METHODOLOGY FOR CREATING AND CONDUCTING RESEARCH ON DIGITAL TWINS OF TRANSFORMERS AT THE STAGE OF RESEARCH WORK

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ABSTRACT

The article is devoted to the problems of creating simulation models of products (transformers) based on the concept of digital twins, since due to the rather large spread in the properties of electrical materials, models of this level need to be corrected for the information received from a really working device. The authors propose a methodology for the development of digital twins for transformers, which will ensure cost reduction, reduce the time spent on their design. The theoretical and methodological base of the research is based on the scientific works of Russian specialists, as well as on the use by the authors of various numerical methods for modeling physical circuits in the Matlab environment. The authors propose a methodology for the development and application of the concept of digital twins of transformers, which will optimize and improve the process of developing and making design decisions.

Keywords: *Digital Twin, Intelligent Monitoring System, Power Transformers, Simulation, Dynamic Models, Life Cycle.*

1. INTRODUCTION

To date, the world is actively developing a new innovative concept of industry "Industry 4.0", which was initiated by the fourth industrial revolution. Computer technologies are the structural basis of this concept and are used not only for the collection, processing and subsequent analysis of huge arrays of data / information, but also for the design of unique virtual high-precision prototypes of technical products, which allows research and improvement of the performance of devices at all stages without exception, product life cycle [1]. The general set of provisions that are associated with the development process and the subsequent use of digital twins of products in the Russian Federation are prescribed in the relevant state standard (GOST R 57700.37-2021). So, according to this standard, the use of digital twins of products in industrial production is a process of development of the existing paradigm of computer-digital engineering of products [2]. This paradigm defines a digital twin as a kind of unique entity, within which various multicomponent mathematical models are combined, which allow to fully describe the technical components of the product, to systematically approach the process of its development, production and subsequent operation [3]. In this case, the importance of obtaining an ambivalent information connection, which is formed between various model data and a real physical device, is emphasized in a special way. So far, digital twins can be classified into three different types:

- digital twin is a prototype, imitates a certain conditional physical object, can be used to create a physical real prototype;
- digital twin is an instance that allows you to describe a specific physical object that is associated with the entire life cycle, it also includes a basic 3D model that contains various specifications and other technical information;
- aggregated digital twin is a system that includes a "prototype" and a "copy".

Within the framework of the conducted scientific research, a digital twin is understood as a multi-component model, which is calibrated according to measurement data obtained on the basis of the operation of a real physical device. The purpose of the study is to develop a methodology for designing digital twins of transformers, which will significantly reduce the cost of production, optimize the design time, and also qualitatively increase the degree of reliability and efficiency of subsequent operation [4].

The objects of the research given in the article are electrical transformers, including power ones. The subject of the study are models of transformers, which should provide an accuracy rate of about 92% -96% when making calculations. To achieve this goal, the following tasks were identified:

- development of a methodology for the design and use of digital twins based on simulation models of transformers, considering the introduction of appropriate adjustments to them based on the practical results obtained;
- design of new and transformation of existing algorithms, within the framework of the relevant software notations, whose task is to organize instrumental support for the developed methodology.

2. METHODOLOGY

The level of technology for calculating transformers has allowed them to approach the level at which their actual life can be more than 50 years. The problem of improving the level of quality was dealt with by many scientists and specialized specialists, research institutes and specialized institutes [5]. The theoretical and methodological base of the research is based on the scientific works of Russian specialists in the field of CAD, such as: Kruzhaev A.V., Daryan L.A., Starozhuk E.A., Shubenkova K.A. and many others.

In the works of the authors, in particular, it is noted that the key goal of designing a digital twin is to ensure the necessary level of reliability of transformers and reduce the costs associated with operation by developing and making optimal decisions that are based on the values of diagnostic criteria obtained using the digital twin. The development of a digital twin involves solving a range of tasks related to data analysis, machine learning and interdisciplinary modeling. The main tasks in this case are:

- organizing the choice of methodological support for the digital twin;
- designing the architecture of the future digital twin;
- organization of data collection and analysis, including technical assessment of the transformer design level;
- development of models for diagnosing defects and assessing the state of the transformer.

To date, models of transformer operating modes have become an integral part of CAD, which allows evaluating and analyzing the efficiency of the product being created, using a numerical experiment. Modern CAD systems are built on the basis of a modular principle, which means that independent subsystems that are used to calculate non-stationary physical fields, which are called engineering analysis systems, should be responsible for the operation of this procedure [6]. In the Russian Federation, for the process of designing transformers, many high-tech enterprises use specialized ANSYS Maxwell software simulation packages, as well as a universal numerical simulation environment for any design direction COMSOL Multiphysics. Simulation models of transformers, characterized by a high level of accuracy, can be implemented on the basis of circuit theory [7]. To date, there are quite a large number of systems that have embodied various theoretical concepts in the field of circuit theory. The most popular in the Russian Federation at present is the Matlab Simulink software package, with the SimSpace simulation base integrated into it for various groups of physical processes.

To solve the problems, theoretical studies were carried out using numerical methods for modeling physical circuits implemented in such software environments as Matlab and Excel, numerical methods for calculating electromagnetic fields using EMLib physical field simulation library and experimental studies using experiment automation methods. Methods of system analysis, methods of operations research and scheduling theory, models and methods for constructing networks of needs and opportunities (PV-networks), set theory, methods of formalized representation of knowledge and construction of ontologies for decision support are used. The reliability and validity of the results obtained in the course of the study is confirmed by the use of proven methods of mathematical modeling, comparison of the calculation results with the results obtained on the tested models and the developed experimental setup.

3. RESULTS AND DISCUSSION

The structural composition of the complex methodology for designing a digital twin of a transformer includes various simulation models for constructing transformers, corrective methods based on data obtained as a result of ongoing experiments [8]. The methods of practical application of the proposed methodology may have certain different ones, which depend on at what stage of the life cycle this methodology will be used. The digital twin of a transformer can be used at the following stages of the product life cycle [9]:

1. Research work and development work allows conducting research on nonstandard options for creating transformers, studying the possible consequences of decisions taken by the company's specialists in terms of making changes to the design features of the transformer being created;
2. Design allows double-checking and clarifying the parameters of earlier calculations for the creation of transformers, has a close relationship with the technological cycle of the production process, also includes an analysis of various modes of operation of the device;
3. Production allows identifying various defects in already released products, making certain adjustments to the already existing digital twin of standard devices [10];
4. Operation allows identifying defects in already operating transformer equipment, and then developing decisions on the advisability of its subsequent use in the event of a breakdown or other unforeseen circumstances.

If a high-tech enterprise does not have the necessary experience in the design and production of special types of transformers, then it is necessary to carry out work that corresponds to the stages of research and development. The production of a digital twin in the form of a digital prototype will make it possible already at the research and development stage to simulate the process of operation of the device being created in various modes, and will allow taking into account a number of different unique specific design features when designing [11]. The use of a digital prototype at the stage of research and development will make it possible to eliminate the need for the production of experimental types of products (Figure 1).

The methodology for creating and conducting research on non-standard versions of transformers based on the application of the concept of a digital twin at the R&D stage is the following algorithm (Figure 2):

First step. The basic data used to create a digital prototype are the requirements specified in the terms of reference. The main provision in this case is the requirements for the execution of the future transformer [12]. The need to develop a digital prototype is the lack of a valid proven methodology in production that would allow the necessary calculations to be carried out.

Second step. Search for information related to possible future versions of a device of this type, for example, search for patents or scientific papers. However, the search for such information in modern conditions is quite complicated, since such information is a trade secret. Available information, in open sources, will not be enough to develop terms of reference [6].

Third step. Having at your disposal enough data on the design of the active part of the device, you can begin to design a model of a magnetic / electric circuit. These models can subsequently be combined into a common simulation model, which is a digital prototype of the transformer:

- development of a unique scheme of the transformer magnetic circuit based on the data on the design features of the magnetic circuit;
- development of a system of equations for a magnetic circuit;
- creation of a simulation model, for example, in a system such as Matlab Simulink, which as a result will allow solving systems of magnetic circuit equations in the form of a matrix;
- designing a scheme for organizing connections of various winding elements based on the data on the design features of the used windings;
- designing a model of a future electrical circuit based on information, taking into account losses in steel and using controlled types of sources for the directions of the magnetizing current [13].

Fourth step. The output information in this technique can be, for example, the results of studies of a digital prototype in completely different modes of operation:

- data on the efficiency and correctness of the operation of the circuit that connects the elements of the windings;

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- conclusions about the correctness of the selected types of connections of the elements included in the magnetic circuit [14];
- clarification of possible voltage losses that may be caused by short circuits.

When designing a digital twin of a transformer, accuracy sufficient for engineering calculations can be obtained using 2D magnetic field models. The authors decided to use a dynamically linked library for calculating the magnetic field EMLib. This library is integrated into MSExcel software package, which in turn has a built-in VBA programming system. VBA macros were written for automatic generation and numerical study of the transformer field model for the refined calculation of current and no-load losses. In the latter case, the following formula was used:

$$P_0 = \gamma \times k_r^v \times k_r^e \times k_z \sum_{k=1}^{N_s} [p(B_{mk}) \times S_K] + \\ + \sum_{i=1}^{N_{st}} [\sqrt{2}\, S_{ai} P_{st} (\frac{B_{mi}}{\sqrt{2}})],$$

where γ is density indicator of electrical steel;
k_r^v and k_r^e are technological groups of coefficients;
N_s is the number of triangles that are filled with steel;
$p(B_{mk})$ is specific indicator of steel losses within the k-th triangle at maximum induction indicators;
N_{st} is the number of joints (oblique) between rods and yokes;
S_{ai} is the indicator of the area of the i-th joint;
$P_{st}(B_{mi})$ is the specific loss index within the i-th junction at the maximum induction index.

The method of practical application of digital twins of a transformer at the stage of scientific research is based on the idea of designing a simulation model of a transformer of an atypical design, followed by a study on the digital twin of a transformer of the features of this type of device. This allows to almost completely get rid of the need to create the construction of prototypes and also makes it possible to develop a methodology for designing devices of a non-standard design. At the design stage, the digital twin of the transformer plays the role of a digital prototype of the designed device. It can also be applied at the stage of extended verification calculation, which is carried out in the form of a numerical experiment on the digital twin of the transformer. As a result, this will make it possible to evaluate the features of the device being designed in various modes under the conditions of a particular electrical network. In addition, the practical application of the digital twin of the transformer will make it possible to adapt the selected (or developed) design methodology to the conditions of a particular production by considering the technological features of the technological cycle of this production. To do this, it is supposed to create a digital twin of a transformer of a serial device by calibrating its simulation model according to the results of acceptance tests (reference copy of the transformer). This will not only correct the accepted standard design methodology for this class of devices, but also simplify the process of rejecting low-quality products by comparing the results of acceptance tests with the results of studying the digital twin of the transformer, which will increase the reliability of the finished product.

4. CONCLUSIONS

The key advantage of the proposed methodology is the possibility of conducting research on non-standard variations in the design of transformers at the research and development stage, without creating real prototypes of products, as well as the opportunity to develop design methods associated with the creation of devices of non-standard designs that can be effectively adapted to production conditions. Each model created at the stage of research and development will require a specific study of its theoretical aspects with the involvement of the mathematical apparatus. Further development of the issues identified in the article related to the development and research of the digital twin of the transformer should be aimed at concretizing the accounting for various groups of stray magnetic fluxes, which as a result will make it possible to more accurately simulate the operation of the device, both in transient and emergency modes. So a specialist with all the necessary competencies in the field of design will be able to independently find an additional range of opportunities and adjust the methodology based on the data obtained from the analysis of the digital twin. Undoubtedly, invariance is the main advantage of the method proposed by the authors. The designer is given all the necessary tools to fine-tune it to solve the problems of organizing production.

The developed technique for creating and using digital twins of power transformers involves a radical restructuring of the very idea of the design process. This is expressed in the use of simulation models for the analysis of various modes of operation of the designed device, which can be carried out both at the stage of research and development and at the stage of verification calculation, which is usually not provided for in CAD transformers. At the stages of design and production, the use of a digital twin in the form of a digital prototype can reduce the cost and design time, as well as the number of defects, and increase the reliability of newly created devices. A digital twin of a device instance is created at the stage of acceptance testing of finished products. The digital twin created in this way is then used at almost all subsequent stages of the product life cycle, in particular, at the operation stage, which makes it possible to optimize the operation and repair modes by timely diagnosing a malfunction of the magnetic system. Further development of the problem of creating and studying digital twins of transformers is seen in the direction of more accurate accounting of stray magnetic fluxes, which will allow more accurate modeling of transient and emergency modes, as well as in the direction of creating digital twins of special transformers and transformers of atypical design.

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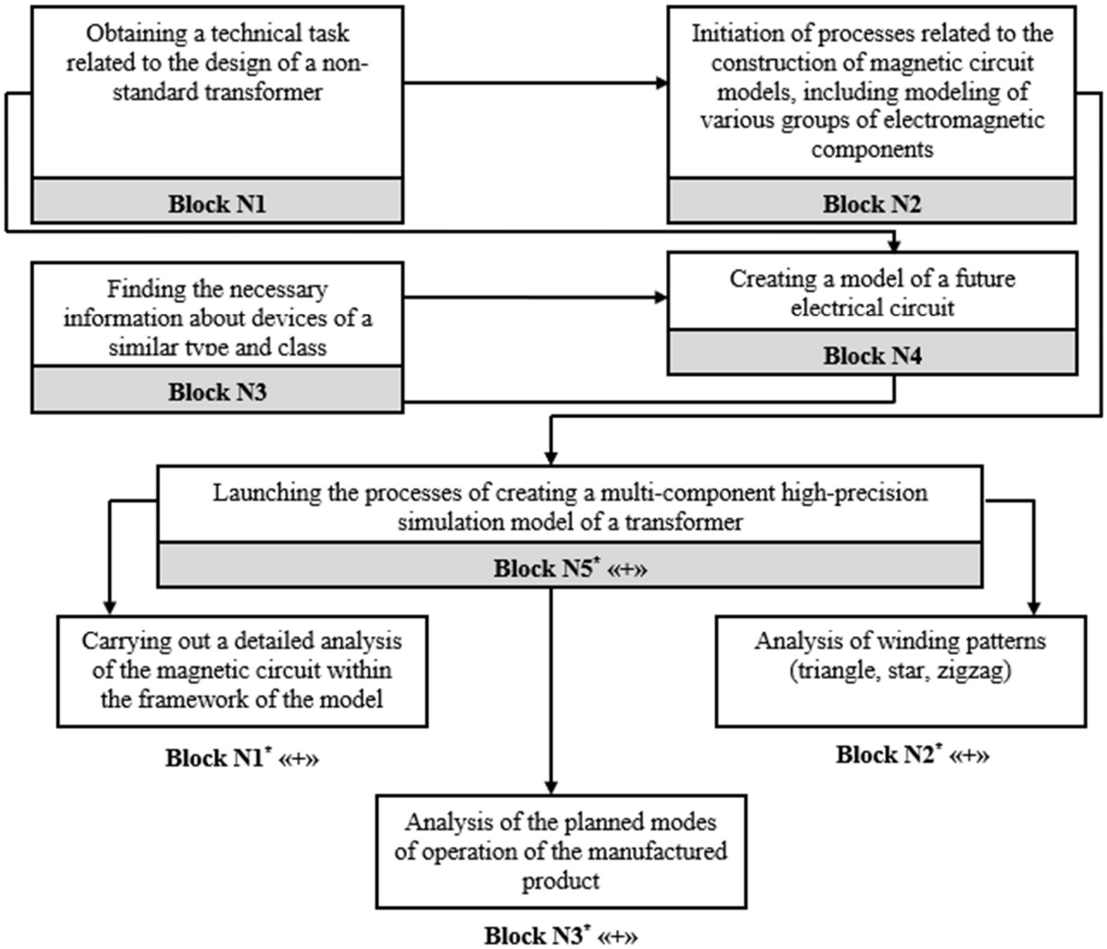

Figure 1. The basic set of provisions included in the methodology for creating and conducting research on digital transformer twins at the research stage

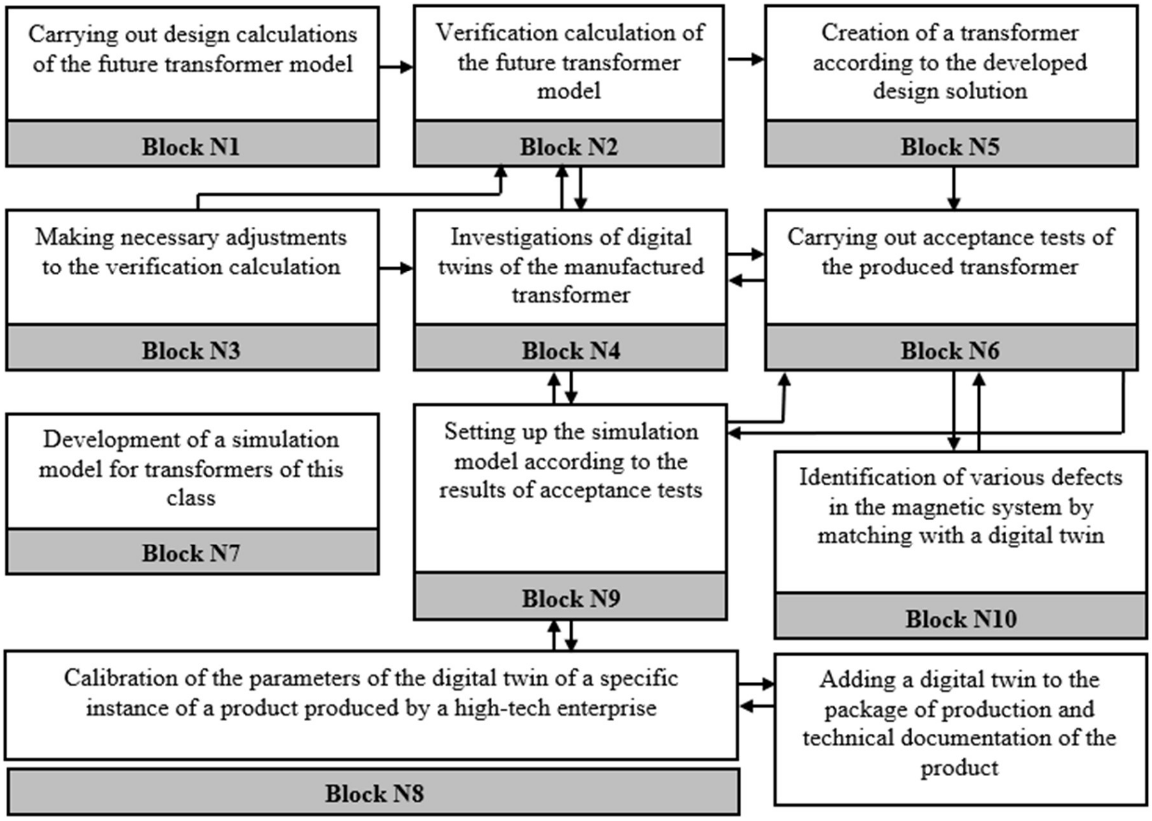

Figure 2. Basic provisions included in the methodology for the development and use of digital transformer transformers at the stages of creating production