DOI: https://doi.org/10.25140/2411-5363-2025-3(41)-432-441
UDC 621.311.4

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RESEARCH ON METHODS OF MODIFICATION OF WINDING MACHINE FOR TOROID TRANSFORMERS

In the paper, the design of a winding machine for toroidal cores, developed to reduce the cost and improve the ergonomics of the machine in the process of its operation is considered. The main shortcomings of analogues are analyzed. Modifications are proposed, including the use of modern production methods to reduce the cost of the winding machine while maintaining quality performance, automation of the winding process and the introduction of a sensor system to control the quality parameters of transformer winding. Special attention is paid to the prospects for the application of machine learning algorithms to improve the quality of winding. The proposed solutions contribute to the creation of an effective and inexpensive winding machine, compared to analogues, for laboratory, educational and small-scale use.

Keywords: *winding machine; toroidal cores; transformer; automation; machine learning; microcontroller; digital interface; Raspberry Pi; electric drive.*
Fig.: 4. References: 13.

Relevance of the research topic. In modern electrical industry and scientific research, toroidal transformers play a key role, have high efficiency, compactness and reduced level of electromagnetic interference, due to the evenly distributed magnetic flux in the form of a circle in the middle of the core [1]. Toroidal coils with several windings such as transformers and chokes on a common core are also widely used. However, the process of their manufacture remains complex and resource-intensive, especially for small-scale production, for the needs of educational, scientific and laboratory research.

The proposed research is aimed at developing an affordable toroid winding machine (TWM), which has a low cost, a fairly simple design and the ability to be individually configured, which will make the technology more accessible to scientific, technological and educational institutions.

Thus, the study of the modification of TWM is of considerable relevance, as it contributes to reducing the cost of equipment, accelerating the development process, automating production and increasing the versatility of the device. This opens up new opportunities for scientific and educational activities, ensuring more efficient use of resources and expanding technological capabilities in the field of manufacturing electronic components.

Problem Statement. Industrial winding machines for toroidal transformers are designed mainly for mass production, which largely determines their design solutions, functionality and cost. Types of these devices are JG-6204[3] and NTK-1[4], which, although they provide high performance, have a number of significant limitations. The vast majority of such machines have a high cost (from 3,000 US dollars), which increases the cost of production, especially in laboratories and small enterprises. The high cost is explained by the industrial high-cost production of components of winding machines and specialized control systems that are adapted to mass production.

In addition, these devices have a significant weight, which complicates their transportation and installation. For example, the mass of the NTK-1 is 460 kg, which limits its mobility and makes it impractical for use in research laboratories or small production workshops. The high weight is due to massive metal structures, which, although they provide strength, at the same time increase the costs of production and operation.

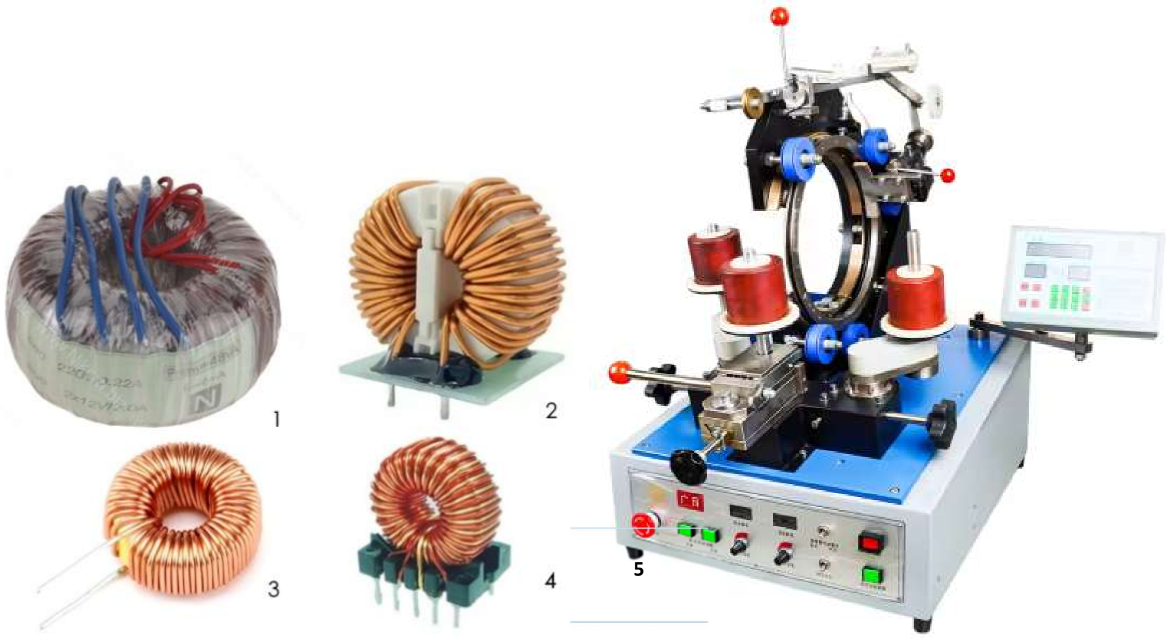


Fig. 1. Electrical products on a toroidal core:
1 – Step-down network transformer [2], 2 – Common-mode coil [2], 3 – Inductance coil [2], 4 – Four-winding choke [2]; 5 – TWM manufactured by Guangri [3]

Another significant drawback is low ergonomics and the complexity of user interaction. For example, in the JG-6204, program control is implemented through a button interface that wears out during use. The NTK-1 lacks even basic means of automation of settings, which significantly increases the requirements for operator qualifications.

Thus, the high cost, significant weight, complexity in use and insufficient automation of existing solutions create serious obstacles to small-scale production of toroidal transformers. These problems necessitate the development of a more accessible and versatile winding device that would allow for efficient wire winding on toroidal cores without significant financial and technical costs.

Analysis of recent research and publications. The development of toroidal transformer winding technologies is reflected in a number of patents that offer various approaches to automating and improving this process. Let us consider patents US4424939 [5], CN110600260 [6], US2850247A [7], US3506207A [8], US3400894A [9] and EP0190929 [10] from the point of view of their suitability for use in small-scale production, educational processes and laboratory research.

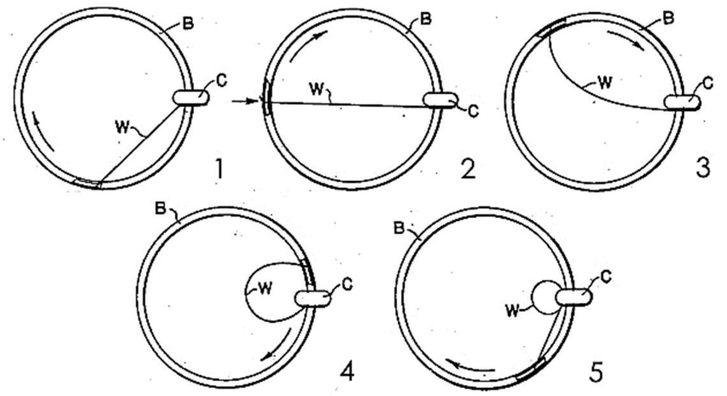


Fig. 2. Illustration from patent US2850247A [6]
stages of wire drawing on a ring-type machine
c – core, w – wire, b – bobbin

The analysis of the mentioned patents revealed both original technical solutions and most of the above-mentioned shortcomings of commercial machines, such as: complexity of design and control, high cost of manufacturing and operation, and limited flexibility and adaptability.

Additionally, the analysis of the patents revealed the following aspects that indicate their obsolescence and inconsistency with modern technological requirements:

1. Lack of flexible digital control. In many cases, the winding process is controlled using analog, mechanical, or simple digital systems with a push-button interface [3], which limits accuracy, ease of use, and repeatability of operations.

2. Use of outdated materials and technologies. Some patents describe the use of massive metal structures and traditional processing methods, which increases the weight and cost of the equipment. Modern technologies, such as 3D printing and laser cutting, allow for the creation of lighter and cheaper components with sufficient strength in small-scale production.

3. Lack of integration with modern manufacturing processes. Many of the described solutions do not take into account the possibility of integration with computer-aided design and manufacturing (CAD/CAM) systems, which is a standard in modern engineering practice.

In accordance with the above limitations, the project [11] deserves attention. This project is aimed at developing an inexpensive and easy-to-use winding machine for toroidal coils and transformers, based on the use of available materials, 3D printing technologies and laser cutting. This approach allows you to significantly reduce the cost of manufacturing equipment, while maintaining the necessary functionality and accuracy.

Thus, the analysis of existing patents and modern developments indicates the need to create affordable, flexible and technologically modern solutions for winding toroidal transformers that would meet the requirements of small-scale production, educational and scientific research.

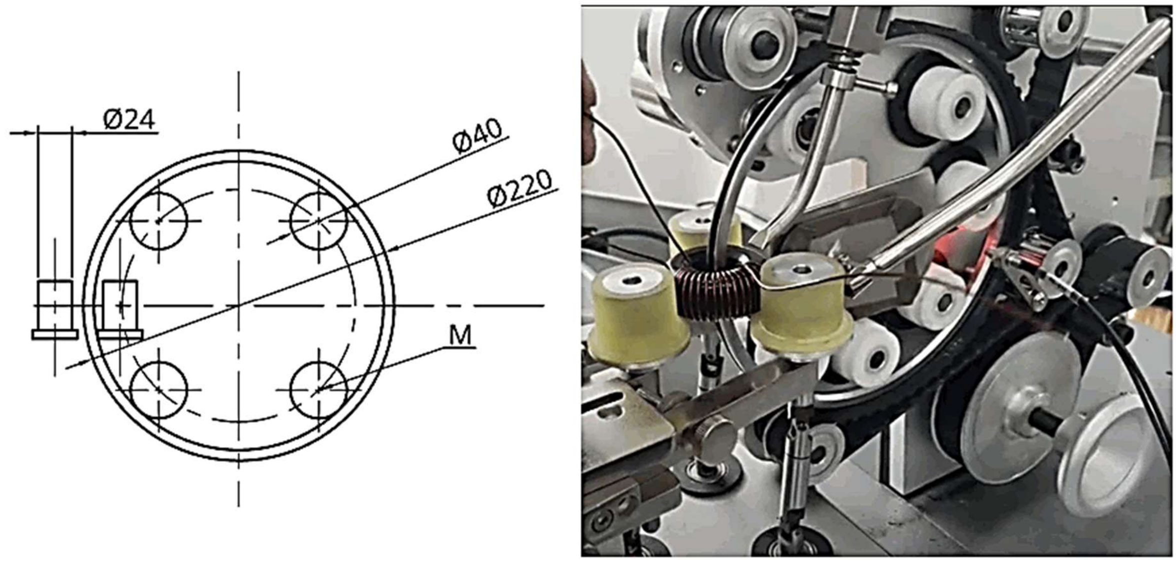
Purpose of the article. The purpose of this article is to find ways to modify the existing TWM, created as part of the project [11], taking into account its further development. The main emphasis is on improving the versatility, increasing the reliability and accuracy of operation, as well as expanding the functionality of the device without significantly increasing its dimensions and weight.

One of the important tasks is to ensure greater versatility of the device, which will allow it to be adapted to different types and sizes of toroidal cores without the need for significant design modifications. Special attention is also paid to increasing the winding accuracy, which is critically important for the quality of transformer parameters, especially in cases where the uniform distribution of turns determines the electromagnetic parameters of the product.

Maintaining the compactness and low weight of the device is another priority area of research, as this will ensure its availability for educational institutions, laboratories and small-scale production. A lightweight and compact design will facilitate transportation and installation.

In addition, an important aspect is the expansion of the device's functionality, which will allow automating some winding processes, reducing the impact of the human factor and increasing the repeatability of results. The proposed improvements are aimed at creating an effective, personalized solution for small workshops and research laboratories, which will significantly simplify the manufacturing toroidal transformers while maintaining its economic feasibility.

Main part. The winding machine considered in the thesis was created to provide an affordable and effective method of winding wire onto toroidal cores. The design solutions used in its development are partly based on the principles set forth in patents [7, 10], which describe the mechanisms for tensioning and uniform distribution of wire. The frame of the machine was made of affordable materials, which significantly reduced the cost of production. The main advantage of such a design will be its compactness and lightness. Fig. 3, *a* shows a diagram with the minimum required number of mechanical elements.



a *b*

Fig. 3.TWM mechanism:
a – Simplified scheme, M – driving roller (motor); b – Vacuz industrial TWM [12]
Source: created by the authors.

However, a number of significant shortcomings were identified during the implementation process. The main problems were the use of secondary materials and insufficient precision in the manufacture of individual parts, which reduced the repeatability and accuracy of the winding process. In addition, due to limited project funding, it was difficult to ensure sufficient structural rigidity and high quality of mechanical components. This, in turn, led to uneven wire tension and increased wear of moving parts.

To improve this design, it is first necessary to preserve the general concept of the device, since its advantages, in particular compactness and economy, remain key. At the same time, the quality of execution can be significantly improved by using modern production methods, such as 3D printing, which will ensure high precision of parts and simplify their replacement. The use of more reliable materials, in particular composites and high-strength polymers, will also contribute to increasing the durability of the device.

The user interface, which in the initial version was limited only to the ability to manually adjust the speed and set the number of turns, also needs a significant update. The introduction of a digital interface will allow the display of additional parameters, including wire tension, rotation speed and diagnostic messages. This will significantly increase the usability of the device and reduce the requirements for operator qualifications. In addition, the interface will display the estimated parameters of the transformer itself, such as: pulse power, overall power, impedance and power dissipation of the windings, transformer efficiency. Auxiliary parameters will also be calculated, such as: minimum conductor diameter, length of the conductor used – to warn the user about possible problems, or provide recommendations. To do this, the user will need to enter the following transformer parameters: K – number of windings; U_i – winding voltage, V, where i=1, 2..К; I_i – pulse current of windings, A, where i=1, 2..К; F – pulse repetition frequency, кГц; t_u – pulse duration, μs; t_{per} – permissible heating temperature of windings, °C; j – desired current density in the conductor,A/mm^2; D_{iC} – diameter of the metal conductor of the winding, mm, where i=1, 2..К; $D_{iC\ in}$ – Diameter of the conductor with insulation, mm, where i=1, 2..К; α_R – temperature coefficient of the metal to the conductor,1/°C; NN_i – number of parallel conductors in the winding, where i=1, 2..К; D_{OUT} – outer diameter of the toroid, mm; D_{INN} – inner diameter of the toroid, mm; H – height of the toroid, mm; w_i – number of turns in the winding, where i=1, 2..К;

Using the formulas from [13], we define the expressions for determining the pulse (1) and overall (effective) (2) powers of the transformer:

$$P_u = \sum_{i=2}^{k} U_i I_i; \quad (1)$$

$$\mathrm{P}_{dim} = \frac{\sum_{\mathrm{i=1}}^{\mathrm{K}} \mathrm{U_{ief}} \mathrm{I_{ief}}}{2}. \quad (2)$$

Taking the formulas from [13] for the transformer transformation ratio (3), for effective winding voltage (4), for effective winding current (5), for the effective current of the primary winding (6).

$$K_{i1} = \frac{U_i}{U_1}. \quad (3)$$

$$U_{\mathrm{ie}\phi} = U_i \frac{1}{\sqrt{Q}}. \quad (4)$$

$$I_{\mathrm{ie}f} = I_i \frac{1}{\sqrt{Q}}. \quad (5)$$

$$I_{1\mathrm{e}f} = \sum_{i=2}^{k} I_{ie} K_{i1}. \quad (6)$$

Substituting (3), (4), (5) into (2) we get (7).

$$P_{dim} = \frac{\frac{U_1}{\sqrt{Q}} \sum_{i=2}^{K} \left(\frac{I_i\ U_i}{\sqrt{Q} U_1} \right) + \sum_{i=2}^{K} \frac{U_i\ I_i}{\sqrt{Q}\sqrt{Q}}}{2}. \quad (7)$$

Simplifying expression (7), we get (8).

$$P_{dim} = \frac{1}{Q} \sum_{i=2}^{K} (U_i \cdot I_i). \quad (8)$$

Knowing that the pulse duty cycle Q is (9).

$$Q = \frac{10^3}{F t_u}. \quad (9)$$

A simplified expression for the overall power (8), provides ease of implementation in software and quick obtaining of an estimated value for the user.

To determine the minimum required conductor diameter to ensure permissible operating characteristics of the winding, we use the corresponding formula from [13] (10).

$$D_{iM} = 1.13 \sqrt{\frac{I_{\mathrm{ie}f}}{j\ NN_i}}. \quad (10)$$

To estimate the length of the conductor used, we first find the perimeter of the cross-section of the toroid (11).

$$l_{TOR} = D_{OUT} - D_{INN} + 2\text{H}. \tag{11}$$

where l_{TOR} – the perimeter of the cross-section of the toroid, mm.

Since the wire will be superimposed on the surface of the toroid, we will determine the average length of the wire used in one turn (12) by modifying the equation for the perimeter of the toroid (11) taking into account the outer diameter of the wire.

$$l_{\text{ср.в}} = D_{\text{ВН}} - D + 2H + 4D_{iCin}. \tag{12}$$

where $l_{av.w}$ – the average length of the wire used in one turn, mm.

Accordingly, the average length of the wire used in the winding will be equal to (13).

$$l_{iH} = \frac{1_{\text{ср.в}}\, w_i}{1000}. \tag{13}$$

where l_{iH} – the average length of the wire used in the winding, m.
To find the winding resistance, we use the corresponding formula from [13] (14).

$$R_i = \rho \frac{4 \cdot l_{iH} \cdot 10^8}{NN_i \cdot \pi \cdot D_{i\text{M}}^2}. \tag{14}$$

Since during the operation of the pulse transformer, the voltage and current in the windings change with the frequency F, the skin effect phenomenon occurs in the conductors in the windings. It occurs due to parasitic self-induction inside the conductor, which makes the current density in the conductor uneven. As a result, the current begins to flow closer to the surface, the higher the frequency F. As a result, the cross-section of the conductor through which the current passes decreases, the resistance of the conductor increases, and therefore the heating costs also increase.

To find the depth of the skin effect, we use the formula [14], and calculate the depth of the skin effect (15).

$$\delta = \sqrt{\frac{1}{\pi f \sigma \mu_0 \mu}}. \tag{15}$$

where δ – the depth of the skin effect, mm.

Knowing the depth of the skin effect, we calculate the effective cross-sectional area of the conductor, marked in green in fig. 4, *a*, and find the conductor diameter$D_{i\text{M}ef}$ (fig. 4-2), which corresponds to this cross-sectional area.

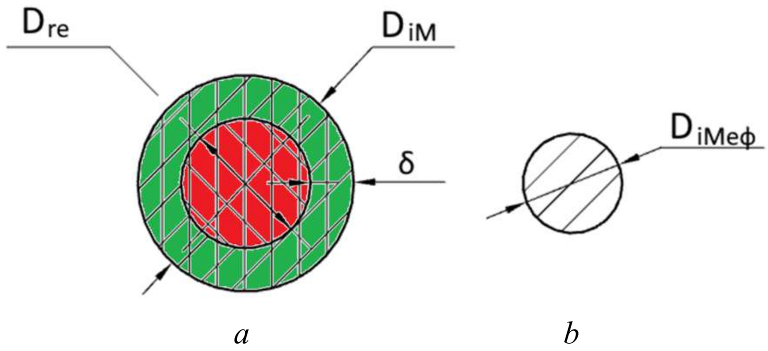


Fig. 4. The influence of the skin effect:
a – the appearance of the influence of the skin effect on the conductor;
b – the effective cross-section of the conductor taking into account the skin effect
Source: created by the authors.

First, we find the diameter of the zone that does not participate in current transfer, marked in red in Fig. 4, *a* (16).

$$D_{re} = D_{i\text{M}} - 2\delta. \tag{16}$$

Knowing the diameter of the inner zone, we find the area of the outer zone through which the current flows (17).

$$S_{ef} = \frac{\pi D_{i\mathrm{M}}^2}{4} - \frac{\pi D_{re}^2}{4}. \quad (17)$$

This area can be represented by an equivalent conductor with a diameter$D_{i\mathrm{M}ef}$,

$$\frac{\pi D_{i\mathrm{M}ef}^2}{4} = S_{ef}. \quad (18)$$

Substituting equation (16) into equation (17) and simplifying, we obtain (19).

$$D_{i\mathrm{M}ef}^2 = D_{i\mathrm{M}}^2 - D_{re}^2. \quad (19)$$

Substituting the formula for D_{re} (16) into equation (18), we obtain (20).

$$D_{i\mathrm{M}ef}^2 = D_{i\mathrm{M}}^2 - (D_{i\mathrm{M}} - 2\delta)^2. \quad (20)$$

Opening the brackets and simplifying (20), we get (21).

$$D_{i\mathrm{M}ef}^2 = 4\delta(D_{i\mathrm{M}} - \delta). \quad (21)$$

Knowing the new equivalent diameter of the conductor, we find the new resistance of the windings (22).

$$R_{ALLi} = \rho \frac{4 \cdot l_{iH} \cdot 10^8}{NN_i \cdot \pi \cdot 4\delta(D_{i\mathrm{M}} - \delta)}. \quad (22)$$

The resistance formula (22) takes into account the influence of the skin effect on the transformer windings, which makes it possible to more accurately estimate the heating losses of the windings.

Knowing the total resistance, we find the power dissipation of the winding (23).

$$P_{iM} = I_{ief}^2 R_{\mathrm{ALLi}}. \quad (23)$$

Since the windings will heat up during operation, we will find the total power dissipation at the permissible winding temperature (about 100 °C … 120 °C)[12] (24).

$$P_M = \left(1 + \alpha_R\left(t°_{\text{доп}} - t°_O\right)\right) \sum_{i=1}^{K} P_{iM}. \quad (24)$$

Knowing the total power dissipation, we find the efficiency of the transformer (25).

$$\eta_{TP} = \frac{\sum_{i=2}^{K} U_{i\text{eф}} I_{i\text{eф}}}{\sum_{i=2}^{K} U_{i\text{eф}} I_{i\text{eф}} + P_{\mathrm{M}}}. \quad (25)$$

Using the calculated values, it is possible to create a number of recommendations and warnings regarding the selected transformer parameters entered by the user. It is possible to initially configure the device before starting the wire winding process, and to provide the user with future parameters of the output transformer.

In addition to mechanical improvements, an important stage of modernization is the introduction of intelligent quality control algorithms. To implement the previously considered improvements, the use of an STM32 microcontroller will be sufficient, since it provides the necessary computing power, supports various interfaces for connecting sensors and has low power consumption. However, the key problem of all existing solutions is the lack of real quality control of winding, since most mechanisms only maintain wire tension without analyzing whether it is evenly distributed.

To solve this problem, the use of artificial intelligence is promising. The use of machine learning algorithms will allow automatically assessing the uniformity of winding, detecting defects and adjusting process parameters in real time. However, the main difficulty is the process of training and testing such algorithms, since it is necessary to collect a significant amount of data on high-quality and defective windings.

One way to solve this problem is to use the machine itself for data collection and testing algorithms. This will not only improve the quality of winding, but also create a platform for further research in the field of automation and quality control of transformer windings. Given the need to process a significant amount of information, it is advisable to use a more powerful controller or one board computer, such as RaspberryPi 5, to implement intelligent algorithms, which will provide sufficient performance for working with neural networks and analytical algorithms.

Thus, the improvement of the considered winding machine is possible through the use of modern production methods, the introduction of digital quality control systems, automation of the winding process and the use of artificial intelligence to evaluate the results of work. This will not only increase the accuracy and reliability of the device, but also make it promising for commercialization, since it will be able to compete with industrial analogues due to its low cost and flexibility in use.

Conclusions. The article considered the design of a winding machine, which is characterized by compactness and availability in production. Despite the advantages, a number of shortcomings were identified that limit the effectiveness of its application. A number of improvements were proposed, including modernization of the design, the use of higher-quality materials, the introduction of a sensor system for controlling wire tension, and automation of the winding process.

A promising direction for further research is the integration of artificial intelligence for analyzing the uniformity of winding and adaptive adjustment of process parameters. This will not only improve product quality, but also minimize the influence of the human factor. The use of modern microcontrollers and digital technologies will ensure increased efficiency and expand the functionality of the device.

Thus, the improved machine has the potential for use in scientific and educational institutions, small-scale production, and laboratory conditions, ensuring high quality winding at an affordable cost.

References

1. Yoganand Velayutham. *Introduction to Toroidal Transformers*. https://talema.com/introduction-to-toroidal-transformers/.

2. Oofitsiinyi veb-sait NIKOM – radiomarket [Official website "NIKOM – radiomarket"]. https://www.nikom.biz/.

3. JG-6204 toroidal transformer winding machine. *Aliexspres*. https://www.aliexpress.com/item/1005006596205764.html?gatewayAdapt=nld2glo.

4. Verstat namotuvannia toroidalnykh kotushok NTK-1. StandartPrybor – ofitsiinyi veb-sait. [Toroidal coil winding machine NTK-1. Official website StandartPribor] https://standart-pribor.com.ua/product/stanok-namotki-toroidalnyh-katushek-ntk-1/.

5. OHASHI TOSHIJIRO [JP]; YAMAGUCHI YASUHIRO [JP]; KOHNO MICHINAGA [JP]; KAMITA NOBU [JP]. *Apparatus for winding wire around toroidal core*. USA Patent. US4424939A. 1984-01-10. https://worldwide.espacenet.com/patent/search/family/012909961/publication/US4424939A?q=pn%3DUS4424939.

6. LI JINGUANG; LI YANGKAN. *Automatic edge sliding type annular winding machine.* China Patent. GCN110600260A. 2019-12-20. https://worldwide.espacenet.com/patent/search/family/068850201/publication/CN110600260A?q=pn%3DCN110600260.

7. Alton K Frederick. *Toroidal coil winder.* USA Patent. US2850247A. 1958-09-02. https://patents.google.com/patent/US2850247A/en?oq=US2850247A.

8. Doyle E Stoppel. *Toroidal coil winder*. USA Patent. US3506207A. 1970-04-14. https://patents.google.com/patent/US3506207A/en?oq=US3506207A.

9. Ralph A McintoshJoseph D HornakLeon J Yarrish. *Toroidal coil winding machine*. USA Patent. US3400894A. 1968-09-10. https://patents.google.com/patent/US3400894A/en?oq=US3400894A.

10. SCHLAKE, RANDALL L. HAMKINS, CLARK J. RICHERSON, JAMES D. *Apparatus and Method for Fabricating a Low Voltage Winding for a Toroidal Transformer*. European Patent. EP0190929. 05.02.1986. https://patentscope.wipo.int/search/en/detail.jsf?docId=EP11650821&_cid=P12-M8UH3A-33892-1.

11. Shevchenko-Hryshko, M. A. Namotuvalnyi stanok dlia toroidalnykh kotushok ta transformatoriv: vypuskna kvalifikatsiina robota: 171 "Elektronika", "Elektronika robotyzovanykh system ta kompleksiv"/ M. A. Shevchenko-Hryshko; kerivnyk roboty A. S. Revko; NU "Chernihivska politekhnika", Kafedra elektroniky, avtomatyky, robototekhniky ta mekhatroniky. [Shevchenko-Gryshko, M. A. Winding machine for toroidal coils and transformers: final qualification work: 171 "Electronics", "Electronics of robotic systems and complexes"/ M. A. Shevchenko-Gryshko; supervisor A. S. Revko; NU "Chernihiv Polytechnic", Department of Electronics, Automation, Robotics and Mechatronics]. – Chernihiv, 2024. – 94 p. Institutional Repository of Chernihiv Polytechnic National University https://ir.stu.cn.ua/handle/123456789/30390.

12. Change Magazine Wheel VA100-MINI VA-200V Belt Type Automatic Toroidal Inductor Core Winding Machine URL: https://youtu.be/IFnrjzNAs0U?si=y0M7TuB14Rj2uDKN.

13. Metodychni rekomendatsii z rozrakhunku impulsnykh transformatoriv / Ukl. V. M. Riadskyi, M. Ya. Velychko [Methodological recommendations for the calculation of pulse transformers / Compiled by V. M. Ryadsky, M. Ya. Velichko]. – Chernihiv: ChTI, 1993 – 60 p.

14. Shvets Ye.Ia., Chervonyi I.F., Holovko Yu.V. (2011) *Materialy i komponenty elektroniky: navchalnyi posibnyk* [Materials and components of electronics: a textbook] / Zaporizhzhia, Ukraine: Zaporizhzhia State Engineering Academy.

Список використаних джерел

1. 1. *Introduction to toroidal transformers*. (n.d.). The Talema Group. https://talema.com/introduction-to-toroidal-transformers/.

2. NIKOM – radiomarket. (n.d.). *Official website.* Retrieved from https://www.nikom.biz/.

3. JG-6204 toroidal transformer winding machine. Aliexspres. https://www.aliexpress.com/item/1005006596205764.html?gatewayAdapt=nld2glo.

4. *НТК-1 станок намотки тороидальных катушек. низкие цены. на складе в наличии.* (б. д.). ООО СтандартПрибор — стандарт качества на украинском рынке измерительной техники. https://standart-pribor.com.ua/product/stanok-namotki-toroidalnyh-katushek-ntk-1/.

5. Ohashi, T., Yamaguchi, Y., Kohno, M., & Kamita, N. (1984). *Apparatus for winding wire around toroidal core* (U.S. Patent No. US4424939A). U.S. Patent and Trademark Office. https://worldwide.espacenet.com/patent/search/family/012909961/publication/US4424939A?q=pn%3DUS4424939.

6. Li, J., & Li, Y. (2019). *Automatic edge sliding type annular winding machine* (China Patent No. CN110600260A). China National Intellectual Property Administration. https://worldwide.espacenet.com/ patent/search/family/068850201/publication/CN110600260A?q=pn%3DCN110600260.

7. Frederick, A. K. (1958). *Toroidal coil winder* (U.S. Patent No. US2850247A). U.S. Patent and Trademark Office. https://patents.google.com/patent/US2850247A/en?oq=US2850247A.

8. Stoppel, D. E. (1970). *Toroidal coil winder* (U.S. Patent No. US3506207A). U.S. Patent and Trademark Office. https://patents.google.com/patent/US3506207A/en?oq=US3506207A.

9. McIntosh, R. A., Hornak, J. D., & Yarrish, L. J. (1968). *Toroidal coil winding machine* (U.S. Patent No. US3400894A). U.S. Patent and Trademark Office. https://patents.google.com/patent/US3400894A/en?oq=US3400894A.

10. Schlake, R. L., Hamkins, C. J., & Richerson, J. D. (1986). *Apparatus and method for fabricating a low voltage winding for a toroidal transformer* (European Patent No. EP0190929). European Patent Office. https://patentscope.wipo.int/search/en/detail.jsf?docId=EP11650821&_cid=P12-M8UH3A-33892-1.

11. Шевченко-Гришко, М. А. (2024). *Намотувальний станок для тороїдальних котушок та трансформаторів: випускна кваліфікаційна робота* (Бакалаврська робота, Національний університет «Чернігівська політехніка», Чернігів, Україна). Institutional Repository of Chernihiv Polytechnic National University. https://ir.stu.cn.ua/handle/123456789/30390.

12. Change Magazine Wheel. (n.d.). *VA100-MINI VA-200V belt type automatic toroidal inductor core winding machine* [Video]. YouTube. https://youtu.be/IFnrjzNAs0U?si=y0M7TuB14Rj2uDKN.

13. Рядський, В. М., & Величко, М. Я. (1993). *Методичні рекомендації з розрахунку імпульсних трансформаторів*. Чернігів: ЧТІ.

14. Швець, Є. Я., Червоний, І. Ф., & Головко, Ю. В. (2011). *Матеріали і компоненти електроніки: навчальний посібник*. Запоріжжя: ЗДІА.

Отримано 04.09.2025

УДК 621.311.4

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ДОСЛІДЖЕННЯ СПОСОБІВ МОДИФІКАЦІЇ НАМОТУВАЛЬНОГО ВЕРСТАТУ ДЛЯ ТОРОЇДНИХ ТРАНСФОРМАТОРІВ

У роботі розглядається процес проєктування та виготовлення намотувального верстата для тороїдальних сердечників, спрямований на зниження виробничих витрат та покращення доступності у дрібносерійному виробництві. Аналіз існуючих рішень, у тому числі і закордонних патентів, визначив ключові недоліки, до яких входять і недостатня жорсткість конструкції та нерівномірний натяг дроту під час намотування. Для вирішення цих проблем запропоновані вдосконалення, які передбачають використання передових виробничих технологій, таких як 3D-друк та лазерне різання, впровадження системи моніторингу на основі оптичних датчиків, зокрема і системи машинного зору, та повну автоматизацію процесу намотування.

Значна увага приділяється можливості потенційного застосування алгоритмів машинного навчання для підвищення якості процесу намотування. Інтеграція штучного інтелекту в систему може забезпечити виявлення дефектів у режимі реального часу, дозволить виконувати адаптивне налаштування параметрів та контролювати якість із мінімальним втручанням людини-оператора. Окрім того, в дослідженні акцентується увага на використанні сучасних мікроконтролерів та одноплатних комп'ютерів, включаючи STM32 та RaspberryPi 5, які застосовуються для обробки та керування даними в режимі реального часу. Наведені математичні вирази, що можуть використовуватися в програмному забезпеченні намотувального верстата для розширення його функціоналу.

Запропоновані вдосконалення сприяють створенню ефективного, економічно доцільного та універсального намотувального верстата, придатного для лабораторних застосувань та дрібносерійного виробництва. Завдяки впровадженню цифрових систем керування та забезпечення якості процесу намотування на основі штучного інтелекту вдосконалена конструкція має потенціал конкурувати з рішеннями промислового класу, зберігаючи при цьому доступність широкому загалу та маючи гнучкість для подальших вдосконалень.

***Ключові слова:** намотувальний верстат; тороїдні осердя; трансформатор; автоматизація; машинне навчання; мікроконтролер; цифровий інтерфейс; Raspberry Pi; електропривід.*

Рис.: 4. Бібл.: 14.

Yevdokymov O., Kolesnyk V., Dovhopolov A., Bykov M., Fesenko D. Research on methods of modification of winding machine for toroid transformers. *Technical sciences and technologies,* (3(41)), 432-441. DOI: https://doi.org/10.25140/2411-5363-2025-3(41)-432-441.