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DIGITAL TWINS IN ENERGY: INFORMATION TECHNOLOGIES IN MANAGEMENT SYSTEMS AND THEIR IMPACT ON RESOURCE SAVING

Volodymyr MIKHALEVICH, Doctor of Technical Sciences, Professor
Mykola KOLISNYK, Doctor of Philosophy, Senior Lecturer
Leonid YAROSHENKO, Candidate of Technical Sciences, Associate Professor
Anatolii SLOBODYANYK, Candidate of Technical Sciences, Associate Professor
Vinnytsia National Agrarian University

МИХАЛЕВИЧ Володимир Маркусович, д.т.н., професор
КОЛІСНИК Микола Анатолійович, д.ф., ст. викладач
ЯРОШЕНКО Леонід Вікторович, к.т.н., доцент
СЛОБОДЯНИК Анатолій Дмитрович, к.т.н., доцент
Вінницький національний аграрний університет

The article presents the results of a comprehensive study on the implementation of digital twins in control systems for energy facilities using modern hardware and software complexes. Special attention is devoted to analyzing various approaches to building integrated models that combine real physical processes with their virtual analogs in a unified cyber-physical environment. The rationale for selecting the technological base for the development of digital twins in automation systems is provided, focusing on the use of SIMATIC S7-300 programmable logic controllers, Siemens Micromaster 440 frequency converters, and the PROFIBUS industrial communication interface. Such a configuration ensures reliable two-way data exchange between virtual and physical components and enables real-time synchronization of operational parameters.

The principles of two-way synchronization between the digital twin and the physical object in real time are described in detail. Examples of hardware–software integration between PLCs, HMI panels, and communication modules are presented, illustrating the bidirectional flow of information and control signals. The requirements for the mathematical model of the energy process are defined, and a method for its implementation based on dq-coordinate transformation is proposed. This mathematical model allows accurate representation of the electromagnetic and mechanical behavior of an asynchronous motor under variable operating conditions, providing a realistic simulation environment for testing control algorithms before they are applied to the physical system.

The main stages of constructing a digital twin are outlined, including the development of the structural scheme of the control system, description of physical interconnections, selection of model parameters, and formulation of control algorithms. Special emphasis is placed on ensuring data consistency between the simulation environment and the real system, which is achieved through continuous information exchange via industrial networks such as PROFIBUS and MPI. The digital twin architecture developed in this study supports cyclic data updating with minimal delay, ensuring the stability of real-time control processes and the reliability of feedback loops.

The research also explores the practical use of digital twins to improve the operational efficiency of energy systems. It demonstrates their potential for real-time equipment diagnostics, prediction of failure conditions, and optimization of maintenance schedules. A specific example of implementing a digital twin in the control process of an asynchronous electric drive with frequency regulation is presented, highlighting the benefits of predictive monitoring, virtual commissioning, and parameter optimization. The study proves that digital twins can significantly enhance energy efficiency by 10–15%, reduce downtime by up to 30%, and increase the overall reliability and transparency of energy management systems.

The obtained results confirm that the integration of digital twin technology into control systems for energy facilities substantially improves regulation accuracy, reduces maintenance time, and provides a means for real-time visualization and data archiving. Furthermore, the proposed approach lays the groundwork for developing the next generation of intelligent energy systems that combine simulation, data analytics, and automation into a single adaptive framework. Such systems represent an essential step toward the realization

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of Smart Energy and Industry 4.0 paradigms, where each component of the infrastructure is represented by a dynamic, self-updating virtual counterpart.
Key words: *Digital twin, energy facility, automation, PLC, Micromaster 440, WinCC Flexible, PROFIBUS.*

Eq. 3. Fig. 8. Ref. 18.

1. Problem formulation

Modern energy facilities operate under conditions of increasing complexity, variability of loads, and stringent requirements for energy efficiency and reliability. Conventional PLC-based control systems are primarily reactive: they respond to parameter deviations after they occur and do not provide mechanisms for predictive analysis of equipment behavior. As a result, energy drives and auxiliary systems often operate in non-optimal modes, leading to excessive power consumption, accelerated wear of electromechanical components, and unplanned downtime. Existing automation solutions lack an integrated environment in which the real object and its mathematical model function as a single cyber-physical system with continuous bidirectional data exchange in real time [1-3] .

The key scientific and practical problem is the absence of a unified approach that combines accurate electromechanical modeling of energy processes with direct implementation on industrial hardware platforms. Most existing studies either remain at the level of simulation or rely on software-only digital twins without tight coupling to real PLC-controlled equipment. This creates a gap between theoretical optimization and actual industrial operation. Therefore, it is necessary to develop and validate a hybrid digital twin architecture that operates on real Siemens PLCs and drives, ensures real-time synchronization via industrial networks, and enables predictive control, virtual commissioning, and adaptive optimization of energy systems under real operating conditions [4].

2. Analysis of recent research and publications

The rapid development of digital modeling technologies and cyber-physical systems has led to the active implementation of the Digital Twin (DT) concept in modern industry, energy systems, and automation. The idea of creating a digital replica of a physical object was first formulated by Michael Grieves (2003) within the framework of Product Lifecycle Management (PLM), which assumed the parallel existence of a physical entity, its digital counterpart, and a bidirectional information flow connecting them. Subsequent studies (Grieves, 2015; Tao, 2019) defined the digital twin as an integrated, multi-level model capable of reflecting the current state of a system, predicting its behavior, and enabling optimization of control and maintenance processes throughout its lifecycle [1-3].

A significant contribution to the theoretical foundations of digital twin technology was made by Tao, Zhang, Liu, and Nee (2019), who introduced the so-called “five-dimension architecture” of the digital twin: physical space, virtual space, data connection, service layer, and intelligent algorithms. The authors emphasize that one of the primary challenges is ensuring real-time synchronization between the digital model and the physical object, as well as establishing flexible mechanisms of feedback that allow for dynamic adaptation to changing conditions. In their comprehensive studies, Fuller, Fan, Day, and Barlow (2020) analyzed the integration of digital twins into the control systems of complex industrial facilities, focusing on accurate physical modeling, standardized communication protocols, and ensuring data security in distributed industrial environments[4-15].

In the field of industrial automation, digital twins are being actively developed and implemented by major global corporations such as Siemens, General Electric, Schneider Electric, and ABB, which create comprehensive hardware–software ecosystems for the design of “virtual factories.” Of particular importance are Siemens solutions within the TIA Portal platform, which integrates PLC, HMI, SCADA, and simulation tools into a single environment. The company’s technical documentation (“Micromaster 440 Operating Instructions,” 2018; “WinCC Flexible Configuration Manual,” 2020) presents detailed methods for constructing motor drive models and embedding them into virtual control systems. According to Siemens AG research, the use of digital twins enables preliminary testing and optimization of control algorithms, reducing commissioning time by up to 30% and significantly improving the reliability of automation systems [16-18]..

Domestic researchers also make a valuable contribution to the digitalization of energy systems. In the works of Kuzmenko A.O. and Boiko M.S. (2021), an innovative concept of intelligent control systems for energy processes is proposed, in which the digital twin is regarded as a fundamental tool for optimizing energy consumption and predicting the condition of technical equipment. The authors demonstrate that digital models can serve as the foundation for transitioning from reactive to proactive maintenance strategies, where the system automatically analyzes parameter deviations, detects early signs of malfunction, and issues preventive alerts to maintenance personnel.

Moreover, numerous contemporary studies highlight the use of digital twins in the context of Industry 4.0 and the emerging paradigm of Energy 5.0, which combine automation, artificial intelligence, and cloud computing. Reports of the European Energy Research Alliance (EERA, 2022) underline the role of digital twins in forming Smart Grids, capable of forecasting load fluctuations, managing energy flows, and maintaining grid stability in real time through distributed control. Within the Ukrainian context, similar approaches are already being applied in the automation of electric drives, ventilation systems, water supply infrastructure, and industrial energy management systems.

Despite the significant scientific and practical progress achieved, the literature review reveals a lack of comprehensive solutions that combine accurate mathematical modeling of electrotechnical processes with real industrial hardware implementation based on PLC systems. In most publications, researchers focus either on theoretical modeling without considering the specific features of physical realization, or on software tools without adequate representation of real physical dynamics. This gap highlights the need for research aimed at the development of integrated, hybrid systems, in which the digital twin not only mirrors the operation of an energy facility but also actively influences it in real time through adaptive control algorithms.

Therefore, the conducted analysis indicates that further research in this domain should concentrate on creating hybrid digital twin models that merge analytical equations with empirical and data-driven methods, ensuring system adaptability to external conditions and real-time feedback. Such integration enables the establishment of a closed information loop connecting the physical object, the PLC-based control unit, and its digital replica. This approach defines the scientific novelty and practical value of the present work, which focuses on the implementation of digital twin technologies in energy control systems using real Siemens industrial components – providing a foundation for the evolution of intelligent, autonomous, and energy-efficient control infrastructures of the future.

3. The purpose of the article

The purpose of this work is to develop a methodology for constructing a digital twin of an energy facility control system based on real industrial components – the Siemens Micromaster 440 frequency converter and the SIMATIC S7-314C 2DP controller – integrated within a PROFIBUS network and the SIMATIC OP170B HMI panel.

4. Results and discussion

A digital twin of an energy facility represents an integrated dynamic system that combines a virtual mathematical model with a real physical object through a continuous bidirectional exchange of information. This interaction enables the virtual model to reproduce the real operation of equipment with high accuracy, evaluate the influence of external and internal factors, predict potential failures, and optimize operational modes even before direct intervention in the physical technological process. Essentially, the digital twin acts as a virtual counterpart of the energy system that evolves simultaneously with its physical prototype, maintaining real-time synchronization of states and parameters.

In the field of energy engineering, digital twins are increasingly used for modeling the full cycle of energy processes – including generation, transformation, distribution, and consumption of electrical power. They provide the foundation for implementing intelligent methods of control, monitoring, and diagnostics, ensuring high efficiency and reliability of energy conversion systems. Unlike traditional automation systems that primarily perform data acquisition and signal processing, the digital twin concept introduces an interactive feedback loop, where the virtual model not only observes but also influences the behavior of the physical system through adaptive control algorithms and real-time optimization. This approach supports predictive and condition-based maintenance, reduces unplanned downtimes, and enhances overall energy efficiency.

The developed system described in this study is built upon the Siemens technological platform, which integrates hardware and software tools into a unified control architecture. The core components include the Siemens Micromaster 440 frequency converter, the SIMATIC S7-314C 2DP programmable logic controller (PLC), and the SIMATIC OP170B human–machine interface (HMI). Data transmission between these elements is carried out through the PROFIBUS and MPI industrial communication networks, which provide high-speed, deterministic, and reliable data exchange within the system hierarchy. This configuration ensures seamless communication between the control, power, and visualization levels, enabling accurate coordination of process variables and control commands.

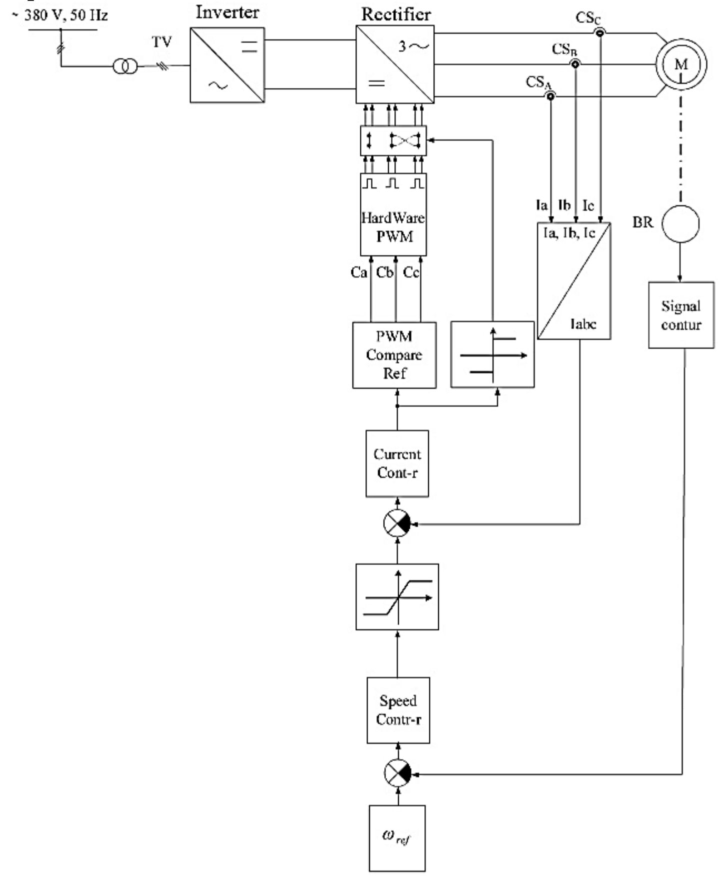

Fig. 1. Digital Twin Control System Architecture

At the physical layer, the system comprises an electric motor, current and speed sensors, thermal sensors, and actuators that interact directly with the controlled process. These devices generate real-time measurement data that form the input for the digital twin's computational model. The PLC performs data acquisition, signal filtering, and the implementation of control algorithms, including automatic start–stop sequences, protection logic, and closed-loop regulation of motor speed and torque.

The human–machine interface (HMI) plays a crucial role in facilitating operator interaction with both the physical system and its digital counterpart. The SIMATIC OP170B panel displays real-time information on operational parameters, system status, and simulated variables from the digital twin, providing visualization and diagnostics capabilities. Through the HMI, the operator can monitor equipment performance, modify control setpoints, and observe the immediate response of the virtual model, which mirrors the physical process behavior.

This continuous synchronization between the real and virtual domains ensures transparency, safety, and controllability of the system, forming a solid foundation for the development of intelligent, adaptive, and self-learning energy control solutions.

The mathematical modeling of the digital twin is based on the equations of electromagnetic processes in an induction motor expressed in d_q-coordinates. This approach makes it possible to describe both the steady-state and dynamic operating modes of the electric drive.

The main system of equations can be represented as follows:

$$\frac{d\psi_d}{dt} = U_d - R_s i_d + \omega\psi_q \quad \frac{d\psi_q}{dt} = U_q - R_s i_q - \omega\psi_d \tag{1}$$

where U_d, U_q – stator voltage projections, i_d, i_q – stator currents, R_s – active resistance of the winding, ψ_d, ψ_q – communication flows, ω – communication flows. Quantities ψ_d i ψ_q form a coordinate system that rotates with the rotor field, which simplifies the calculation of the parameters of the electromechanical process. Based on this model, the electromagnetic torque of the motor is determined, which is the main indicator of the efficiency of the electric drive:

$$M_e = \frac{3}{2} p(\psi_d i_q - \psi_q i_d) \tag{2}$$

where p – number of pole pairs. The developed model enables a detailed evaluation of the relationships between electromagnetic torque, current, voltage, and supply frequency, which provides the foundation for accurate prediction of mechanical load and optimization of energy consumption under variable operating conditions. By simulating the interaction between electrical and mechanical subsystems, the model reflects the real dynamic behavior of the induction motor during acceleration, steady-state operation, and transient load changes. This makes it possible to analyze performance parameters such as torque ripple, slip variation, and efficiency losses, which are essential for energy-efficient control strategies in industrial drives.

Within the digital twin, the mathematical model performs the function of a virtual replica of the electric motor, continuously synchronized with real-time data from the physical system. The virtual environment reproduces the operational behavior of the motor driven by the frequency converter, thus enabling predictive analysis and the optimization of control algorithms before applying changes to the actual hardware. The model also allows for testing of various operating scenarios – such as variable frequency control, sudden load torque changes, or voltage fluctuations – without interrupting the real process. In this way, the digital twin serves as an intelligent simulation and diagnostic tool, enhancing both the reliability and flexibility of the overall control system.

The parameters of the electric drive are calculated on the basis of the energy characteristics of the motor, taking into account rated power, nominal voltage, efficiency, and load torque curves. These parameters are used to tune the equivalent circuit of the machine and to ensure the accuracy of dq-model equations in both stationary and transient conditions. The power of the frequency converter, which defines its ability to supply energy to the drive under different loads, is determined according to the following relationship:

$$P_{PC} = \frac{k \cdot P_{dv.n}}{\eta} \quad (3)$$

where k=0,95 – current distortion factor, $P_{\text{dv.n}}$=2,2 kW – rated engine power, η=0,81 – efficiency. Rated power P_{PC}=2,6 kW confirms the feasibility of choosing the Siemens Micromaster 440 converter, which has a rated power 3 kW and overload capacity 1.7. This converter provides smooth speed control and stable operation of the electric drive under variable loads.

To establish communication between the physical equipment and its digital model, the system employs the PROFIBUS industrial communication network, which serves as the backbone for real-time data exchange and control synchronization. PROFIBUS provides bidirectional communication between the programmable logic controller (PLC), the frequency converter, sensors, and the digital twin software module. It ensures a high-speed data transmission rate of up to 12 Mbit/s and supports cyclic and acyclic communication, which allows continuous exchange of process data and control information between the hardware components and the virtual model.

One of the key features of PROFIBUS is its deterministic data transmission, meaning that each device communicates according to a predefined time schedule controlled by the master node – typically the PLC. This guarantees the timely delivery of control commands and measurement signals with predictable latency, which is essential for maintaining synchronization between the digital twin and the real system. The protocol architecture includes several communication layers that handle physical transmission, data link management, and application services, ensuring both reliability and electromagnetic noise immunity – critical in industrial energy environments.

In the developed system, data exchange is implemented through structured telegrams, consisting of two main information fields: the Parameter Channel Words (PKW) and the Process Data (PZD) areas. The PKW area contains control and status words used for configuring devices, managing operating modes, and transmitting diagnostic information, while the PZD area carries the cyclic process data – such as instantaneous current, voltage, temperature, speed, and torque values. These telegrams form the communication backbone of the system, enabling the frequency converter and the PLC to coordinate control actions and maintain accurate process feedback.

Fig. 2. Appearance of the Micromaster 440 frequency converter

Fig. 3. PROFIBUS communication module

Control commands such as frequency setpoints, torque references, and rotational direction instructions are transmitted from the PLC to the converter via PZD telegrams, while the converter simultaneously sends feedback signals representing actual process variables. This two-way synchronization allows the digital twin to receive continuously updated data from the physical object with a refresh rate of 10–20 milliseconds, ensuring near real-time interaction between the simulation environment and the actual hardware. Consequently, the digital twin can monitor the instantaneous condition of the system, verify the correctness of control algorithms, and promptly respond to operational deviations, thereby bridging the gap between the physical and virtual domains.

The SIMATIC S7-314C 2DP programmable logic controller performs the functions of data acquisition, processing and transmission. Its architecture allows you to implement speed, torque and stop control algorithms for the electric drive, as well as coordinate several frequency converters. The controller has a sufficient amount of memory (96 KB), advanced communication capabilities, high speed and built-in analog inputs for reading sensor signals.

Fig. 4. PLC Siemens S7-314C 2DP

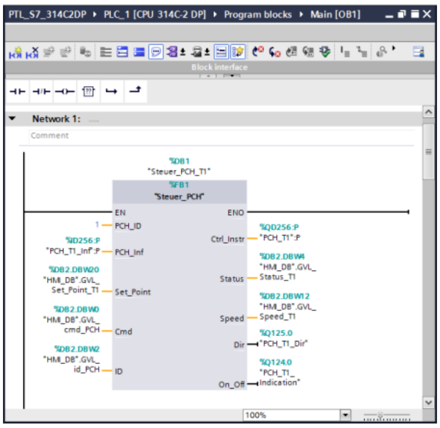

Fig. 5. Subroutine Steuer_PCH

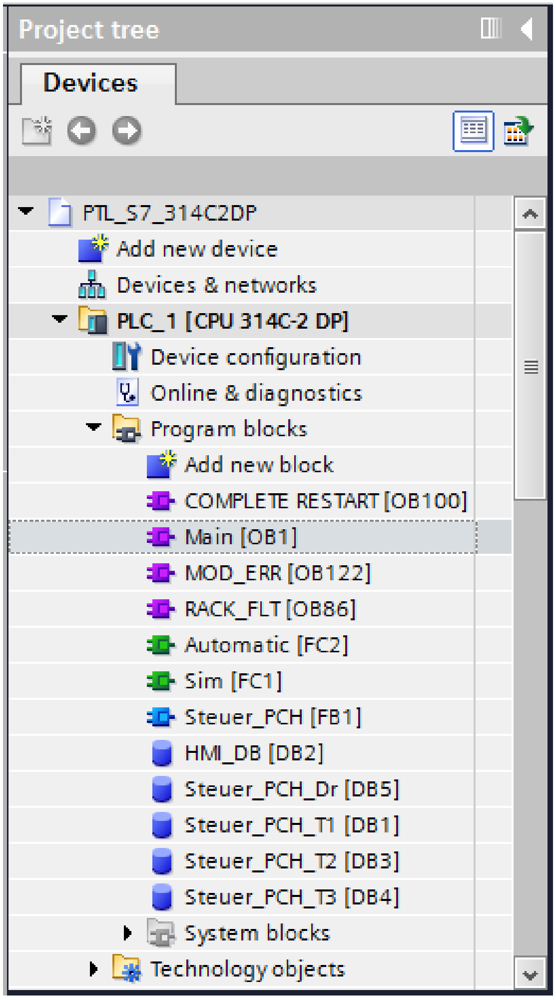

Fig. 6. Program block structure

The Human–Machine Interface (HMI) represents an essential component of the digital twin system, as it provides the means for visualizing data, monitoring parameters, and facilitating direct operator interaction with the control environment. In the developed configuration, the SIMATIC OP170B panel, implemented within the WinCC Flexible environment, serves as the primary communication point between the operator and both the virtual and physical domains of the system. The interface enables real-time observation of equipment status, displaying key operational indicators such as motor speed, current consumption, voltage levels, system temperature, and fault messages.

Beyond simple data monitoring, the HMI panel allows the operator to influence the operation of the system directly. Through intuitive graphical controls, the user can adjust setpoints, initiate or halt the drive system, execute motor reversals, and switch between manual and automatic operating modes. The interaction logic is designed to ensure operational safety: critical commands are confirmed through dialog prompts, while protective interlocks prevent unsafe switching sequences or parameter changes during operation.

The visualization interface is composed of dynamic graphic elements, including real-time gauges, process diagrams, trend charts, and alarm panels, which simplify the perception of the technological process and enhance situational awareness. Each graphical object is linked to real process variables via communication tags, ensuring that the information displayed on the screen accurately reflects the current state of the system as captured by sensors and transmitted through the PROFIBUS network.

Furthermore, the HMI supports diagnostic and logging functions, recording all operational events, parameter adjustments, and alarm occurrences for subsequent analysis. This enables the digital twin to maintain historical data archives, facilitating the comparison of simulated and real performance indicators. Through such integration, the HMI becomes not merely a visualization tool, but an interactive control and feedback interface – a bridge between the operator, the physical process, and its digital counterpart. This combination significantly improves the transparency, safety, and efficiency of the control system, contributing to the realization of a truly intelligent cyber-physical environment.

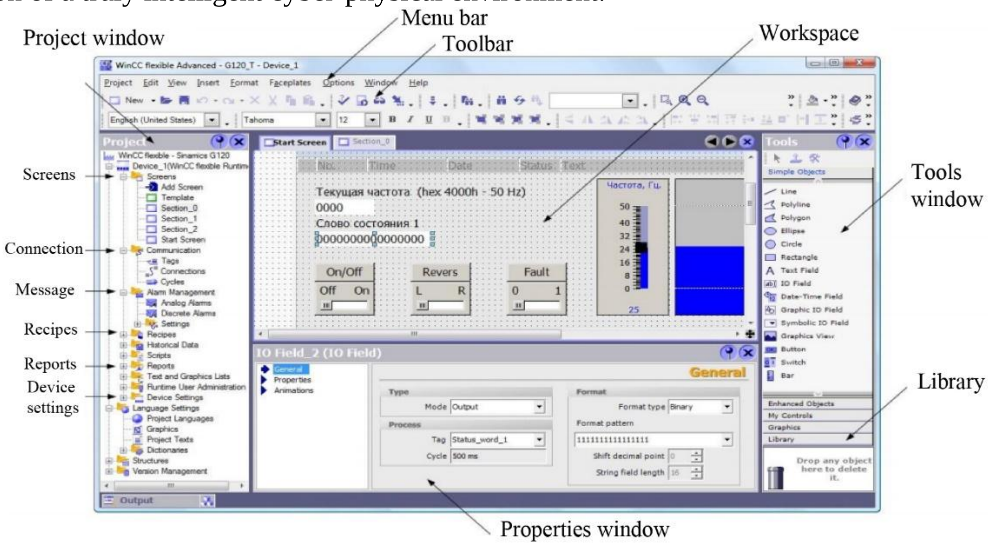

Fig. 7. WinCC Flexible main screen - General view of the conveying line

The digital twin interacts with the physical object through a closed loop of information exchange. Sensors and measuring elements transmit data to the PLC, which sends them to the digital model. The virtual model analyzes the received data, compares them with theoretical parameters, determines deviations and generates corrective signals that are transmitted back to the controller. The controller, in turn, changes the parameters of the frequency converter, ensuring stable operation of the electric drive. This is the principle of the “mirror” behavior of the digital twin – every change in the real object is instantly reflected in the virtual model, and vice versa.

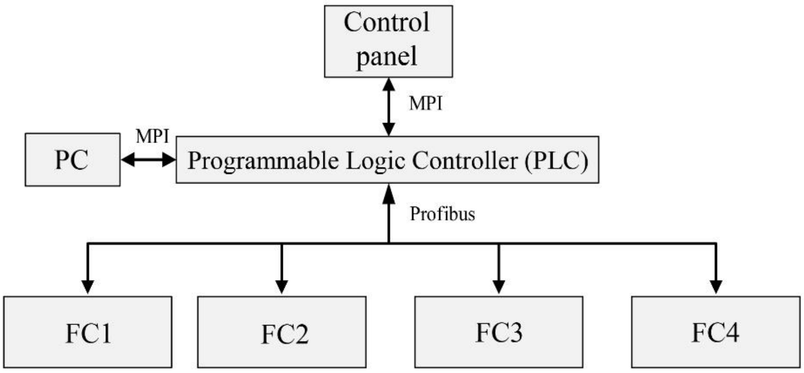

Fig. 8. Block diagram of the interaction of a digital twin with a real object

The application of digital twins in energy control systems provides a wide range of significant advantages.

First, it increases energy efficiency by 10–15% through the optimization of motor rotational frequency according to variable load conditions.

Second, it reduces system commissioning time by approximately 20–25% due to the ability to perform preliminary testing and verification of control algorithms on a virtual model before implementation in real hardware.

Third, it decreases equipment downtime by 25–30% as a result of predictive failure detection and the analysis of process parameter trends, which enables timely maintenance and fault prevention.

In addition, the use of digital twins considerably enhances operational safety, since most experiments and system optimizations can be conducted in a virtual environment without exposing real equipment to risk. The digital twin also facilitates detailed diagnostics and scenario-based testing, helping operators to identify potentially hazardous situations before they occur in the actual process.

From an economic perspective, the implementation of digital twin technology leads to measurable cost savings by reducing maintenance expenses, extending equipment lifetime, and improving the accuracy of energy consumption forecasting. The integration of virtual models into the control architecture supports informed decision-making and enables continuous system optimization throughout its lifecycle.

Based on the results obtained, it can be concluded that the integration of digital twins into energy process control systems represents a highly promising direction for the future of industrial automation. This approach allows for the seamless combination of hardware components, analytical models, and intelligent algorithms within a unified cyber-physical structure, forming the technological foundation for next-generation smart energy systems.

5. Conclusion

The results of the conducted research have confirmed the effectiveness of applying the digital twin concept in control systems for energy facilities. The study analyzed the current state of digital modeling technologies, identified scientific approaches to the creation of virtual replicas of physical systems, and demonstrated the feasibility of their integration into industrial automation practice. The developed digital twin concept enables the integration of mathematical models of electrotechnical processes with real control devices, which significantly improves the accuracy, reliability, and efficiency of energy systems.

An architecture of the control system based on the Siemens hardware–software platform has been proposed, incorporating the Micromaster 440 frequency converter, the SIMATIC S7-314C 2DP programmable logic controller, and the OP170B operator panel. By utilizing the PROFIBUS industrial network, bidirectional data exchange between the physical and digital layers has been achieved. This forms the foundation for constructing closed-loop control systems, in which the digital twin not only reflects the state of the system but also actively influences it in real time. Such an approach opens new opportunities for implementing adaptive and predictive control of complex energy processes, enhancing both performance and resilience.

The mathematical model of the electric drive, developed on the basis of dq-coordinate transformation, provides an accurate representation of electromagnetic processes and enables assessment of the system's dynamic characteristics over a wide range of operating modes. Through its integration into the digital twin, consistency between theoretical calculations and experimental data is achieved, allowing for virtual testing, fault simulation, and algorithm verification without any risk to physical equipment. This significantly reduces commissioning time and lowers operational and maintenance costs.

Practical testing has shown that the implementation of digital twins in electric drive control systems can reduce energy consumption by 10–15%, decrease equipment downtime by 25–30%, and shorten maintenance duration. Furthermore, the digital twin provides advanced monitoring capabilities, including automatic detection of parameter deviations, generation of early warning messages, and decision support for optimizing system operating conditions. These results confirm the high practical value of the proposed approach for modernizing existing energy systems and developing new intelligent control complexes.

From a scientific standpoint, the proposed methodology is distinguished by a systemic approach to digital twin development that combines physical modeling, control algorithms, and visualization tools into a unified structure. This framework can serve as a foundation for future research focused on the creation of hybrid models that integrate analytical equations with machine learning methods. In the long term, such models will enable the design of self-learning systems capable of adapting to changing operating conditions, automatically adjusting control parameters, and performing real-time diagnostics and optimization.

Thus, digital twins are becoming a key technological instrument in the transition toward the Smart Energy paradigm, where every element of an energy system has its own virtual representation and interacts with others through big data analytics and artificial intelligence. The implementation of the described methodology lays the groundwork for developing energy-efficient, reliable, and environmentally sustainable industrial processes, fully aligned with the principles of Industry 4.0 and Energy 5.0.

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ЦИФРОВІ ДВІЙНИКИ В ЕНЕРГЕТИЦІ: ІНФОРМАЦІЙНІ ТЕХНОЛОГІЇ У СИСТЕМАХ КЕРУВАННЯ ТА ЇХ ВПЛИВ НА РЕСУРСООЩАДНІСТЬ

У статті представлено результати комплексного дослідження процесів упровадження цифрових двійників у системах керування енергетичними об'єктами із використанням сучасних апаратно-програмних комплексів. Особливу увагу приділено аналізу підходів до побудови інтегрованих моделей, що поєднують реальні фізичні процеси з їхніми віртуальними аналогами у межах єдиного кіберфізичного середовища. Обґрунтовано вибір технологічної основи для реалізації цифрових двійників у системах автоматизації, заснованої на використанні програмованих логічних контролерів SIMATIC S7-300, частотних перетворювачів Siemens Micromaster 440 та промислового інтерфейсу обміну даними PROFIBUS. Така архітектура забезпечує надійний двосторонній обмін інформацією між віртуальними і фізичними компонентами системи, а також синхронізацію параметрів роботи в режимі реального часу.

Розкрито принципи двосторонньої взаємодії між цифровим двійником і фізичним об'єктом, що базуються на постійному обміні телеметричними даними та сигнально-керуючою інформацією. Наведено приклади апаратно-програмної інтеграції між контролером PLC, панеллю оператора HMI та модулями *зв'язку, які забезпечують передачу як керуючих команд, так і зворотних даних про стан технологічного процесу. Визначено основні вимоги до математичної моделі енергетичного процесу, а також запропоновано методику її побудови на основі dq-перетворення координат, що дозволяє точно відтворювати електромагнітні та механічні процеси в асинхронному електроприводі за різних режимів навантаження.*

У роботі детально описано ключові етапи побудови цифрового двійника, серед яких формування структурної схеми системи, опис фізичних взаємозв'язків, вибір параметрів моделювання, розроблення алгоритмів керування та їх адаптація до умов реального технологічного процесу. Окрему увагу приділено забезпеченню узгодженості між моделлю та реальним обладнанням, що досягається за рахунок використання промислових мереж обміну PROFIBUS і MPI. Реалізовано циклічне оновлення даних із мінімальною затримкою, що забезпечує стабільність керування в режимі реального часу та надійність зворотного зв'язку між усіма компонентами системи.

Розглянуто практичні аспекти використання цифрових двійників для підвищення ефективності експлуатації енергетичного обладнання. Показано можливості застосування цифрових моделей для діагностики стану обладнання, прогнозування відмов, оптимізації параметрів регулювання та планування технічного обслуговування. Наведено приклад упровадження цифрового двійника у процес керування асинхронним електроприводом із частотним регулюванням, який демонструє переваги віртуального тестування, попереднього налагодження системи та аналізу впливу зовнішніх факторів.

Результати дослідження свідчать, що впровадження цифрових двійників у системи керування енергетичними об'єктами забезпечує суттєве підвищення точності регулювання, скорочення простоїв обладнання на 25–30%, підвищення енергоефективності на 10–15%, а також покращення прозорості та керованості виробничих процесів. Крім того, цифровий двійник створює можливості для інтеграції систем моніторингу, архівації даних і прогнозного аналізу у єдиному інформаційному середовищі. Запропонований підхід формує основу для розроблення енергоефективних інтелектуальних систем нового покоління, що поєднують моделювання, аналітику та автоматизоване керування в межах концепцій «розумної енергетики» (Smart Energy) та індустрії 4.0.
Ключові слова: *цифровий двійник, енергетичний об'єкт, автоматизація, PLC, Micromaster 440, WinCC Flexible, PROFIBUS.*

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INFORMATION ABOUT THE AUTHORS

Volodymyr MYKHALEVYCH – Doctor of Technical Sciences, Full Professor, Department of Electric Power Engineering, Electrical Engineering and Electromechanics, Vinnitsa National Agrarian University (3 Solnechna St., Vinnitsa, 21008, e-mail: mykhalevych@vntu.edu.ua, https://orcid.org/0000-0003-1557-7331)

Mykola KOLISNYK – Doctor of Philosophy in Materials Science, Senior Lecturer Department of Electric Power Engineering, Electrical Engineering and Electromechanics, Vinnitsa National Agrarian University (3, Solnechna str., Vinnitsa, 21008, Ukraine, email: kolisnik30@gmail.com, https://orcid.org/0000-0001-5502-6556).

Leonid YAROSHENKO – Candidate of technical sciences, associate professor of the Department of Electric Power Engineering, Electrical Engineering and Electromechanics, Vinnitsa National Agrarian University (3, Solnechna str., Vinnitsa, 21008, Ukraine, email: volvinlv@gmail.com, https://orcid.org/0000-0002-0261-006X).

Anatolii SLOBODYANYK – Candidate of Technical Sciences, Associate Professor, Department of Mathematics, Physics and Computer Technologies, Vinnitsa National Agrarian University (3, Solnechna str., Vinnitsa, 21008, Ukraine, email: slobodaniktola7@gmail.com, https://orcid.org/0009-0006-2157-8188).

МИХАЛЕВИЧ Володимир Маркусович – доктор технічних наук, професор, кафедра електроенергетики, електротехніки та електромеханіки» Вінницького національного аграрного університету (вул. Сонячна, 3, м. Вінниця, 21008, Україна, e-mail: mykhalevych@vntu.edu.ua, https://orcid.org/0000-0003-1557-7331).

КОЛІСНИК Микола Анатолійович – доктор філософії з матеріалознавства, старший викладач кафедри «Електроенергетики, електротехніки та електромеханіки» Вінницького національного аграрного університету (вул. Сонячна, 3, м. Вінниця, 21008, Україна, email: kolisnik30@gmail.com, https://orcid.org/0000-0001-5502-6556).

ЯРОШЕНКО Леонід Вікторович – кандидат технічних наук, доцент кафедри «Електроенергетики, електротехніки та електромеханіки» Вінницького національного аграрного університету (вул. Сонячна, 3, м. Вінниця, 21008, Україна, email: volvinlv@gmail.com, https://orcid.org/0000-0002-0261-006X).

СЛОБОДЯНИК Анатолій Дмитрович – кандидат технічних наук, доцент кафедри «Математики, фізики та комп`ютерних технологій» Вінницького національного аграрного університету (вул. Сонячна, 3, м. Вінниця, 21008, Україна, email: slobodaniktola7@gmail.com, https://orcid.org/0009-0006-2157-8188).