического сложного эфира SYN-ESTER® 7131. Связь температуры с характеристиками воды в сложноэфирной жидкости, включая вязкость, плотность и растворимость, видна из данных, представленных в

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таблице 1. Значимость этих характеристик объясняется выбранной технологией сушки. Повышение эффективности сушки при повышенных температурах требует расширения порога водонасыщения внутри эфира и снижения вязкости жидкости. Данные, приведенные в таблице, наглядно подтверждают это утверждение. Первоначальное измерение содержания воды в синтезированном сложном эфире было зафиксировано как 120 частей на миллион (м.д.). Уровни влажности сложного эфира показаны на рисунке 5, демонстрируя его продвижение через молекулярное фильтр (WCE1), последующий выход из фильтра и последующее движение через камеру нагрева (WCE2). Процесс тщательной сушки занял неделю. Модификацию молекулярного фильтра адсорбера наблюдали через 48 часов. После замены сита произошло значительное снижение уровня влаги. В процессе сушки материал, прошедший через фильтр, демонстрировал умеренное увеличение содержания влаги. Молекулярный фильтр показал ожидаемые характеристики. Содержание влаги сложного эфира изменялось примерно на 10 частей на миллион (ppm) при прохождении через фильтр. Для поддержания заданного содержания влаги для эфира, выходящего через фильтр, постоянно поддерживался диапазон влажности 100-130 частей на миллион.

Таблица 1 - Исследование влияния температуры на отдельные характеристики синтетических эфиров

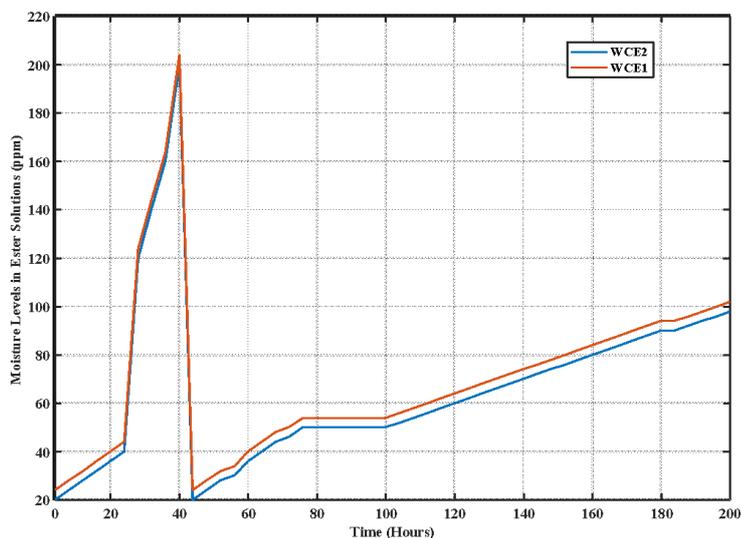| Свойства	Температура (градусы Цельсия)						
	35	45	55	65	75	85	95
Предел насыщения водой. (ppm)	3168	3474	3781	3899	3913	4122	4791
Вязкость (mm^2/s)	51	31	20.2	15	12.7	9.5	7,1
Плотность (Kg/m^3)	1015	976	955	945	934	928	921

Рисунок 5 – Молекулярный фильтр измеряет содержание эфирной воды на входе (WCE1) и выходе (WCE2)

Прогнозируемый период сушки составил 168 часов, что соответствует 7 дням. В результате оценивали содержание влаги в образцах целлюлозы, полученных из полос прессованного картона. Три образца были получены из разных участков полосы.

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Влажность оценивалась по методике Карла Фишера. В таблице 2 показаны доля влаги в массовых процентах после процесса сушки целлюлозы.

Таблица 2 – Массовая доля влаги в процентах после процесса сушки целлюлозы

Оптимальные точки отбора проб на полосе	Оценка содержания влаги в образцах		Количественная оценка потери воды в высушенных образцах
	Начальное содержание воды в образце перед сушкой	Содержание воды в образце после сушки	
Верхний	2,71	1,27	1,05
Средний	2,91	2,12	2,23
Нижний	2,84	2,41	1,97

На рисунке 6 показана кривая равновесия влажности, которая позволяет поддерживать содержание влаги в синтетическом эфире на уровне 130 частей на миллион при одновременном сокращении времени сушки прессованного картона до 0,5%. Увеличение продолжительности процесса сушки, чтобы облегчить поглощение воды целлюлозой и, следовательно, снизить содержание влаги. Эксперимент показал отличные результаты при использовании метода сушки, что составило 1,2%. При воздействии меньшего количества влаги трансформатор может работать более стабильно и иметь меньшую вероятность отказа.
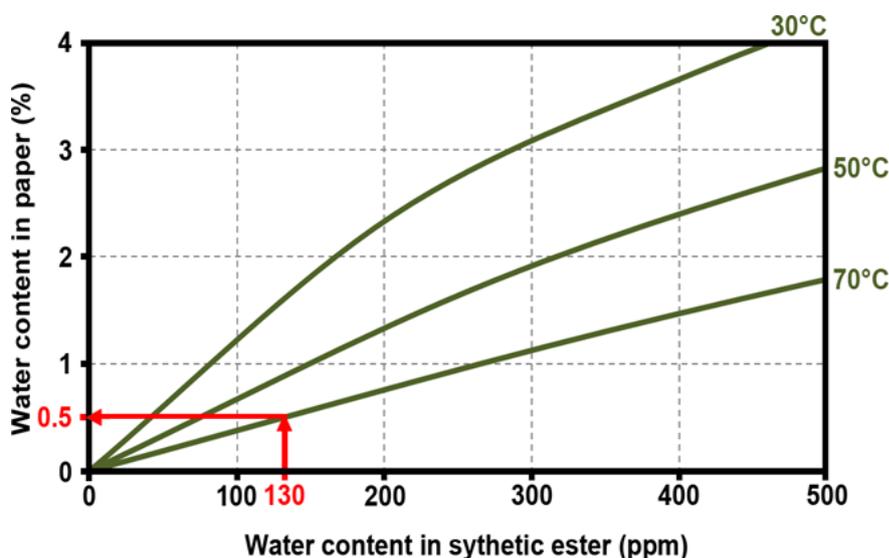

Рисунок 6 - Анализ кривых равновесия влаги в системе целлюлозная бумага-синтетический эфир

По сравнению с другими методами сушки изоляции трансформатора, показанный на рисунке 7, настоящая методология имеет значительные перспективы. Исследования и анализ показывают, что этот метод будет очень успешным и эквивалентен методу LFH с установкой масляного распыления. Предполагается, что для достижения уровня влажности трансформатора 1,5% потребуется период сушки в течение одной недели. Это предположение основано на тщательно выбранных экспериментальных условиях и содержании влаги 3%. Эффективность сушки текучего синтетического эфира оценивали в лабораторных исследованиях [17]. Однако авторы работы считают, что такую сушку можно проводить только на площадке, оснащенной стационарной техникой.
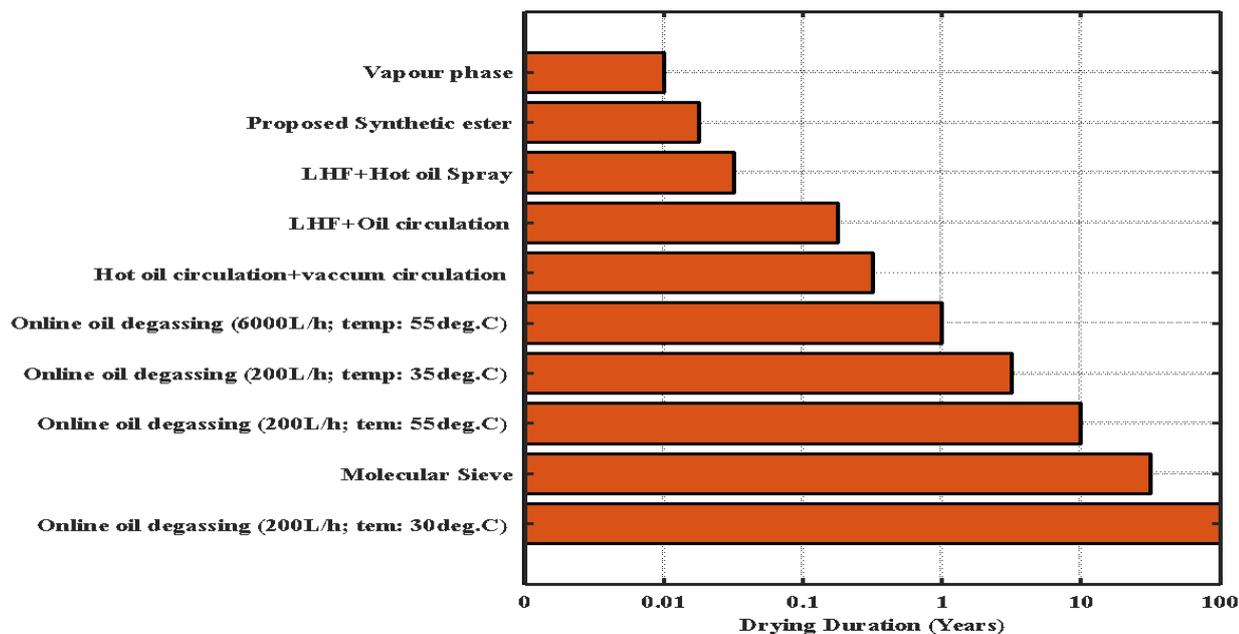
Рисунок 7 - Определение необходимого времени сушки трансформатора с массой изоляции 20 тонн

Эффективность этой процедуры обусловлена равномерным и интенсивным нагревом изоляции за счет использования водорастворимого синтетического эфира. Герметизировать резервуар не требуется. За счет отказа от использования вакуума сокращается время, необходимое для подготовки трансформатора к сушке. Срок службы и безопасность трансформаторов можно повысить за счет снижения содержания изолирующей влаги. По мере снижения содержания воды в изоляции наблюдается увеличение электрической прочности и снижение скорости деполимеризации целлюлозы.

Заключение.

Твердая изоляция распределительного трансформатора при вакуумной сушке создает проблемы из-за отсутствия герметизации или низкой прочности бака на сжатие. Поэтому рекомендуется использовать электроизоляционную жидкость, обладающую высокой растворимостью в воде, для сушки целлюлозного наполнителя. Проведено экспериментальное исследование модели системы изоляции трансформатора, подвергшейся сушке с использованием текучего синтетического эфира. Изначально влажность прессованного картона составляла 2,3%. Эфир, используемый для сушки целлюлозы, содержит воду в концентрации 100-130 частей на миллион. Температура верхнего слоя намоточной модели колебалась от 74 до 78 градусов по Цельсию. После 168 часов эксплуатации полоски прессованного картона потеряли воду на 1,08 процентных пункта. Прежде чем внедрять этот подход в полевых условиях, важно усовершенствовать как сам процесс, так и прототип системы. С точки зрения энергоэффективности следует рассмотреть два варианта: использование молекулярного фильтра в качестве влагопоглотителя или агрегат вакуумного нагрева и сушки. Соответственно, эти методы сушки проверены на распределительных трансформаторах на основе результатов наших экспериментов.

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ЖҰМЫС ЦИКЛІН ҰЛҒАЙТУ МАҚСАТЫНДА КҮШТІК ТРАНСФОРМАТОРЛАРДЫҢ ҚАТТЫ ОҚШАУЛАМАСЫН ҚЫСЫП КЕПТІРУ ӘДІСТЕРІН ЗЕРТТЕУ

Аңдатпа. Ылғалдың болуы күштік трансформаторларға зиянын тигізуі мүмкін, тозу процесін жеделдетеді, диэлектрик қорын, бастапқы жартылай разрядтық кернеуді азайтады, бұл өз кезегінде күтпеген істен шығу қаупін арттырады. Заманауи электр қондырғылары кептірудің әртүрлі әдістерін пайдаланады, олардың көпшілігі көбінесе тиімділігі төмен. Осы мәселелерді шешу үшін бұл мақала құрғақ оқшауламалы тарату трансформаторында синтетикалық эфирді пайдалануды ұсынады. Зерттеу үшін трансформатордың оқшауламасының жетілдірілген эксперименттік үлгісі қолданылды. Бұл модельді пайдалана отырып, эфир молекулалық сүзгінің көмегімен кептірілді және адсорбцияланған масса мұқият таңдалды. Целлюлоза оқшаулағышының кептіру тиімділігін анықтау үшін кептіру алдында және одан кейінгі пресс тақтасының жолақтарындағы су құрамы талданды. Судың мөлшері Карл Фишер титрлеу әдісімен анықталды. Эфир ылғалдылығының деңгейі 105-120 ppm және оқшаулау жүйесінің температурасы 70 градус болса, 5 күн бойы кептірілген үлгілер 1% -дан астам су шығынын көрсетті. Зерттеу тәжірибелері қуатты тарату трансформаторларында сыналған.

Түйінді сөздер. Кептіру технологиясы, тарату трансформаторлары, ылғал, синтетикалық эфир.

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STUDY OF PRESS DRYING METHODS OF SOLID INSULATION OF POWER TRANSFORMERS TO INCREASE THE LIFE CYCLE

Abstract. The presence of moisture can harm power transformers by accelerating the aging process, reducing the dielectric reserve, initial partial discharge voltage, which in turn

increases the risk of unexpected failures. Modern electrical engineering enterprises use various drying methods, often many of them are less effective. To solve these problems, this article proposes to use synthetic ether in a dry distribution transformer. An improved experimental model of transformer insulation was used for the study. Using this model, drying of the ester was carried out using a molecular filter and carefully selected adsorbed mass. The water content of pressed cardboard strips before and after drying was analyzed to determine the drying efficiency of cellulose insulation. Water content was determined by Karl Fischer titration. At ether moisture level of 105-120 ppm and insulation system temperature of 70 degrees, samples dried for 5 days showed water loss above 1%. The experiments of the study were tested on power distribution transformers.

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