A DIGITAL TWIN DESIGN OF INDUCTION MOTOR WITH SQUIRREL-CAGE ROTOR FOR INSULATION CONDITION PREDICTION

Vladyslav Pliuhin[1], Sergiy Zaklinskyy[2], Sergiy Plankovskyy[1], Yevgen Tsegelnyk[1], Oleksandr Aksonov[1], Volodymyr Kombarov[1, 3]
[1] O.M. Beketov National University of Urban Economy in Kharkiv, Kharkiv, Ukraine
[2] National Aerospace University "Kharkiv Aviation Institute", Kharkiv, Ukraine
[3] Czech Technical University in Prague, Faculty of Mechanical Engineering, Department of Production Machines and Equipment (RCMT), Prague, Czech Republic
Email: y.tsegelnyk@kname.edu.ua

Abstract – The purpose of this paper is to develop a digital twin of induction motor with a squirrel-cage rotor. The problem of efficient operation of electric motors is primarily related to the reliability of insulation. Meanwhile, there is no such device that could show the operator at least an approximate value of the insulation resource on the display and warn about possible emergency situations when the current loads of the windings of the electric machine increase. To solve this problem, you can use modern technology based on Digital Twins. The paper analyzes existing developments in this area and draws conclusions about research directions. The construction of a reduced-order model (ROM) for an induction motor with a squirrel-cage rotor and the layout structure of the blocks of such a model in ANSYS Twin Builder are shown. As input data for the model, archival records of laboratory studies of readings of stator winding currents, rotation speed, temperature, torque on the shaft and others, which were kept from the built laboratory stand, were used. The simulation results indicate the acceptable accuracy of the obtained results, which indicates the possibility of using the developed digital twin of the induction motor both for further deeper research and improvement, and for experimental developments.

Keywords: Digital Twin, Optimization, Control System, ANSYS Twin Builder, Reduced Order Model, Controller, Motor.

1. Introduction

Digital Twins (DT) are a powerful tool that changes the design, manufacture, and operation of products and processes. They display the real object in the virtual world, allowing for virtual experiments, testing, and optimization, which significantly reduce the time and costs of development and production [1–4]. DT can be used to create virtual models of production and operation processes, which allows for analysis and optimization directly at the design and production stage [5, 6]. This direction is related to the use of digital models to analyze and optimize the operation of technical systems in real time. It includes the use of analytical methods and algorithms to analyze and optimize production processes, such as the assembly and testing processes of devices, and the production of parts, machines, and other components [7]. In accordance with the strategy of the Industry 4.0 [8, 9], as well as with flexibility, productivity, and automation, requirements are placed on the digitization of production processes and the design of Digital Twins processes. A DT is created as a virtual copy of a physical object for use as a simulator, predictive model, and/or tool for diagnosing and adjusting equipment through real-time monitoring. In controlling the technological process, the DT process allows for testing and verifying different flow strategies, while the performance of the control system depends on the available sensors and executive mechanisms of the DT [10–16]. Optimizing production processes can include reducing waste, increasing productivity, improving product quality, and reducing production time. DT allows you to virtually test different production scenarios and experiment with different equipment settings, which allows you to find optimal solutions before the actual start of production. The use of DT allows you to get a detailed analysis of the operation of the technical system in real time, which allows you to identify possible problems and avoid unforeseen situations. The use of DT allows considering all the parameters that affect the operation of the system, such as temperature, humidity, pressure, etc. [17, 18].

In the field of operation, DT can be used to predict the technical condition of equipment and prevent emergency situations. With the help of virtual models, it is possible to monitor and diagnose the state of equipment, which allows you to make predictions about possible breakdowns and carry out scheduled maintenance. In addition, DT can be used to analyze the impact of changing conditions on production and operational processes, such as changes in the composition of raw materials or changes in production parameters. This makes it possible to determine optimal working conditions and increase production efficiency [19, 20].

Another important direction in the development of DT is the integration of artificial intelligence (AI) and machine learning (ML) technologies [21–23]. AI and ML algorithms can be used to analyze data collected from sensors and other sources to identify patterns and anomalies, predict and optimize performance. In addition to AI and ML, another new technology that is expected to have a significant impact on the development of DT is the Internet of Things (IoT) [24]. IoT devices such as sensors and actuators can be integrated into digital counterparts to collect data from physical assets in real-time. This data can be used to monitor and optimize performance and to identify potential problems before they become serious [25].

In this investigation a combination of remote control with the function of analyzing the obtained results and forecasting the condition of the equipment is implemented. Thus, the simple direct management, which was previously supplemented by a research module, significantly increases the level of training of future specialists.

ANSYS Twin Builder is an environment for building models of electrical, mechanical, and other systems. With this tool, you can build an induction motor model by specifying parameters such as stator type, rotor size, magnetic field parameters, etc. [26]. In addition, other drive components such as inverters, controllers, and sensors can be included in the model. ANSYS Digital Twin is a tool for creating DT of real systems. This tool allows you to integrate an induction motor model built with ANSYS Twin Builder with data from a real induction motor used in a real drive. At the same time, it is possible to provide a more accurate simulation of the operation of a real system. ANSYS Twin Builder is a key part of the multi-domain model-oriented design in leading enterprises in the automotive, aerospace, energy, electronics, and industrial equipment industries. Extensive integration capabilities of power electronics, dynamic models of various fields of physics, and embedded software allow you to use Twin Builder for the deployment of Digital Twins, electric drive design, electromechanical systems, power generation, conversion, and distribution systems, EMI/EMC research, general optimization and verification of multi-domain systems.

One of the examples of the use of DT is the reservoir filling by gas mixture components developed by the authors of this paper [14] (Fig. 1). In accordance with the concept of digitalization of modern production in relation to the researched technology of thermal pulse processing, the need for DT development for the inherent separate physical and chemical processes is substantiated.

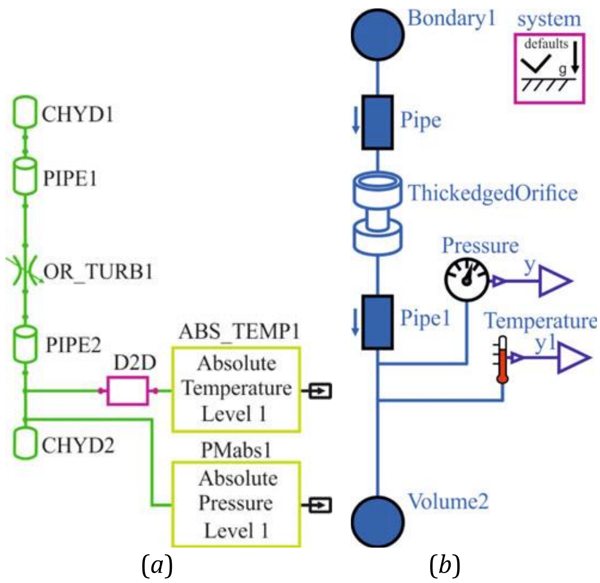

Figure 1: A DT of the reservoir filling subsystem by the gas mixture component, created using the Twin Builder standard library (a) and using the component-oriented Modelica language (b) [14]

A DT is a real-time, virtual copy of an actual operating machine that provides insight into individual product performance and maintenance. Sensors on the machine relay data – temperature, pressure, flow rate, voltage, loading, etc. – to the digital twin, and the twin evolves in step with the machine's working environment.

The DT can then use physics-based simulation to predict conditions long before they happen, so you can monitor the twin and replace a distressed component – or take other corrective actions – during scheduled downtime, rather than making an untimely shutdown.

The insulation of electric machines determines the safety of operation, and the service life of the insulation is equal to the service life of the electric machine. Many studies have been devoted to the question of determining the service life of insulation, and one of them is a modern approach based on Digital Twins.

Another example is the development of electric cars [15, 16]. The advance of new technology and electric cars has been taking place recently. As a result, many companies want to ensure their electric engines are the best in the market regarding reliability, autonomy for the client, and durability.

Therefore, these companies perform tests digitally to prevent any damage to the actual product and find the best temperature interval in which the engines work the best. Having robust rotor and stator temperature estimators helps the automotive industry improve their motors, reducing power losses and, eventually, heat build-up.

The purpose of this paper is to solve the following problems with the help of the introduction of Digital Twins of an induction motor: calculate the real-time temperature of the rotor, stator, and case; determine the expected lifetime of the motor, and plan for optimal maintenance schedules (avoiding unscheduled downtime).

2. Research Methodology

In order to place model reduction in a mathematical context, it is necessary to realize that many models developed in computational science consist of a system of partial and/or ordinary differential equations, supplemented with boundary conditions. When partial differential equations are used to describe the behavior, one often encounters the situation that the independent variables are space and time. Thus, after discretizing in space, a system of Ordinary Differential Equations (ODE) is obtained in time. For example, consider the following explicit finite-dimensional dynamical system:

$$\frac{dx}{dt} = f(x,u),$$
$$y = g(x,u).$$

where u is the input of the system, y is the output, and x is the state variable.

The complexity of the system is characterized by the number of its state variables, i.e. the dimension n of the state space vector x. Model Order Reduction can be viewed as the task of reducing the dimension of the space vector $x(n)$ while preserving the character of the input-output relations. This means find a dynamical system with the form

$$\frac{d\hat{x}}{dt} = \hat{f}(\hat{x},u),$$
$$y = \hat{g}(\hat{x},u).$$

where the dimension of $\hat{x}$ is much smaller than n.

The dynamical system can be represented as an input-output system, as shown in Fig. 2. It is this setting in the creation of the model that led to the creation of reduced-order models, which in this paper is applied to the induction motor. The fundamental methods in the area of Model Order Reduction were published in the eighties and nineties of the past century (Fig. 3). In more recent years such research has been done in this area, developing a large variety of methods where some are tailored to a specific application, others are more general [27–29].

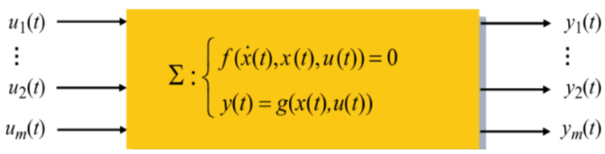

Figure 2: 6-poles input-output system

In the laboratory of the automated electric drive and electrical devices of the O.M. Beketov National University of Urban Economy in Kharkiv developed a laboratory stand that combines technical equipment with its digital counterpart (Fig. 4).

The ATV320 frequency converter, M241 digital controller, HMIST-U human-machine interface touch panel, current, voltage, speed feedback modules, power supply, control and parameter registration units are presented at the stand. All devices are manufactured by Schneider Electric with licensed software. An induction motor with a squirrel-cage rotor with a capacity of 1 kW manufactured by ABB is connected to the control system. It was this electric motor that became the object of research – its DT was implemented in the ANSYS Twin Builder.

The condition or integrity of the electric motor is monitored remotely. The electric motor has voltage and current sensors, the load is regulated using an electromagnetic brake. The frequency converter is connected to the software on the computer via a digital controller. The appearance of the structural model of the controller is shown in Fig. 5.

The DT of this motor is built as a result of previous multiphysics 3D modeling and collapsed into a reduced-order model (ROM), the so-called ROM model (Fig. 6). The ROM model, unlike the simulation models of other software products, such as Matlab/Simulink, and SciLab, is not a compilation of systems of differential equations, but a multi-gigabyte storage of complete information about the magnetic, electrical, thermal, and mechanical states of an electric machine [30–33].

Such a model does not need any sensors and works synchronously with a real machine. The power signals that enter the input of the real motor are digitally duplicated through the controller to the power input of the ROM model. It is physically impossible to install a temperature sensor on the rotor of a real motor because the rotor rotates. Instead, temperature analysis can do a DT and output that information to a computer display or a digital panel on a lab bench. The correctness of the model is determined by preliminary testing of the duplicate and the real object and comparing their characteristics. If the readings are synchronized, the model is ready for use [34].

In Fig. 7 shown the use of a DT in operation – through the sensor, the current of the electric motor is measured and in real-time the digital double provides the value of the current and future temperature in real-time.

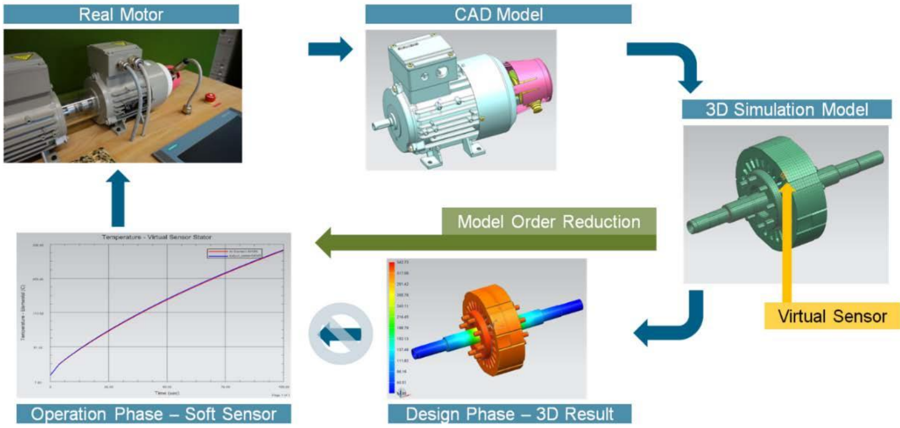

Figure 3: Model Order Reduction advantages on closed loop electric motor control drives

Figure 4: Laboratory stand for the study of a controlled induction electric drive

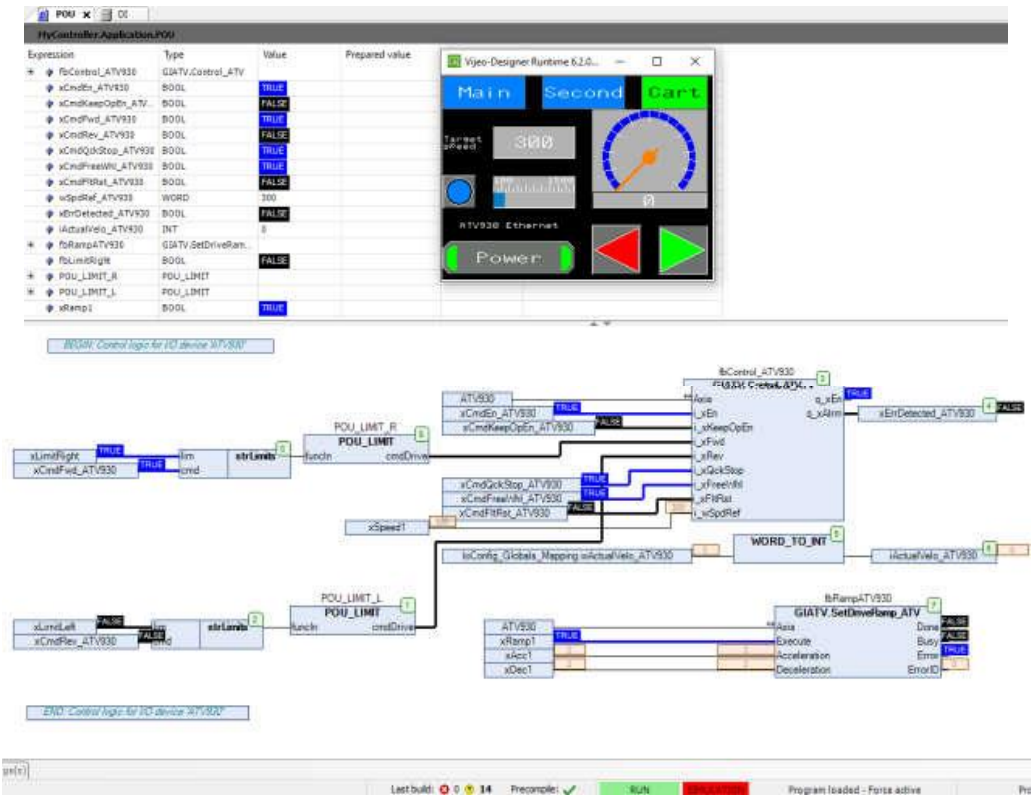

Figure 5: The model of working out the digital and analog signals of the controller

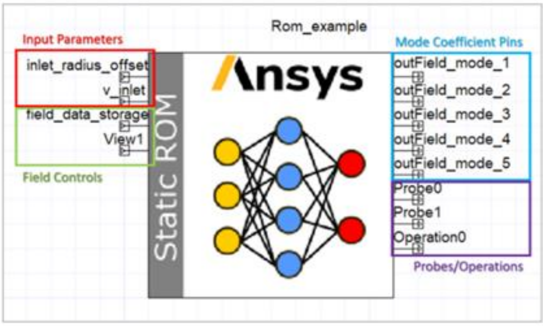

Figure 6: An example of a reduced-order ANSYS model control element

3. Simulation Results

Sensors on the machine transmit data – voltage and current – to a DT, and the double evolves according to the machine's operating environment. The DT can then use physics-based simulations to predict emergency conditions long before they occur, so the twin can be controlled and replaced in advance without prematurely stopping operations, replacing a damaged component, or taking other corrective actions, such as during planned downtime.

The developed DT can automatically determine the current and predict the future maximum engine temperature in real-time based on the current (Fig. 8, 9). The DT can be exported and deployed on an IoT platform to predict the remaining useful life of an engine for predictive maintenance purposes.

Thus, DT can be used in university laboratories to simulate and reproduce physical experiments, processes, and systems. This can have several advantages, including:

- *Savings*: DTs can save universities money by reducing the need for expensive laboratory equipment and materials;
- *Flexibility*: DTs allow students and researchers to experiment with different variables and scenarios without the constraints of physical equipment or space;
- *Safety*: DTs can provide a safe environment for students to practice experiments and procedures without the risk of injury or equipment damage.
- *Collaboration*: DTs can facilitate collaboration between students and researchers from different locations and disciplines, providing a common platform for experimentation and analysis.

Overall, DTs can enhance the learning experience for students and researchers by providing a dynamic, flexible, and secure laboratory environment that supports innovation and discovery.

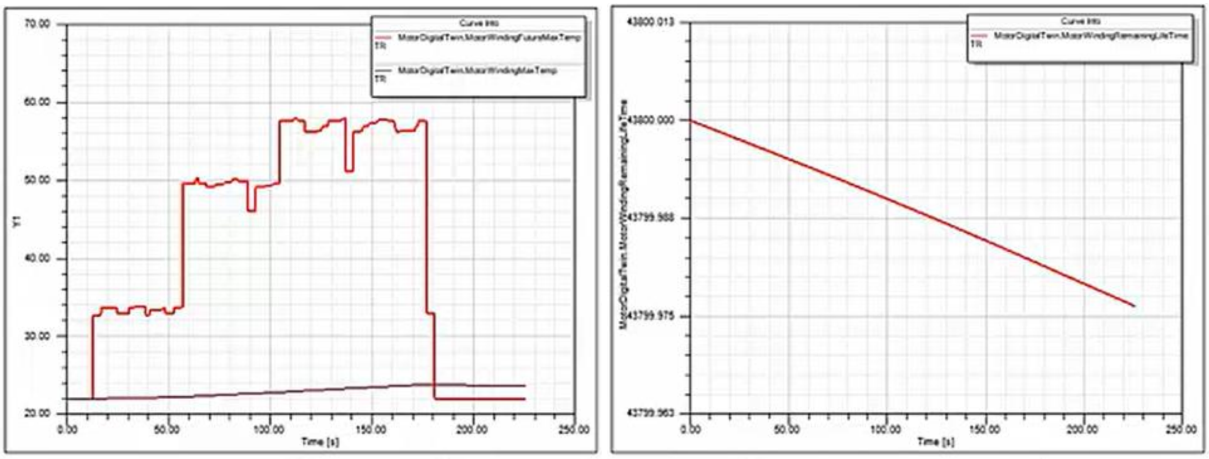

Figure 7: Laboratory tests of a DT

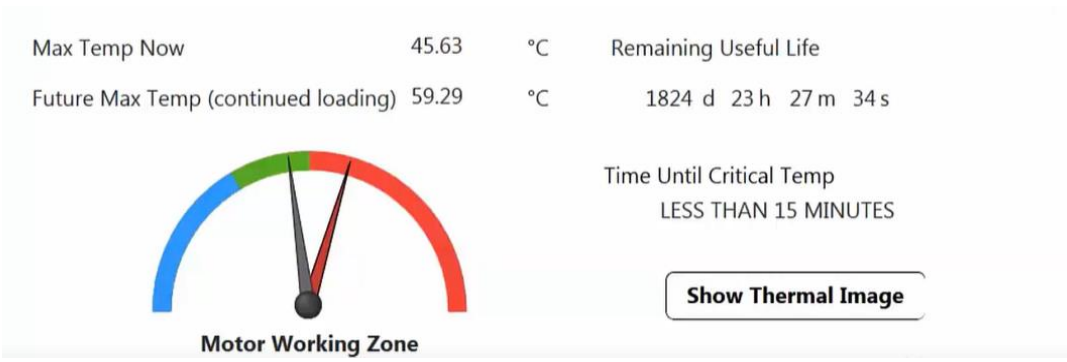

Figure 8: Digital panel of the current thermal state of the motor

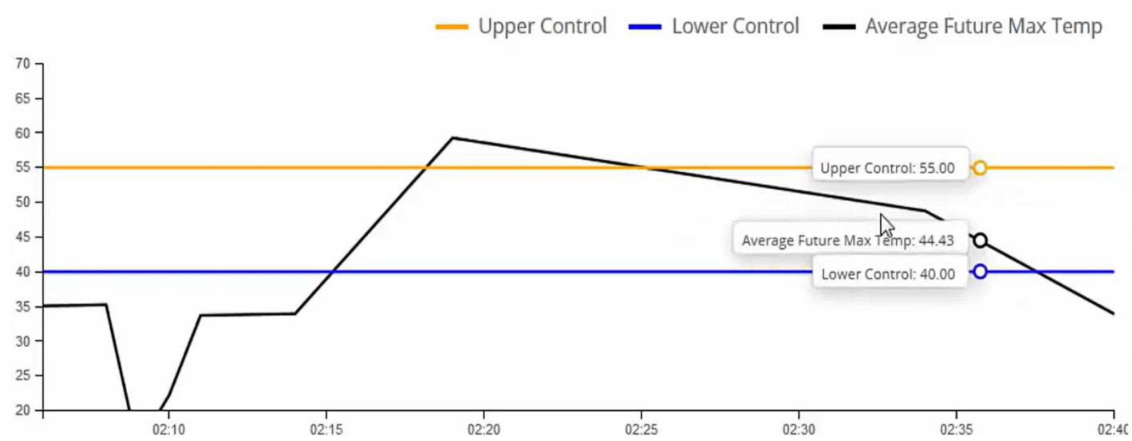

Figure 9: Control of the motor temperature level in a DT

4. Conclusions

The use of ANSYS Twin Builder and ANSYS Digital Twin allowed for the creation of a more accurate and realistic digital twin of an induction motor with an electric drive, which can be used to investigate the operation of real electric drives with induction motors and improve their efficiency and reliability. The features of the induction motor operation by the method of thermal analysis and the corresponding determining equations for the components of the life cycle as well as the time predicted stable work are given. A reduced-order model (ROM model, ANSYS Ice Pack) of an induction motor was developed and used in the ANSYS Twin Builder for the construction of the DT.

The conducted studies prove that the use of DTs allows to reduce the time and costs of testing new designs of electric drives and provides more accurate predicted operation of the system. In addition, it makes it possible to conduct virtual testing of various options for solving the problem, which reduces risks and contributes to more effective problem-solving in electric drives.

Acknowledgement

This research is supported by the Ministry of Education and Science of Ukraine as a part of the scientific research project No. 0122U001145.

References

[1] Singh, M., Fuenmayor, E., Hinchy, E.P., Qiao, Y., Murray, N., & Devine, D. (2021). Digital twin: Origin to future. *Applied System Innovation, 4*(2), 36.

[2] Kombarov, V., Sorokin, V., Tsegelnyk, Y., Plankovskyy, S., Aksonov, Y., & Fojtů, O. (2021). Numerical control of machining parts from aluminum alloys with sticking minimization. *International Journal of Mechatronics and Applied Mechanics, 1*(9), 209–216.

[3] Xu, L. D., Xu, E. L., & Li, L. (2018). Industry 4.0: state of the art and future trends. *International journal of production research, 56*(8), 2941–2962.

[4] Reed, S., Löfstrand, M., & Andrews, J. (2021). Modelling cycle for simulation digital twins. *Manufacturing Letters, 28*, 54–58.

[5] Schluse, M., Priggemeyer, M., Atorf, L., & Rossmann, J. (2018). Experimentable digital twins – Streamlining simulation-based systems engineering for industry 4.0. *IEEE Transactions on Industrial Informatics, 14*(4), 1722–1731.

[6] Aksonov, Y., Kombarov, V., Fojtů, O., Sorokin, V., & Kryzhyvets, Y. (2019). Investigation of processes in high-speed equipment using CNC capabilities. *MM Science Journal, 2019*(04), 3271–3276.

[7] Cimino, C., Negri, E., & Fumagalli, L. (2019). Review of digital twin applications in manufacturing. *Computers in industry, 113*, 103130.

[8] Qi, Q., Tao, F., Hu, T., Anwer, N., Liu, A., Wei, Y., ... & Nee, A. (2021). Enabling technologies and tools for digital twin. *Journal of Manufacturing Systems, 58*, 3–21.

[9] Söderberg, R., Wärmefjord, K., Carlson, J.S., & Lindkvist, L. (2017). Toward a Digital Twin for real-time geometry assurance in individualized production. *CIRP Annals, 66*(1), 137–140.

[10] Aksonov, Y., Kombarov, V., Tsegelnyk, Y., Plankovskyy, S., Fojtù, O., & Piddubna, L. (2021). Visualization and analysis of technological systems experimental operating results. In *2021 IEEE 16th International Conference on Computer Sciences and Information Technologies (CSIT)* (Vol. 2, pp. 141–146). IEEE.

[11] Brovkova, M., Molodtsov, V., & Bushuev, V. (2021). Implementation specifics and application potential of digital twins of technological systems. *The International Journal of Advanced Manufacturing Technology, 117*, 2279–2286.

[12] Kritzinger, W., Karner, M., Traar, G., Henjes, J., & Sihn, W. (2018). Digital Twin in manufacturing: A categorical literature review and classification. *IFAC-PapersOnline, 51*(11), 1016–1022.

[13] Robles, J., Baca, G., Chong, J., & Gonzales, S. (2021). Nonsingular terminal sliding mode control for a variable speed wind turbine system using face mock-up interface co-simulation. In *2021 11th International Conference on Power, Energy and Electrical Engineering (CPEEE)* (pp. 158–164). IEEE.

[14] Shypul, O., Garin, V., Tkachenko, D., Zaklinskyy, S., Tryfonov, O., Plankovskyy, S. (2023). Development of a digital twin of reservoir filling by gas mixture component. In S. Shkarlet, A. Morozov, A. Palagin, D. Vinnikov, N. Stoianov, M. Zhelezniak, V. Kazymyr (Eds.) *Mathematical Modeling and Simulation of Systems*. LNNS, vol. 667 (pp. 85–98). Springer.

[15] Bhatti, G., Mohan, H., & Singh, R.R. (2021). Towards the future of smart electric vehicles: Digital twin technology. *Renewable and Sustainable Energy Reviews, 141*, 110801.

[16] Zhang, Z., Zou, Y., Zhou, T., Zhang, X., & Xu, Z. (2021). Energy consumption prediction of electric vehicles based on digital twin technology. *World Electric Vehicle Journal, 12*(4), 160.

[17] Zhou, K., Pries, J., & Hofmann, H. (2015). Computationally efficient 3-D finite-element-based dynamic thermal models of electric machines. *IEEE Transactions on Transportation Electrification, 1*(2), 138-149.

[18] Krukovskyi, P.G., Diadiushko, Y.V., Garin, V.O., Tryfonov, O.V., & Kabanov, Y.Y. (2020). CFD model as a digital twin of the radiation state of the new safe confinement of the Chernobyl NPP. *Problems of Atomic Science and Technology, 128*(4), 54-62.

[19] Schilders, W. (2008). Introduction to model order reduction. In W. Schilders, H. van der Vorst, J. Rommes (Eds.) *Model Order Reduction: Theory, Research Aspects and Applications*. TECMI, vol. 13 (pp. 3–32). Springer.

[20] Brandtstaedter, H., Ludwig, C., Hübner, L., Tsouchnika, E., Jungiewicz, A., & Wever, U. (2018). Digital twins for large electric drive trains. In *2018 Petroleum and Chemical Industry Conference Europe (PCIC Europe)* (pp. 1–5). IEEE.

[21] Alexopoulos, K., Nikolakis, N., & Chryssolouris, G. (2020). Digital twin-driven supervised machine learning for the development of artificial intelligence applications in manufacturing. *International Journal of Computer Integrated Manufacturing, 33*(5), 429–439.

[22] Groshev, M., Guimarães, C., Martín-Pérez, J., & de la Oliva, A. (2021). Toward intelligent cyber-physical systems: Digital twin meets artificial intelligence. *IEEE Communications Magazine, 59*(8), 14–20.

[23] Rathore, M.M., Shah, S.A., Shukla, D., Bentafat, E., & Bakiras, S. (2021). The role of AI, machine learning, and big data in digital twinning: A systematic literature review, challenges, and opportunities. *IEEE Access, 9*, 32030–32052.

[24] Kaur, M.J., Mishra, V.P., Maheshwari, P. (2020). The convergence of digital twin, IoT, and machine learning: Transforming data into action. In M. Farsi, A. Daneshkhah, A. Hosseinian-Far, H. Jahankhani (Eds.) *Digital Twin Technologies and Smart Cities*. ITTCC (pp. 3–17). Springer.

[25] Hartmann, D., Herz, M., Wever, U. (2018). Model order reduction a key technology for digital twins. In W. Keiper, A. Milde, S. Volkwein (Eds.) *Reduced-Order Modeling (ROM) for Simulation and Optimization* (pp. 167–179). Springer.

[26] Demir, U., & Aküner, M.C. (2018). Design and analysis of radiaxial induction motor. *Electrical Engineering, 100*, 2361–2371.

[27] Pliuhin, V., Plankovskyy, S., Zablodskiy, M., Biletskyi, I., Tsegelnyk, Y., Kombarov, V. (2023). Novel features of special purpose induction electrical machines object-oriented design. In D.D. Cioboată (Ed.) *International Conference on Reliable Systems Engineering (ICoRSE) – 2022*. LNNS, vol. 534 (pp. 265–283). Springer.

[28] Pliuhin, V., Tsegelnyk, Y., Plankovskyy, S., Aksonov, O., Kombarov, V. (2023). Implementation of induction motor speed and torque control system with reduced order model in ANSYS Twin Builder. In D.D. Cioboată (Ed.) *International Conference on Reliable Systems Engineering (ICoRSE) – 2023*. LNNS, vol. 762 (pp. 514–531). Springer.

[29] Pliuhin, V., Zablodskiy, M., Tsegelnyk, Y., & Slovikovskyi, O. (2022). Development of imitation model of an electromechanical energy converter with a solid rotor in ANSYS RMxprt, Maxwell and Twin Builder. *Lighting Engineering & Power Engineering, 61*(1), 21–29.

[30] Rasheed, A., San, O., & Kvamsdal, T. (2020). Digital twin: Values, challenges and enablers from a modeling perspective. *IEEE Access, 8*, 21980–22012.

[31] Lopes, T.D., Raizer, A., & Valente Júnior, W. (2021). The use of digital twins in finite element for the study of induction motors faults. *Sensors, 21*(23), 7833.

[32] Falekas, G., & Karlis, A. (2021). Digital twin in electrical machine control and predictive maintenance: State-of-the-art and future prospects. *Energies, 14*(18), 5933.

[33] Adamou, A.A., & Alaoui, C. (2023). Energy efficiency model-based Digital shadow for Induction motors: Towards the implementation of a Digital Twin. *Engineering Science and Technology, an International Journal, 44*, 101469.

[34] Aksonov, Y., Tsegelnyk, Y., Piddubnyi, O., Kombarov, V., Plankovskyy, S., & Piddubna, L. (2022). Interactive design of CNC equipment operator panels. *International Journal of Mechatronics and Applied Mechanics, 2022*(12), 156–162.