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ELECTROTECHNICAL MATERIALS IN THE CONTEXT OF INDUSTRY 4.0: TRENDS, CHALLENGES AND PROSPECTS

Introduction. The energy sector of Ukraine and the world faces challenges of sustainable development, resource shortages, increasing environmental requirements and rapid digitalization. This creates a demand for a new generation of electrotechnical materials that ensure energy efficiency, reliability and ecological safety. **Problem statement.** Traditional materials no longer meet modern requirements due to toxicity, recycling difficulties, resource scarcity and limited compatibility with digital technologies. It is necessary to assess the potential of innovative materials and determine directions for their implementation. **Goal.** To analyze current trends and challenges in electrotechnical materials and define their prospects within Industry 4.0. To develop a model for modernizing the course “Electrotechnical Materials”. **Methodology.** The study applies analytical review of literature and standards, comparative analysis of materials, evaluation of digital tools (AI, digital twins, smart systems) and analysis of modern engineering education approaches. **The scientific novelty** of the work lies in proposing a classification of innovative materials within the context of Industry 4.0, substantiating the role of AI and digital twins in accelerating material research, developing a model for updating the course with smart, nano-, and IoT-compatible materials, and demonstrating the importance of digitally active materials for future energy systems. **Practical value.** The results may be applied in designing cable and insulation systems, sensor technologies, and in modernizing educational programs. They support the development of energy-efficient and environmentally safe electrotechnical solutions.

Ключові слова: electrotechnical materials, sustainable development, Industry 4.0, smart materials, nanomaterials, fiber optic sensor, graphene, energy efficiency, education.

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ЕЛЕКТРОТЕХНІЧНІ МАТЕРІАЛИ В КОНТЕКСТІ ІНДУСТРІЇ 4.0: ТЕНДЕНЦІЇ, ВИКЛИКИ ТА ПЕРСПЕКТИВИ

Вступ. Енергетичний сектор України та світу переживає виклики сталого розвитку, ресурсний дефіцит, зростання екологічних вимог і цифровізацію. Це зумовлює потребу в новому поколінні електротехнічних матеріалів, що забезпечують енергоефективність, надійність та екологічну безпеку. **Постановка проблеми.** Традиційні матеріали не відповідають сучасним вимогам через токсичність, складність утилізації, дефіцит ресурсів та несумісність із цифровими технологіями. Необхідно оцінити потенціал інноваційних матеріалів і визначити напрями їх упровадження. **Мета.** Проаналізувати тенденції та виклики у сфері електротехнічних матеріалів і визначити перспективи їх використання в умовах Industry 4.0. Розробити модель модернізації курсу «Електротехнічні матеріали». **Методологія.** Застосовано аналітичний огляд літератури й стандартів, порівняльний аналіз матеріалів, оцінку цифрових технологій (AI, цифрові двійники, Smart-системи) та аналіз освітніх підходів. **Наукова новизна роботи полягає в** запропонованні класифікації інноваційних матеріалів у контексті Індустрії 4.0, обгрунтуванні ролі штучного інтелекту та цифрових двійників у прискоренні досліджень матеріалів, розробці моделі для оновлення курсу розумними, нано- та IoT-сумісними матеріалами, а також демонстрації важливості цифрово активних матеріалів для майбутніх енергетичних систем. **Практична значимість.** Результати можуть бути використані в проєктуванні кабельних і ізоляційних систем, сенсорних технологій та при модернізації освітніх програм. Це сприятиме створенню енергоефективних і екологічно безпечних електротехнічних рішень.

Keywords: електротехнічні матеріали, сталий розвиток, Індустрія 4.0, розумні матеріали, наноматеріали, волоконно-оптичний сенсор, графен, енергоефективність, освіта.

Introduction. Every year, Ukraine's energy sector faces certain challenges, and since 2022, it has also faced the consequences of military aggression. For example, in 2024, our country lost more than 9 GW of generating capacity of power plants (according to official data from NPC Ukrenergo [1]), which led to an energy deficit for consumers of almost 35%, and the increase in the cost of electricity from September 2023 to September 2024 was approximately 34%. In addition, a decision to terminate the transit of Russian gas through the territory of Ukraine came into effect on January 1, 2025. Given all this, certain key trends in the energy sector have been formed that will determine the development of the electricity industry for years to come, including investments by businesses and communities in their own energy independence, the rapid development of distributed generation capacities and energy storage facilities, increased investments in utility-scale alternative energy projects, etc. Given the rapid growth rates and active innovative technological developments, alternative energy is compared to IT. This approach to the development of key energy trends is shaping new requirements for electrotechnical materials.

Problem statement. Rapid globalization dictates that governments of countries form new development strategies that should include the introduction of Industry 4.0. Changes in Ukraine contribute to the rapid introduction of digital technologies, artificial intelligence and Smart solutions into everyday life.

Currently, the era of the 4th industrial revolution, which the whole world has entered, is underway. This is a trend based on an automated and technological approach. Industry 4.0 opens up opportunities for the integration of intelligent systems, automation, big data and AI in the development and use of new generation materials.

At the same time, challenges are emerging that force us to reconsider traditional approaches to the selection, production and disposal of electrotechnical materials:

– *shortage of certain materials* (copper, silver, lithium, tin, rare earth metals), which necessitates the search for substitutes and the reduction of the mass-dimensional characteristics of materials;

– *environmental safety issues* (the process of producing plastics requires a significant amount of energy and causes greenhouse gas emissions, contributing to climate change, in addition, many polymer insulation compositions form toxic products such as dioxins, furans and heavy metals when burned, which can pollute soil, water and air);

– *disposal and recycling of electronic waste (*more than 50 million tons of waste are generated each year, with only 17% of it being recycled. Disposal of electrotechnical waste can lead to the release of harmful chemicals into the environment). This creates a need for materials that are easily recycled and biodegradable.

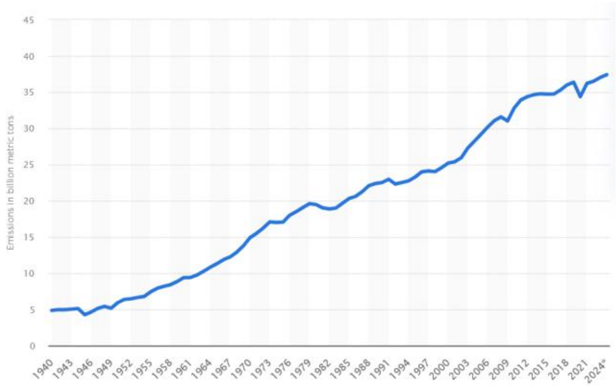

Fig. 1. Annual carbon dioxide (CO$_2$) emissions worldwide from 1940 to 2024 (in billion metric tons) [2]

Review of the literature. New materials play a key role in ensuring sustainable electrotechnical development, as they combine energy efficiency, durability and environmental safety in the face of global challenges and the transition to Industry 4.0. Among them, new generation dielectric materials, nano- and Smart materials with adaptive properties, etc. can be distinguished.

Electrical gas sulfur hexafluoride (SF$_6$) is widely used in the power industry. The most important application of SF$_6$ is in high-voltage power transmission equipment. Approximately 10,000 tons of sulfur hexafluoride are used for this purpose per year, which corresponds to approximately 80% of the total production. The properties of sulfur hexafluoride allow manufacturers to design switchgear that are compact, weather-resistant and require minimal maintenance, but SF$_6$ is one of the 7 gases included in the Kyoto Protocol [3] aimed at reducing greenhouse gas emissions. Components containing of sulfur hexafluoride must be completely gas-tight, as the release of just 1 kg of SF$_6$ into the atmosphere would have a global warming impact equivalent to approximately 23.5 tons of CO$_2$ [4, 6].

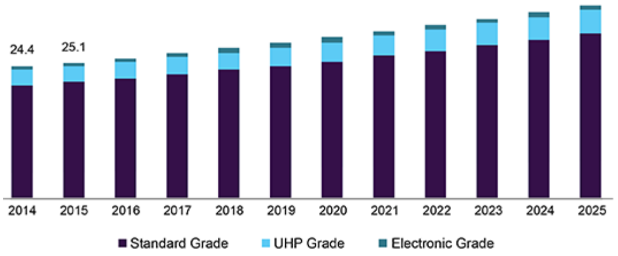

Fig. 2. US sulfur hexafluoride market size, by product, 2014-2025 (USD Million) [5]

During long-term research to find an alternative to SF$_6$, a special compound, heptafluoroisobutyronitrile Novec 4710 (Fig. 4), from the family of fluoronitriles with low toxicity, was synthesized. The Novec 4710 liquid has a dielectric strength approximately twice that of sulfur hexafluoride SF$_6$ at atmospheric pressure, high heat transfer and low toxicity, which makes it the best candidate for replacing of SF$_6$ gas. However, pure Novec 4710 has a boiling point significantly higher than sulfur hexafluoride (-5°C vs. -63.9°C, respectively), so this dielectric fluid cannot replace SF$_6$ (Fig.5) [6, 7].

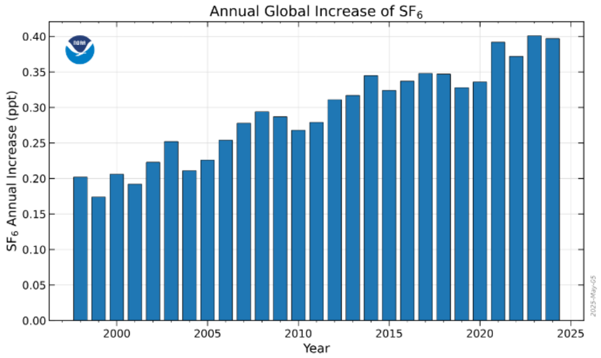

Fig. 3. Annual Increase in Globally-Averaged Atmospheric Sulfur Hexafluoride [6]

Therefore the best solution for creating a gas mixture suitable for arc extinguishing is the mixing of Novec 4710 with CO$_2$, which has been called the green gas for grid "g^3". The "g^3" gas mixture will certainly have a positive impact on the environmental problem, which is increasingly becoming the focus of attention of the world community [7].

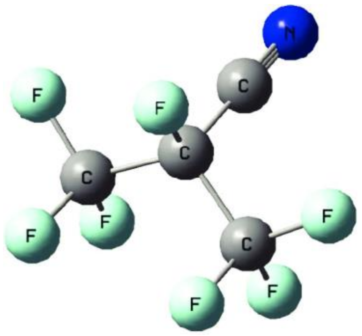

Fig. 4. Novec 4710 gas consists of iso-C$_3$F$_7$CN

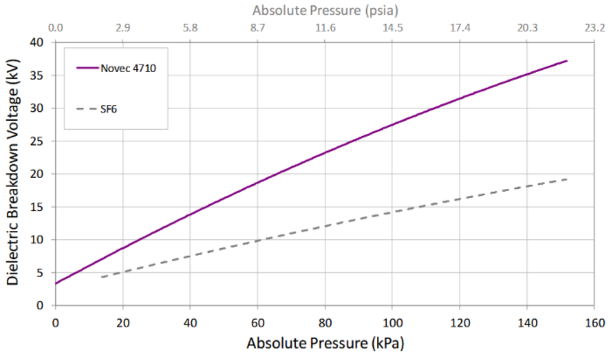

Fig. 5. Dielectric strength of insulating gases at different pressures [12]

The latest "smart" materials (Smart Materials) play a key role in ensuring sustainable electrotechnical development, combining innovative properties with energy efficiency and environmental safety. Smart or intelligent materials are able to respond to internal or external influences (environmental changes) and activate their functions in accordance with these changes. In the context of Industry 4.0, Smart Materials become the basis for integration into digital production systems, among which we can highlight:

- *piezoelectric materials*, such as Rochelle Salt, work as small energy transformers: they convert electrical energy into mechanical energy and back. Such materials are used in wireless sensors to monitor vibrations, pressure, deformations and loads in real time, and thanks to the piezoelectric effect, self-sufficiency of sensors with energy is possible, which reduces the need for batteries. Therefore, they are key components in energy-autonomous devices.
- *nanomaterials*, such as graphene. It is the strongest material in the world, and has a very high surface area to volume ratio, making it ideal for storing energy. This could rapidly improve the performance of energy devices. For example, graphene batteries are very light, can operate over a wide temperature range, and have a larger volume. They also allow for faster charging and give you more choice. To store as much energy as possible, these batteries are also used in energy absorbers, supercapacitors, and electromagnetic devices. Graphene and its derivatives are a potential basis for creating superinsulators and thermally stable shells [8].
- *magnetostrictive materials*. Materials such as iron, nickel, and cobalt can change their shape or size slightly when exposed to a magnetic field. This property is extremely useful because these materials can convert magnetic energy into motion and vice versa. This makes them ideal for creating sensors and actuators, that is, devices that can respond to changes in their environment.
- *shape memory alloys* (SMA) are a class of metallic materials with unique properties that allow them to “remember” and recover their original shape after deformation. This behavior is explained by the phase transformation of a solid that occurs in response to changes in temperature or applied stress. The most commonly used materials for shape memory alloys are based on nickel-titanium (Ni-Ti) compositions known as nitinol. Nitinol alloys are usually composed of approximately equal atomic percentages of nickel and titanium, although composition variations are possible. The shape memory properties of these alloys allow for easier insertion and improved fit, and their superelasticity allows them to withstand dynamic loads and reduces the risk of damage or breakage. The ability of shape memory alloys to change shape in response to temperature or stress is used to optimize aerodynamic performance and improve fuel efficiency in the aviation industry. The unique properties of shape memory alloys make them valuable in various industries where precise actuation, shape change, and mechanical performance are important.
- *optical fibers*: Using polarization, phase, intensity, or frequency, these fibers detect various parameters such as strain, temperature, electric/magnetic fields, and pressure, making them excellent sensors [9-11].

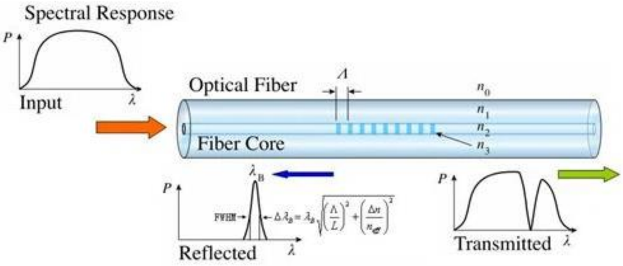

Fig. 6. Operating principle of the fiber Bragg grating (FBG) sensor

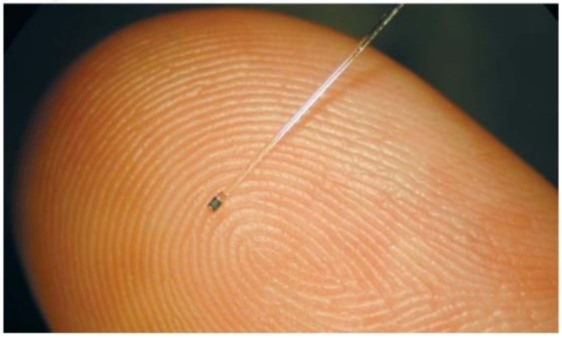

Fig.7. Fiber optic pressure sensor

SMART materials often exhibit nonlinear behavior, which can be used to improve the efficiency of energy conversion from a variety of sources.

Materials and methods. Industry 4.0 tools in materials development:

– *Using AI and modeling*

Artificial intelligence (AI) and machine learning algorithms enable researchers and scientists to predict the behavior of materials under different loading conditions, aggressive environments, or aging. This allows for faster development times for new materials and lowers the cost of experimental research. For example, automated systems using AI are able to model polymer mixtures, selecting their composition in such a way as to achieve maximum dielectric strength at minimum weight and cost.

– *Digital twins*

The creation of a so-called digital double, that is, the creation of a virtual model of an electrotechnical material or component that fully replicates its characteristics and behavior in real operating conditions. A digital twin allows for numerous virtual experiments (without manufacturing physical samples) to simulate aging processes; analyze properties; optimize the compositions of insulating or conductive mixtures; detect defects even before prototypes are manufactured.

Such tools significantly increase the efficiency of research and development in the field of electrotechnical materials, reduce the time to market for innovations, and reduce the risks of technical errors.

– *Smart systems and IoT-compatible materials*

Modern electrotechnical materials must not only perform their basic functions, but also actively interact with digital control and monitoring systems. In this context, the importance of so-called IoT-compatible materials is growing - materials with built-in sensor, communication or adaptive properties that allow the concept of "smart" energy to be implemented. Insulating materials can change their physical characteristics (resistance, capacitance, conductivity) in response to external influences - overheating, humidity, mechanical damage. These changes will be recorded in real time, transmitting data via built-in sensors to the monitoring system. Such materials are integrated into Smart systems. This ensures continuous monitoring of temperature, load, insulation status; predicting failures or the beginning of material degradation. Cables with built-in sensors, conductive composites with the ability to transfer data, as well as structural materials for transformers that analyze their own state without human intervention have already been created today. Such technological solutions are an integral part of the electrical infrastructure of Industry 4.0, where each component of the system is a source of data and interacts with the overall digital ecosystem.

Discussion. Modernization of the course “Electrotechnical Materials” in the context of Industry 4.0 and the current state of the energy sector in Ukraine is a relevant step in training specialists capable of solving the problems of sustainable development, energy efficiency and digitalization of the electric power sector. Taking into account the challenges associated with the transformation of the Ukrainian energy system, decentralization of generation, the introduction of renewable energy sources and the need for energy security, the course should cover the study of modern materials (Smart Materials, nanomaterials, etc.), as well as digital monitoring, diagnostics and automation tools. What is the strategic approach to studying the course “Electrotechnical Materials” in the context of Industry 4.0? Given the goals of sustainable development, the digital transformation of industry and the need for highly qualified engineers of a new generation, the strategic approach to teaching this discipline should be based on the following key principles:

a) integration of interdisciplinary knowledge. The course should combine materials science, electrical engineering, energy, digital technologies, ecology and sustainable development engineering. This will allow students to better understand the relationship between the properties of materials and their impact on the efficiency of energy systems;

b) orientation to practical significance. Study of materials used in the domestic energy sector, in particular: cable and wire products, modern insulation systems, materials for solar panels and energy systems;

c) study of innovative solutions. Special attention should be paid to the latest materials, such as Smart Materials, nanostructured coatings, conductive polymers, which contribute to increasing the efficiency, adaptability and environmental safety of electrical installations;

d) digitalization of learning processes. Use of digital laboratories, simulations, augmented and virtual reality, as well as online platforms to provide access to modern knowledge and increase student motivation;

e) formation of critical thinking and engineering responsibility. Thanks to case methods, a project approach and analysis of real problems of the Ukrainian energy sector, students will be able to learn to make informed engineering decisions taking into account environmental, economic and social factorsf) Promotion of energy security. The course should form in students an understanding of the importance of choosing materials that can ensure energy efficiency, durability, autonomy and sustainability of energy systems in the face of today's challenges.

Such a strategic approach will contribute to the training of specialists who are able not only to work effectively in the conditions of Industry 4.0, but also to actively influence the development of energy independence and sustainability of countries.

Acknowledgment. Sustainability and digitalization are two key axes of the transformation of electrotechnical materials. The integration of environmental standards and smart technologies contributes to the creation of energy-efficient, reliable and safe new generation materials.

The need to update curricula, actively involve students in interdisciplinary projects. It is important to implement modern educational approaches that encompass knowledge in the field of materials science, ecology, automation and digital technologies.

It is recommended to strengthen cooperation between higher education institutions, scientific institutions and industry in order to implement innovative solutions in the production of electrotechnical materials.

It is advisable to promote the development of research in the field of secondary processing of materials, the use of bio-oriented and nanostructured electrical insulation systems.

The training of new generation specialists should be based on the concepts of sustainable development, digital competencies and a deep understanding of Industry 4.0 trends.

Conflict of interest. The authors declare that they have no conflicts of interest.

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