Л.Н. Гумилев атындағы Еуразия ұлттық университетінің ХАБАРШЫСЫ.
ISSN: 2616-7263. eISSN: 2663-1261

ТЕХНИКАЛЫҚ ҒЫЛЫМДАР ЖӘНЕ ТЕХНОЛОГИЯЛАР СЕРИЯСЫ /
TECHNICAL SCIENCES AND TECHNOLOGY SERIES/
СЕРИЯ ТЕХНИЧЕСКИЕ НАУКИ И ТЕХНОЛОГИИ

IRSTI 55.30.03
Review

https://doi.org/10.32523/2616-7263-2026-154-1-216-228

Robotization in the Production of Distribution Power Transformers - Technologies, Advantages and Prospects of Industry 4.0

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Abstract. This paper explores modern approaches to introducing robotic automation in the production of power distribution transformers within the Industry 4.0 framework. It identifies the key manufacturing stages where industrial robots provide the greatest efficiency, including electrical steel cutting, coil winding, magnetic core assembly, insulation application, tank welding, and quality control. Particular attention is given to integrating robotic systems with digital manufacturing management platforms, as well as using sensors, machine vision, and real-time monitoring technologies. The findings show that robotic automation significantly improves precision and operational consistency, reduces production cycle time by approximately 30–40%, lowers defect rates from 5–7% to 2–3%, and decreases overall manufacturing costs by 15–20%. Additional benefits include improved energy efficiency, enhanced workplace safety, reduced occupational injuries, optimized resource use, and minimized human error. The study concludes that implementing robotics in transformer manufacturing establishes a foundation for smart factories and fully automated intelligent production systems driven by digitalization, big data, artificial intelligence, and predictive maintenance.

Keywords: robotization, distribution transformer, technological process, industrial automation, digital manufacturing, Industry 4.0.

Received 11.11.2025. Revised 29.01.2026. Accepted 03.02.2026. Available online 30.03.2026

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Introduction

In the modern world, electricity forms the backbone of nearly all spheres of human activity - from industry and transportation to information technologies and utilities. The growing demand for energy, the transition to renewable sources, and ongoing digitalization place increasing requirements on the reliability and efficiency of power systems. In this context, distribution power transformers, which ensure the transmission and distribution of electricity across different voltage levels, play a particularly crucial role [1].

The growth of electricity consumption, the active integration of renewable energy sources, the development of distributed generation, and the expansion of digital grids are forming new requirements for substation and distribution equipment. Transformers must demonstrate high energy efficiency, resistance to overloads, long service life, and minimal operating costs. At the same time, the importance of manufacturing accuracy and stability of electrical characteristics is increasing, since even minor deviations in winding geometry or insulation quality can affect the reliability of the entire power system.

Traditional transformer manufacturing technologies rely heavily on manual labor and semi-automated machines. For decades, operations such as coil winding, magnetic core assembly, installation of insulation, and integration of tank components have been performed either manually or with a minimal degree of mechanization. This approach has several drawbacks: high labor intensity, dependence on worker skills, low repeatability of operations, higher risks of defects and workplace injuries. Moreover, traditional production methods often fail to meet current requirements for flexibility, scalability, and responsiveness to changes in market demand [2].

An additional limitation of the traditional approach is the high labor intensity and extended production cycle. Under conditions of increasing competition and the need to shorten delivery times, such a model becomes less effective. Moreover, heavy and potentially hazardous operations- welding, handling large components, working with impregnation compounds- raise the risk of occupational injuries and require strict safety measures.

The development of industrial robotics has opened new opportunities for modernizing transformer manufacturing. Modern industrial robots are characterized by high positioning accuracy, repeatability, and the ability to operate continuously. Their implementation makes it possible to automate key stages of the technological process: cutting electrical steel, assembling magnetic cores, winding coils, applying insulation coatings, welding transformer tanks, and performing quality control. Robotic systems ensure parameter stability and significantly reduce the influence of the human factor [3].

Meanwhile, advancements in industrial automation and robotics open new opportunities for the electrical engineering industry. Industrial robots, characterized by their precision, consistency, and reliability, are becoming key tools for modernizing production processes. Robotization addresses multiple challenges simultaneously: it shortens production time, reduces costs, improves product quality and workplace safety, and creates favorable conditions for digital monitoring and control methods [3].

Robotics gains particular importance within the framework of the Industry 4.0 concept. This concept involves the integration of cyber-physical systems, digital twins, big data technologies, and artificial intelligence into manufacturing processes. In such an environment, robotic equipment becomes part of a unified digital ecosystem in which data on machine condition, processing parameters, and product characteristics are analyzed in real time. This not only increases productivity but also enables the prediction of potential deviations, preventing defects at early stages.

Global practice confirms the effectiveness of this approach. Leading manufacturers of power equipment, including ABB, Siemens Energy, and other companies, are actively implementing robotic production lines in transformer manufacturing, achieving significant reductions in production cycle time and defect rates [5–7]. According to industry studies, automation can reduce manufacturing time by 30–40%, decrease labor intensity by approximately one third, and lower production costs by up to 20%. These figures demonstrate the strong economic feasibility of investing in robotics [5–7,10].

In addition to technical and economic aspects, the social dimension is also significant. The transition to automated systems changes the workforce structure within enterprises: the demand for low-skilled manual labor decreases, while the need for engineers specializing in programming, maintenance, and diagnostics of robotic systems increases. This transformation requires revision of educational programs and systematic upskilling of personnel [2].

Thus, the introduction of robotization into the production and distribution of power transformers is not only a technical necessity but also a strategic direction for the development of power engineering. It allows manufacturers to address complex challenges: improving production efficiency, ensuring higher product quality and reliability, reducing costs, enhancing occupational safety, and aligning with global digitalization trends.

The objective of this study is to analyze modern approaches to the robotization of technological processes in the production of distribution power transformers, to identify their advantages and limitations, and to outline promising directions for development within the transition toward digital manufacturing systems [1-3].

The methodology

This study is based on the analysis of current trends and technologies applied in the production of distribution power transformers, with a special focus on the robotization of key technological stages. The section describes the information sources, regulatory framework, robotic equipment considered, and the methods applied to evaluate the efficiency of automation [1-7,9,10].

The following materials were used as the basis for this study: international standards IEC 60076, which regulate the design, testing, and operation of power transformers; national standards (GOST 3484.1-88, GOST 11677-85) that define quality and parameter requirements for transformers; technical reports and white papers from leading global manufacturers of robotic systems (ABB Robotics, KUKA, FANUC, Yaskawa, Siemens Energy); recent academic publications in the field of robotization of electrical engineering production and digital factories; as well as data from industry conferences and analytical reviews on the implementation of Industry 4.0

ISSN: 2616-7263. eISSN: 2663-1261

technologies [8,9]. These materials provided a comprehensive understanding of the current state of transformer manufacturing and highlighted the areas where robotization yields the most significant results [1-3].

The manufacturing process of distribution power transformers includes several key stages: preparation and processing of electrical steel - cutting, stamping and preparing sheets for magnetic core assembly; magnetic core assembly - stacking, pressing and fixing the sheets; coil winding - forming primary and secondary windings with high precision; insulation and impregnation - applying insulating materials, vacuum impregnation and drying; assembly of the tank and active part - integrating the magnetic core, windings and insulation; testing and quality control - measuring electrical parameters, checking mechanical strength and ensuring tightness [1,4]. At each of these stages, robotic systems can be applied, which became the subject of analysis [1-3,5,6].

In the study the following categories of equipment were considered: manipulator robots for stacking magnetic core sheets and installing coils; automated CNC and laser cutting lines ensuring high precision in processing electrical steel; robotic winding complexes providing uniformity and repeatability in coil formation; robots for applying coatings and insulating materials, including spraying and impregnation systems; automated welding complexes for assembling transformer tank components; machine vision systems for assembly quality control and defect detection [5,6].

To assess the impact of robotization on the production process the following methods were applied: comparative analysis - comparison of traditional and robotized production indicators such as production cycle duration, labor intensity, unit production cost, defect rate and energy efficiency (Figure 1); economic analysis - evaluation of ROI (Return on Investment), the payback period of investments in robotization, TCO (Total Cost of Ownership), total costs of equipment ownership, and economic effect achieved through reduced manual labor and lower defect rates (Figure 2); technological modeling - use of digital twins of production processes to predict the results of implementing robotic systems; socio-organizational analysis - assessment of the influence of robotization on employment structure, staff retraining needs, and changes in occupational safety and health [1-3].

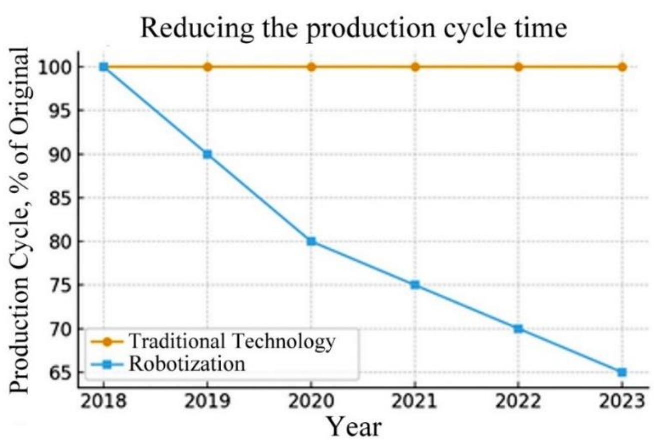

Figure 1. Dynamics of production cycle reduction

Note: Compiled based on the data presented in references [1–3]

The application of a combined methodology made it possible not only to quantify the benefits of robotization (cost reduction, higher quality, faster production) but also to account for organizational, economic, and social consequences. This approach ensures a holistic understanding of the role of robotization in modernizing transformer manufacturing.

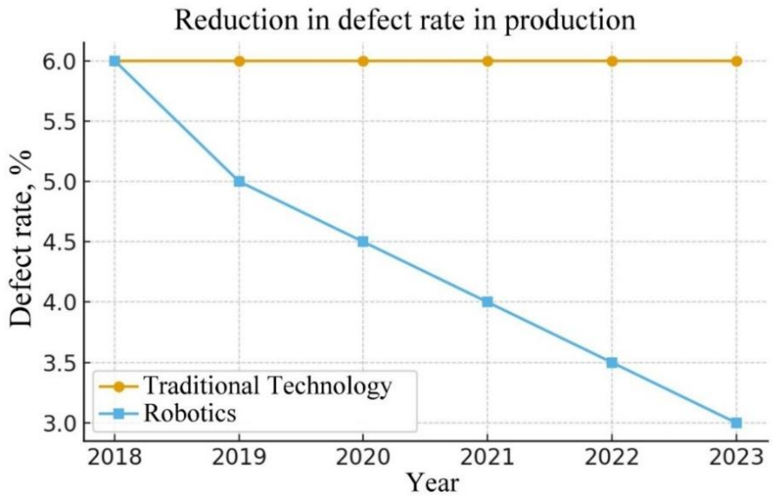

Figure 2. Reducing the level of defects in production

Note: Compiled based on the data presented in references [1–3]

Findings/Discussion

Key Directions of Robotization in Transformer Manufacturing. Robotization in the production and distribution of power transformers covers almost all stages of the technological process. The greatest efficiency is demonstrated in the following areas [3,5,6].

Automated cutting of electrical steel. CNC laser and plasma installations ensure high accuracy and speed of sheet processing, minimize waste and increase the yield of suitable products. The use of robotic loaders accelerates material handling and reduces the workload on personnel.

Magnetic core assembly. Manipulator robots are used for stacking, pressing and fixing the sheets into packages. This reduces the likelihood of misalignment, ensures repeatability of operations and improves magnetic core quality.

Coil winding. One of the most labor-intensive and critical processes is the formation of transformer windings. Robotic winding complexes provide uniform conductor distribution, high density and precision of winding. This reduces overheating risks, improves electrical performance and extends transformer service life.

Insulation and impregnation. Robots ensure the consistent application of insulating materials, perform vacuum impregnation and drying operations. This approach minimizes defects, increases reliability and dielectric strength of insulation.

Tank welding and machining. Robotic welding systems are used in the production of transformer tanks. They provide consistent seams, reduce the risk of defects and improve tightness. Automated machining lines reduce dimensional deviations and improve the accuracy of fits [11-15].

Quality control. Machine vision and non-destructive testing systems integrated with robots enable the inspection of each unit. This eliminates human error and ensures objectivity of quality control. Comparative Analysis of Traditional and Robotized Production. To evaluate the effectiveness of robotization, a comparative analysis of key production parameters was carried out (Tables 1,2).

Table 1. Comparison of traditional and robotized transformer production

Indicator	**Traditional Technology**	**Robotized Technology**
Production cycle duration	100%	60-70%
Labor intensity	High	30-40% lower
Coil winding quality	Medium, operator-dependent	High accuracy and repeatability
Defect rate	5-7%	2-3%
Occupational safety	Medium, heavy workload	High, minimal manual operations

Note: Compiled based on the data presented in references [1–3]

Table 2. Economic Effect of Robotization

Indicator	**Before Implementation**	**After Implementation**
Productivity	100 units/year	140-150 units/year
Cost per unit	100%	80-85%
Payback period	-	3-5 years
Energy efficiency	100%	110-120%

Note: Compiled based on the data presented in references [1–3]

The results showed:

- Production cycle duration reduced by 30-40%;
- Labor intensity decreased by 35-45%;
- Coil winding precision reached up to 99% repeatability;
- Defect rate reduced from 5-7% to 2-3%;
- Unit production cost decreased by 15-20%.

Additionally, the introduction of robotization increases the energy efficiency of the enterprise by 10-15% through more rational use of equipment.

The economic analysis showed that ROI (Return on Investment) is 3-5 years, depending on the scale of production; TCO (Total Cost of Ownership) decreases due to reduced labor costs and fewer defects; the use of robotic systems increases production output by 40-50% [3,5,6]. For example, the introduction of automated winding machines at a Siemens plant made it possible to increase transformer output by 35% without expanding the workforce. Case Studies of Implementation.

ABB (Germany, 2022) implemented an automated cutting and magnetic core assembly line, which reduced steel waste by 12% and decreased the cycle time by 25%. Hyundai Heavy Industries (South Korea, 2021) introduced robotic welding complexes for transformer tank manufacturing. As a result, tightness improved and the number of warranty cases decreased by 18%.

Siemens Energy (Austria, 2020) developed a digital twin system for transformer production integrated with robotic lines. This made it possible to predict product output parameters and optimize production processes [5,6,7].

Robotization affects not only technical and economic indicators but also the social sphere: the demand for unskilled manual labor decreases; the demand for specialists in the maintenance of robots and automation systems increases; working conditions improve and the level of occupational injuries decreases; the development of staff retraining programs is required [1-3].

Further development of robotization is associated with the introduction of artificial intelligence to optimize robot performance; the use of collaborative robots (cobots) capable of interacting with humans on the same production line; the integration of robotic systems into enterprise digital twins; and the transition to fully smart factories, where production processes are managed in real time based on big data.

Conclusion

The conducted study showed that robotization of the technological process of manufacturing distribution power transformers is a strategic direction for the development of the modern electrical engineering industry [1-3,5].

Summary of Analysis Results:

1. Reduction of production cycle duration. Robotization reduces transformer manufacturing time by 30-40% through the automation of key operations such as steel cutting, coil winding, magnetic core assembly and tank welding.

2. Improvement of product quality. The use of robotic systems ensures consistent repeatability of technological operations and reduces defect probability by a factor of 2-3 compared with traditional technology.

3. Cost reduction and increased economic efficiency. By lowering manual labor, reducing material waste and optimizing processes, production costs decrease by 15-20%, while the payback period of investments in robotization averages 3-5 years.

4. Improvement of working conditions and safety. Robots eliminate human involvement in the most dangerous and heavy operations (welding, moving heavy parts, insulation impregnation). This reduces the level of injuries and improves the environmental situation at the enterprise.

5. Social and workforce changes. Robotization requires staff retraining and a shift from mass manual labor to specialists in the maintenance and programming of robotic systems.

Scientific and Practical Significance. The introduction of robotization in transformer manufacturing makes it possible to increase product competitiveness in the global market; ensure higher production energy efficiency; lay the foundation for the creation of “digital factories” and the transition to the Industry 4.0 concept; and expand the use of artificial intelligence and machine vision technologies for quality control [3,6].

Prospects for Further Research. Development and implementation of digital twins of transformers and production processes to predict product characteristics already at the design stage; application of collaborative robots (cobots) for joint work with operators on assembly lines; integration of robotic systems with Big Data and IoT platforms to enable real-time monitoring and production management; exploration of artificial intelligence methods for adaptive optimization of production modes and defect prevention [3,10].

General Conclusion. Thus, robotization of the technological process of manufacturing distribution power transformers not only improves product quality and reduces production costs but also forms the foundation for the transition to fully automated intelligent production systems. This direction is key for the long-term development of power engineering, as it combines technological progress, economic benefits and social significance [1-3,5-7,10-15].

The contribution of the authors.

Smailova G.A. – significant contribution to the concept of the work; collection, interpretation of the results of the work, consent to be responsible for all aspects of the work, and writing a text.

Alshynova A.M. – analysis or interpretation of the results of the work.

Uderbayeva A.E. – worked on data collection, analysis, interpretation, drafting, and editing.

Koshanova Sh. – is responsible for literature review and scientific consulting.

Zhamankulov Y. – collection, analysis or interpretation of the results of the work.

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Таратушы күштік трансформаторлар өндірісіндегі роботтандыру - заманауй технологиялар, Индустрия 4.0 артықшылықтары мен перспективалары

Аңдатпа. Бұл жұмыста «Индустрия 4.0» тұжырымдамасы аясында тарату күштік трансформаторларын өндіру үдерісіне роботтандыруды енгізудің заманауи тәсілдері талданады. Зерттеу нәтижелері өндірістің қай кезеңдерінде өнеркәсіптік роботтарды қолдану ең жоғары тиімділік беретінін анықтайды: электротехникалық болатты кесу, орамдарды орау, магниттік өзекшелерді жинақтау, оқшаулағыш материалдарды жағу, бактарды дәнекерлеу және сапаны бақылау. Сонымен қатар роботтық кешендерді өндірісті

ISSN: 2616-7263. eISSN: 2663-1261

цифрлық басқару жүйелерімен біріктіру, датчиктерді, машиналық көру жүйелерін және нақты уақыт режиміндегі мониторинг құралдарын пайдалану мәселелеріне ерекше назар аударылады. Зерттеу нәтижелері роботтандыру операциялардың дәлдігі мен қайталанғыштығын едәуір арттыратынын, өндірістік цикл уақытын шамамен 30–40%-ға қысқартатынын, ақаулар деңгейін 5–7%-дан 2–3%-ға дейін төмендететінін және өнімнің өзіндік құнын 15–20%-ға азайтатынын көрсетеді. Қосымша артықшылықтар ретінде энергия тиімділігінің артуы және еңбекті қорғау деңгейінің жақсаруы атап өтіледі, соның ішінде өндірістегі жарақаттанудың төмендеуі, ресурстарды ұтымды пайдалану және адами қателіктердің азаюы. Қорытындылай келе, трансформатор өндірісіндегі технологиялық үдерістерді роботтандыру «ақылды зауыттарға» және толық автоматтандырылған зияткерлік өндірістік жүйелерге көшуге негіз қалайды. Мұндай жүйелерде цифрландыру, үлкен деректерді интеграциялау, жасанды интеллект және жабдықтардың предиктивтік талдауы негізгі рөл атқарады.

Түйін сөздер: роботтандыру, таратушы трансформатор, технологиялық процесс, өнеркәсіптік автоматтандыру, цифрлық өндіріс, Индустрия 4.0.

Г.А. Смаилова[1], А.М. Алшынова[2], А.Е. Удербаева[*1], Ш.Кошанова[3], Е. Жаманқұлов[1]

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Роботизация в производстве распределительных силовых трансформаторов - технологии, преимущества и перспективы Индустрии 4.0

Аннотация. В данной работе анализируются современные подходы к внедрению роботизации в производство распределительных силовых трансформаторов в рамках концепции «Индустрия 4.0». Исследование выявляет технологические этапы, на которых промышленные роботы обеспечивают наибольшую эффективность: резка электротехнической стали, намотка катушек, сборка магнитных сердечников, нанесение изоляционных материалов, сварка баков и контроль качества. Особое внимание уделяется интеграции робототехнических комплексов с цифровыми системами управления производством, применению датчиков, систем машинного зрения и средств мониторинга в реальном времени. Результаты показывают, что роботизация значительно повышает точность и повторяемость операций, сокращает время производственного цикла на 30–40%, снижает процент брака с 5–7% до 2–3% и уменьшает себестоимость продукции на 15–20%. Дополнительные преимущества наблюдаются в энергоэффективности и охране труда, включая снижение травматизма на рабочем месте, оптимизацию использования ресурсов и минимизацию человеческих ошибок. В заключении исследования делается вывод, что роботизация технологического процесса в производстве трансформаторов

закладывает основу для перехода к «умным заводам» и полностью автоматизированным интеллектуальным производственным системам, где центральную роль играют цифровизация, интеграция больших данных, искусственный интеллект и предиктивная аналитика оборудования.

Ключевые слова: роботизация, распределительный трансформатор, технологический процесс, промышленная автоматизация, цифровое производство, Индустрия 4.0.

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