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DEVELOPMENT OF A SIMULATION MODEL AND TESTING METHODOLOGY FOR FREQUENCY CONTROL SYSTEMS OF AN INDUCTION DRIVES USING SINAMICS G220 AND DIGITAL TWIN TECHNOLOGY

The object of research is information processes of control in Sinamics G220 frequency converters with an induction drive. The research problem lies in the need to develop simulation models of components of control systems for technological objects, as well as to design methodology and implement procedures for their testing based on Digital Twin technology.

A functional scheme of a Sinamics G220 simulation model with an integrated induction drive has been developed in the TIA Portal environment. A project of a frequency control system for a 5.5 kW induction drive has been developed through parameterization, and setup of the communication environment based on Simatic S7 tools. Procedures for parameterization and Digital Twin generation were applied to create a virtual Sinamics G220 with an integrated induction drive.

The functionality of the operating modes of the Digital Twin has been defined and implemented, involving the application of the following variable parameters of rotational speed and mechanical load:

- Speed setpoint (1000 rpm and 2950 rpm with a period of 20 s);
- Ramp Function Generator (1.0 s "Up" and 1.0 s "Down");
- Constant load torque (0.95 and 0.75 p. u.).

A procedure for setting the "Speed setpoint" via virtual digital inputs has been implemented for the operating modes "Setpoint channel", "Fixed setpoint", and "Binary", providing 16 predefined "Speed setpoints".

Testing of the Digital Twin was carried out using the built-in WEB server for two parameter sets with switched "Speed setpoints" and variable mechanical load "Constant load torque". The testing results confirmed the adequacy of the simulation model's response to changes in input parameters and operating modes of the Digital Twin of the Sinamics G220.

The obtained results are of practical significance for the commissioning of frequency control systems for induction drives using Sinamics G220.

Keywords: control system, Sinamics G220 frequency converter, induction drive, simulation model, Digital Twin.

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1. Introduction

In the conditions of modern technological development, automated control systems for technological objects (ACS TO) play a significant role, resulting in an increase in productivity, quality, safety and efficiency of industrial production as a whole [1]. The application of virtual commissioning concepts in automation and robotics is a priority for solving compatibility problems between virtual modeling and real systems [2]. One of the directions for increasing the technical and economic indicators of robotic systems is the development of mathematical models that describe the behavior of the robot and their verification based on experimental data [3]. Such criteria for ACS TO [4] necessitate the use of the latest technologies for the design, digital modeling, testing, commissioning and maintenance of ACS TO components,

including for power electronics [5]. Issues of methodology and assessment of trends in conceptual development and digital transformation of real cyber-physical systems based on their "Digital Twins" are reflected in the work [6]. A systematic review of the literature on the application of "Digital Twins" in the energy sector for smart grids identifies architectures that include a physical entity, bidirectional communication, a virtual entity (modeling and simulation), data management, and services [7]. Distributed energy systems are complex and require continuity of service. In this context, "Digital Twins" with an appropriate architecture can be an effective solution for real-time management of such systems and control of physical assets [8].

One of the promising trends in the development of the methodology for building modern ACS TO is the use of "Digital Twins" to study the operating modes and information processes of interaction between

ACS TO components based on virtualization technologies. This approach also correlates with the modern concepts of the industrial revolutions "Industry 4.0" and "Industry 5.0". The theoretical concept of "Digital Twins" can also be transformed into a practical mechanism with empirical evaluation and achieve high accuracy of forecasting based on machine learning (ML) [9].

A systematic review of the functionality of the transition from the concept of "Industry 4.0" to "Industry 5.0" based on scientific findings indicates that the technological component based on "Digital Twins" is transformed into the digitalization of human-machine interaction [10]. The tasks and results of the application of "Digital Twins" for virtual commissioning of IoT components of robotic complexes based on SCADA and cloud technologies in the direction of "Industry 4.0/5.0" are highlighted in the research [11]. The potential of "Digital Twins" technology for synchronous motors, its feasibility assessment for real-time modeling, fault detection, predictive maintenance and identification of key problems are considered in [12].

At the same time, the creation and testing of hardware and software tools based on simulation models and "Digital Twins" is an integral part of a comprehensive approach to solving the above scientific and technical problems. The results of applied research focused on the development of a hybrid software solution for potential communication between equipment from different manufacturers, as well as virtual commissioning of unified components of control systems are given in [13].

A feature of the developed methodology for testing ACS TO based on "Digital Twins" is the use of the TIA Portal tool environment (Siemens AG, Germany), which provides simulation modeling modes approaching real time [14]. In [15] it is shown that the evaluation of the results of indirect control of the torque value is acceptable for specific industrial applications of Sinamics G120 frequency converters (Siemens AG, Germany).

Emulation of energy systems, such as asynchronous drives, has increased due to the development of computing resources and the possibilities of digitalization of ACS TO components. Tool platforms provide a universal approach to the design, optimization and research of frequency control systems for electric drives. In [16], the results of the design of an asynchronous machine using "Digital Twin", which models its performance and behavior under failure conditions, are presented.

The use of "Digital Twins" in the power industry and other industries is a relevant topic of research, especially regarding the potential of "Digital Twins" for optimizing automated control processes. In [17], generalized approaches to the creation of "Digital Twins" and models in general are presented. At the same time, the proposed recommendations are aimed at supporting the further development and use of "Digital Twins" as a promising direction of modern ACS TO engineering. Requirements for the reliability of energy converters in various industries form separate tasks of accurate "on-line" identification of system parameters under different load conditions. Identification technologies based on "Digital Twins" provide fast and accurate identification of system parameters based on modeling methods without existing real equipment [18]. Methods of applying "Digital Twins" for the development and testing of frequency control systems of electric drives are especially relevant for the dynamically developing electromobility industry [19]. In addition, the widespread use of frequency control systems of electric drives in modern conditions of industrial production is closely related to the need to optimize production through maximum automation of technological processes and saving energy resources.

Based on the above, the development of a testing methodology based on simulation models and the "Digital Twin" technology creates new prospects for expanding the functionality, improving control algorithms and studying information processes of interaction between components of the ACS TO.

In [20], the development of the "Digital Twin" of the frequency converter of an asynchronous machine for predicting electrical parameters in stationary modes using machine learning methods was considered.

The effectiveness of different model architectures (simple neural network, parallel, serial and serial with a physical component) for predicting the main parameters (voltage, current, frequency and temperature of IGBT) was compared. The models were trained on experimental data from the test bench, and their accuracy was assessed by error metrics. The best results were shown by the sequential physically-oriented model, which provided a low relative error within 0.2–0.7%. The results obtained indicate that the combination of "Digital Twins" and machine learning allows for accurate real-time forecasting and opens up prospects for condition monitoring and optimization of power electronic systems. The limitation of the research is that only stationary modes of system operation were considered, the model analysis was not generalized to other types of converters or dynamic modes, and the interpretation of ML components needs to be clarified.

In [21], an approach to diagnostics and fault-tolerant control of three-phase converters (T-type rectifier) based on "Digital Twins" is considered. The proposed "Digital Twins" model is implemented using a Deep Neural Network (DNN), which is trained on experimental data in the "off-line" mode and refined in the "on-line" mode to increase accuracy. The main task is to detect and localize faults (failures of power switches, failures of current and voltage sensors. Diagnostics is based on a comparison of the dynamic behavior of the real system and its "Digital Twin". Experimental results confirm that the proposed approach increases the reliability of the converter and allows the implementation of the "sensorless-control" mode. A feature of the research is the use of the difference in dynamic characteristics as a diagnostic feature and experimental validation. The limitations of the work include the orientation on a specific type of converter (T-type rectifier), dependence on the quality of training data and the interpretation of the DNN model that requires clarification. In [22], the application of the "Digital Twins" technology for Primary Frequency Control (PFC), forecasting the technical condition and increasing the reliability indicators of a hybrid wind-diesel power system is considered. The main idea is to create an integrated model that combines the physical system, its "Digital Twin" and bidirectional data exchange between them in real time. This approach allows for monitoring, diagnostics and predicting component degradation. The paper analyzes the topological features of the "Digital Twin" including models (physics-based and data-driven), data flows, network interaction, failure prediction and predictive maintenance technologies. This corresponds to the current direction of technology development – hybrid "Digital Twins" (physics and AI). At the same time, given the originality of the proposed approaches, further solutions are required to validate and adapt the research results to real unified hardware and software tools of control systems, operating conditions of technological equipment.

In [23], a method for building "Digital Twins" for monitoring the state of three-phase power converters in real time is proposed. The method is based on the creation of "Digital Twins", which works synchronously with the real control system and performs the function of a constant "watchdog", providing evaluation of electrical signals without the use of additional sensors or calibration. The practical implementation is demonstrated on the example of a 3L-NPC (Neutral Point Clamped) converter with experimental validation. To assess the degradation of components (in particular, the LC filter) a hybrid optimization approach was applied, combining Particle Swarm Optimization and a genetic algorithm (GA), which work sequentially to increase the accuracy and reliability of parameter identification. The advantage of the work is real-time orientation, the absence of additional hardware, and experimental verification. In addition, the use of hybrid optimization provides a more accurate assessment of degradation processes compared to separate algorithms. At the same time, the research has a number of limitations – the approach was tested only for a specific 3L-NPC topology, the use of evolutionary algorithms can create additional computational load when scaling the system.

In [24], the application of the "Digital Twins" concept for electric drives using the Extended Kalman Filter (EKF) is investigated to estimate the internal states of an induction motor in real time. The proposed approach involves the creation of a synchronized "Digital Twins", which is integrated with the control system and allows estimating parameters such as speed, currents and magnetic fluxes without the use of physical sensors. The results obtained demonstrate that the use of EKF as part of "Digital Twins" allows achieving high accuracy of state estimation and ensuring stable operation of the electric drive in real time. The main advantage of the research is the combination of "Digital Twins" with classical methods of state estimation, which provides an acceptable interpretation and the possibility of practical implementation. At the same time, the proposed solutions have a number of limitations related to the dependence on the accuracy of the mathematical model of the electric drive in real conditions with uncertainties. In addition, the use of EKF involves linear approximations, which reduces accuracy with significant nonlinearity of the control modes.

In [25], a comprehensive review of advanced control of induction motors is presented. A systematic synthesis of control methods (including control strategies, advanced algorithms, and sensorless methods) is presented. A comparative analysis highlights the effectiveness of direct torque control strategies based on artificial intelligence methods that provide an optimal balance between torque dynamics and system stability. However, their industrial implementation remains limited due to algorithmic complexity and high hardware requirements. The main goal of the work is to generalize existing approaches to control electric drives, classify them, and determine development prospects. The authors consider both classical control methods (in particular, PID control and vector control) and modern intelligent approaches, including algorithms based on AI, fuzzy logic, and neural networks. Considerable attention is paid to "sensorless" control methods. The considered control algorithms can serve as the basis for building behavioral models as part of "Digital Twin" systems. At the same time, the problems of constructing topologies of "Digital Twins" and implementing interaction between a physical object and its model remain unsolved. In addition, the research is limited only to aspects of control, not including design, operation and maintenance.

In [26], deals with the problem of increasing the accuracy of positioning and tracking trajectories in feed drives of high-speed machines. The main aim of the research is to analyze the influence of different methods of "feedforward" control on the quality of reproduction of the given motion. The work developed a simulation model of the feed drive, which allows studying the behavior of the system when using different control strategies. It is shown that the use of "feedforward" components allows to significantly reduce the errors of tracking trajectories in feed drives of high-speed machines. The work also emphasizes that the dynamic limitations of the mechanical structure and the presence of oscillations can significantly affect the efficiency of control, and therefore the balance between the complexity of the model and its practical implementation is important. The proposed approaches allow to assess the acceptable limits of accuracy improvement and to formulate recommendations for tuning feedforward algorithms. However, the research has a limitation, which is the need for integration with real data and equipment, as well as synchronization between the physical system and its "Digital Twin" in real time.

In [27], a method and an example of using "Digital Twin" for virtual commissioning of technological equipment to accelerate engineering processes, improve employee skills, and save material resources are presented. Ways to solve this problem are formulated by identifying promising approaches to creating environments with integrated "Digital Twins" for virtual commissioning of equipment in the process of industrial production. The developed system includes different levels of interaction between the operator and the "Digital Twin" of the "Cossembly" type, which can be implemented on the

basis of behavioral "Cobots" to optimize production. The proposed solution is based on "WinMOD" (Winmod GmbH, Germany) – a platform for creating "Digital Twin" real-time systems for PLC, SCADA simulation, production line modeling and operator training. As a PLC Simatic S7-1500 (Siemens, Germany), the simulator "PLCSIM Advanced" (Siemens, Germany) was used, which interacts with industrial robots. At the same time, if "Digital Twins" PLCs have been used for a relatively long time, then building simulation models based on "Digital Twins" frequency converters for electric drive equipment requires the use of the latest technologies and further research.

The results of the analysis of literary sources [20–27] allow to conclude that the problem of improving the topologies of "Digital Twins" optimized for real hardware and for operation in modes close to real time needs to be solved. At the same time, the complexity of approaches, the unification of design procedures, the compatible functionality of components and the adaptation of "Digital Twins" for their scaling to real industrial control systems and technological equipment are especially relevant.

Considering that modern industrial production massively uses frequency-controlled electric drives [28–30], it is advisable to integrate the latest tools for creating "Digital Twins" into the modeling systems of ACS TO, for example, based on the "DriveSim Engineer" toolkit (Siemens, Germany).

Thus, *the object of research* is defined as information control processes in Sinamics G220 frequency converters with an asynchronous drive.

The aim of research is to develop a simulation model and a methodology for testing the operating modes of the Sinamics G220 frequency converter with an asynchronous drive with a variable mechanical load in the ACS TO based on the "Digital Twin" technology.

To achieve the aim, the following tasks were set:

- 1) to develop a functional diagram of the Sinamics G220 simulation model with an asynchronous drive based on the "Digital Twin";
- 2) to perform parameterization and configuration of the simulation model components in the tool development environment;
- 3) to implement the functionality of the "Digital Twin" Sinamics G220 operating modes with an asynchronous drive;
- 4) to test the "Digital Twin" Sinamics G220 with an asynchronous drive for operating modes with a variable speed and mechanical load.

2. Materials and Methods

The aim of research will be achieved if, in the process of developing a simulation model and testing methodology, separate "Digital Twins" of a frequency converter, asynchronous drive and communication environment are combined and their joint functioning in real time is implemented.

Before conducting the research, the following assumptions were made: information processes during the interaction between "Digital Twins" of a simulation model of a frequency converter, an asynchronous drive can be reproduced with certain restrictions in relation to physical systems.

The following simplifications were made: the developed simulation model and testing methodology based on "Digital Twins" is tied to a specific type of hardware and software and will require expansion of functionality and improvement for further scaling.

The simulation model and testing methodology were developed on the basis of unified hardware and software Simatic S7 (Siemens, Germany) [31]. The testing methodology and simulation model based on "Digital Twins" provide for a vector "sensorless-control" mode of frequency control of an asynchronous drive.

To implement the simulation model and methodology for testing the frequency control system of an asynchronous drive based on "Digital Twins" technology, the following hardware was used:

- frequency Converter: Sinamics G220 PN (Siemens AG, Germany) [32];

- asynchronous Drive: SIMOTICS 1LE1 (Siemens AG, Germany) [33];
- communication: SINAMICS DriveSim Virtual Network Interface (Siemens AG, Germany) [34].

The following instrumental software was used to implement the tasks:

- TIA Portal V20 software platform (Siemens AG, Germany) [35];
- optional software for integrating Sinamics Frequency Converters into TIA Portal V20 projects "StartDrive Advanced V20" (Siemens AG, Germany) [36];
- software for generating and parameterizing "Digital Twins" Sinamics G220 and asynchronous drives "DriveSim Engineer V2.1" (Siemens AG, Germany) [34].

The above unified hardware and software tools are tools for project management, configuration, parameterization, implementation of a communication environment, application programming, simulation modeling and testing of ACS TO, including those based on "Digital Twins".

3. Results and Discussion

3.1. Development of a functional diagram of a simulation model of Sinamics G220 with an asynchronous drive based on "Digital Twin"

The simulation model of FC Sinamics G220 PN with induction motors based on "Digital Twin" provides for interaction between the TIA Portal V20 tool software environment and the virtual Frequency

Converter via the virtual "SINAMICS DriveSim Virtual Network Interface".

The simulation model includes the following components:

- TIA Portal V20 (software environment for project development, configuration and parameterization of hardware, communication setup, development of control algorithms, visualization and interaction with virtual components of process control systems);
- SINAMICS StartDrive Advanced V20 (optional software package for integrating the Frequency Converter into TIA Portal projects with configuration, parameterization, diagnostics and commissioning functions);
- DriveSim Engineer V2.1 (software package for generating and parameterizing "Digital Twins" of the FC Sinamics G220 PN);
- "Digital Twin" of the Frequency Converter Sinamics G220 PN with integrated induction motors (from integrated in TIA Portal V20 to induction motors with individually defined parameters);
- SINAMICS DriveSim Virtual Network Interface (for communication of TIA Portal with "Digital Twin");
- built-in WEB server of the Frequency Converter (for parameterization, commissioning, visualization and study of operating modes).

Fig. 1 shows the functional diagram of the simulation model of the FC Sinamics G220 PN with integrated induction motors based on "Digital Twin" technology.

SIMULATION MODEL OF THE «FC SINAMICS G220» WITH INTEGRATED INDUCTION MOTORS

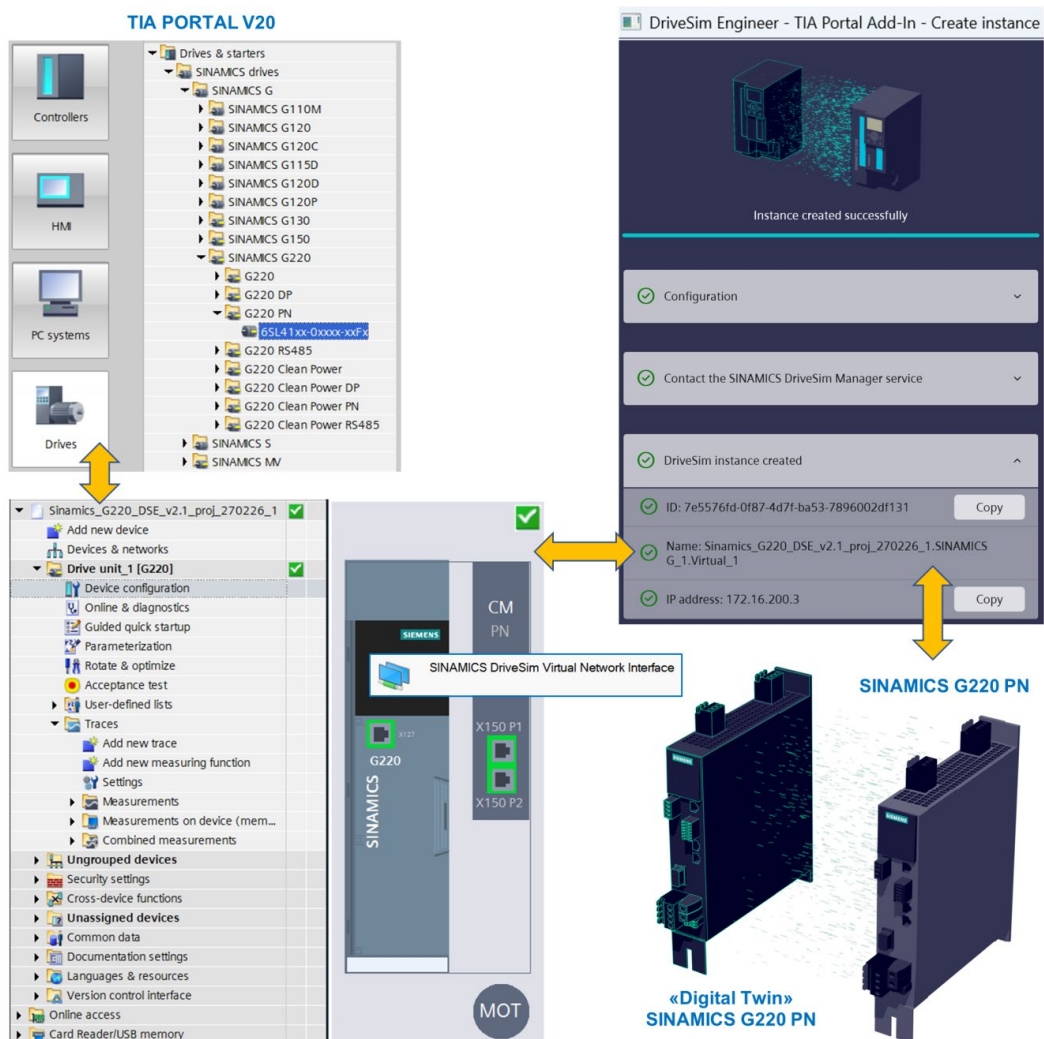


Fig. 1. Functional diagram of the simulation model of FC Sinamics G220 PN with integrated induction motors based on the "Digital Twin" technology

The functional diagram of the simulation model is developed based on an integrated approach, which involves the use of unified hardware and software tools and the latest technologies for building "Digital Twins" of components of electric drive control systems. The TIA Portal tool platform with the integrated SINAMICS StartDrive software package form a design environment for the implementation and study of operating modes of electric drive systems based on Frequency Converters with integrated induction motors. When developing the functional diagram, the latest technologies for generating "Digital Twins" of the Frequency Converter using the DriveSim Engineer V2.1 software package were used [14, 34]. Bidirectional interaction between the TIA Portal tool platform and the "Digital Twin" of the FC Sinamics G220 PN is carried out via the SINAMICS DriveSim Virtual Network Interface. Additionally, for the tasks of parameterization and study of the operating modes of the simulation model, the use of the built-in WEB server "Digital Twins" of the FC Sinamics G220 PN [37] is envisaged.

3.2. Parameterization and configuration of the components of the simulation model in the instrumental development environment

3.2.1. Parameterization and configuration of FC Sinamics G220 PN with integrated induction motor

Before the start of development, the following parameters of the FC Sinamics G220 PN simulation model with integrated induction motor were determined:

- the FC Sinamics G220 PN simulation model with an asynchronous drive is developed to study the operating modes, testing and commissioning of unified hardware and software tools of the Simatic S7 control systems (Siemens AG, Germany);
- development environment – instrumental software "TIA Portal V20" with an additional extension package for the integration of frequency converters "SINAMICS StartDrive Advanced V20";
- "Digital Twin" Sinamics G220 PN with integrated asynchronous drive 1LE1001-1BA62-2xxx is generated and parameterized using the DriveSim Engineer V2.1 software package);
- the algorithm and control parameters are implemented in the "Digital Twin" of FC Sinamics G220 PN and provide for the speed setting mode via "Digital Input" (DI);
- the power of Sinamics G220 PN with integrated asynchronous drive 1LE1001-1BA62-2xxx is 5.5 kW;
- the nominal speed of the asynchronous drive 1LE1001-1BA62-2xxx is 2950 rpm.

For the simulation model and testing methodology of FC Sinamics G220 PN with asynchronous drive, the following speed and variable dynamic load settings will be used:

- variable speed setting (1000 rpm, 2950 rpm with a period of 20 s);

– "Rump-Function-Generator" parameters (1.0 s → "Up" and 1.0 s "Down");

– "Constant load torque" parameters (0.95 and 0.75);

– "Intrinsic moment of inertia" parameters (0.0012 kg · m²).

Development, configuration and parameterization of components of the simulation model of FC Sinamics G220 PN with an asynchronous drive in the tool environment "TIA Portal V20" includes the following:

– creation of a simulation model project in the tool environment "TIA Portal V20";

– configuration and parameterization of FC Sinamics G220 PN;

– configuration and parameterization of the asynchronous drive 1LE1001-1BA62-2xxx;

– parameterization of the communication environment of the FC Sinamics G220 PN simulation model with integrated drive;

– generation of the "Digital Twin" of the Sinamics G220 PN with the integrated asynchronous drive 1LE1001-1BA62-2xxx with defined parameters using the "DriveSim Engineer V2.1" tools;

– activation and parameterization of the FC Sinamics G220 WEB server "Digital Twin".

Fig. 2 shows the result of configuring and parameterizing the FC Sinamics G220 PN in TIA Portal V20.

The section (Devices & networks) of the developed project "Sinamics_G220_DSE_v2.1_proj_270226_1" for FC Sinamics G220 includes the following components (from left to right):

– Project tree: Drive_unit_1 [G220];

– Device view: Drive control (Sinamics G220), Communication Module PROFINET (CM PN: X150 P1, X150 P1), MOTOR (MOT);

– Hardware catalog: SINAMICS G220 → G220 PN (6SL4113-0Cx15-xxxx, 5.5 kW).

Fig. 3 shows the result of configuration and parameterization of Induction motor 1LE1001-1BA62-2xxx in TIA Portal V20.

The section (Devices & networks) of the developed project "Sinamics_G220_DSE_v2.1_proj_270226_1" for 1LE1 Induction motor includes the following components (from left to right):

– Project tree: Drive_unit_1 [G220];

– Device view: Drive control (Sinamics G220), Communication Module PROFINET (CM PN: X150 P1, X150 P1), MOTORS (MOT);

– Hardware catalog: Motors → Induction motors (1LE1001-1BA62-2xxx, 5.5 kW, No encoder).

Fig. 4 shows the result of parameterization of the communication environment [38] of the FC Sinamics G220 PN simulation model with integrated 1LE1 induction motors.

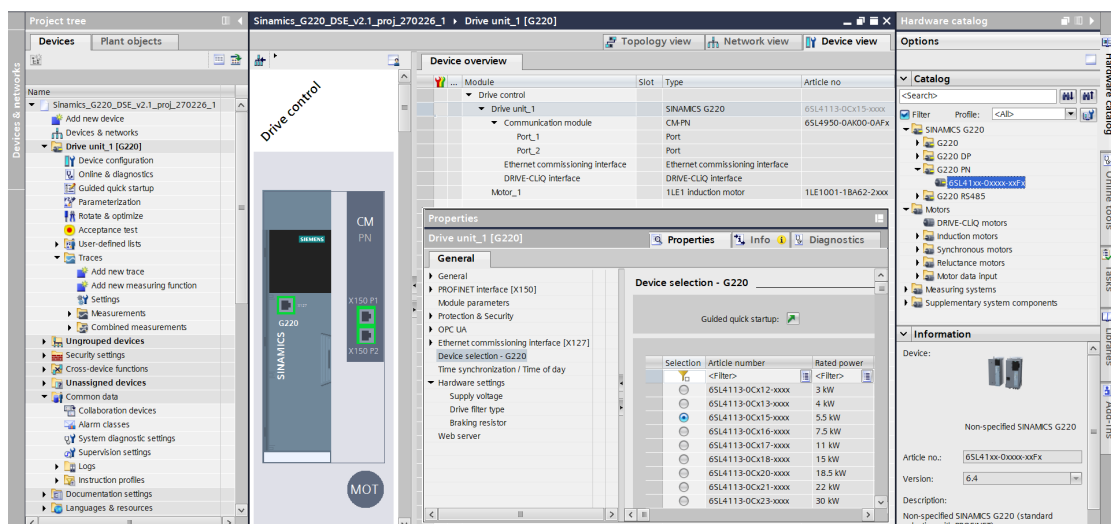


Fig. 2. Result of configuration and parameterization of FC Sinamics G220 PN in TIA Portal V20

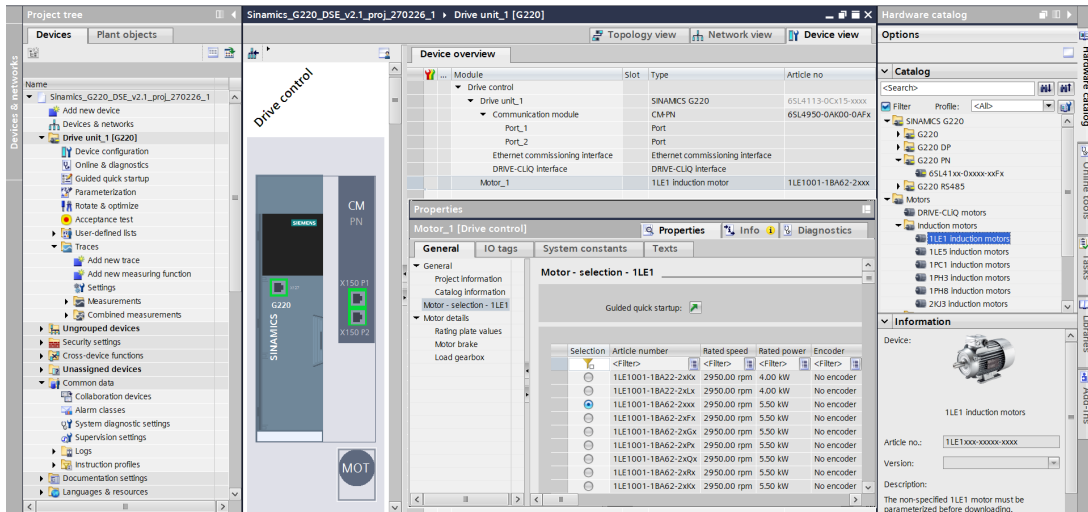


Fig. 3. Result of configuration and parameterization of induction motor 1LE1001-1BA62-2xxx in TIA Portal V20

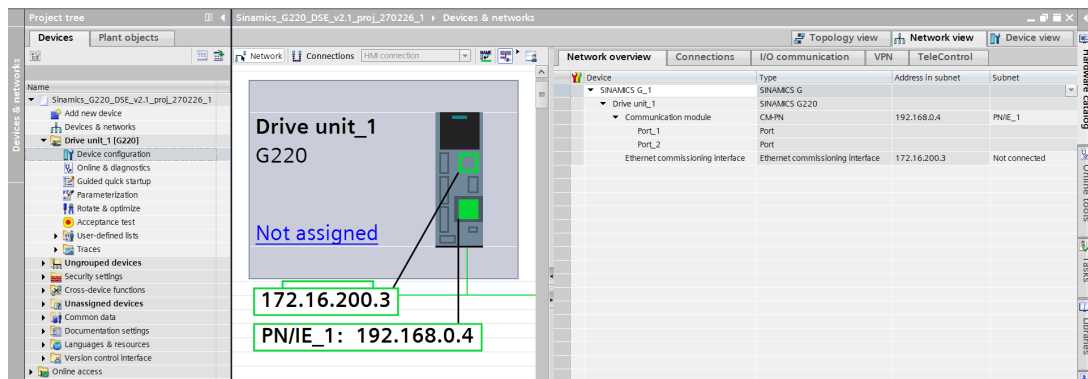


Fig. 4. Result of parameterization of the communication environment of the FC Sinamics G220 PN simulation model with integrated 1LE1 induction motors

The section (Devices & networks) of the developed project "Sinamics_G220_DSE_v2.1_proj_270226_1" for the communication environment includes the following components (from left to right):

- Project tree: Drive_unit_1 [G220];
- Network view: Network → Drive_unit_1 [G220];
- Network overview: Communication module (CM-PN – IP address 192.168.0.4), Ethernet commissioning interface (IP address 172.16.200.3).

3.2.2. Generation of the Sinamics G220 PN Digital Twin with an integrated asynchronous drive

The simulation model assumes that a full-fledged project for real hardware is first developed in the TIA Portal tool environment, and then this project is transferred to the generated Sinamics G220 PN FC Digital Twin. This approach ensures the maximum approximation of the simulation model to real hardware by using the same tool environment for both real components and their Digital Twin.

To create the Sinamics G220 PN FC Digital Twin, the DriveSim Engineer V2.1 software package was used, which allows, in addition to generating the Digital Twin, to simulate various types of mechanical loads on virtual induction motors [14, 34]. Fig. 5 shows the procedure for generating the Sinamics G220 PN FC Digital Twin with integrated induction motors and specified parameters using DriveSim Engineer V2.1.

- As a result of executing the "Digital Twin" generation procedure:
- the correctness of the hardware configuration "Configuration" was checked;
 - the "Contact the SINAMICS DriveSim Manager service" service was activated;
 - the FC Sinamics G220 PN instance "DriveSim instance created" was opened.

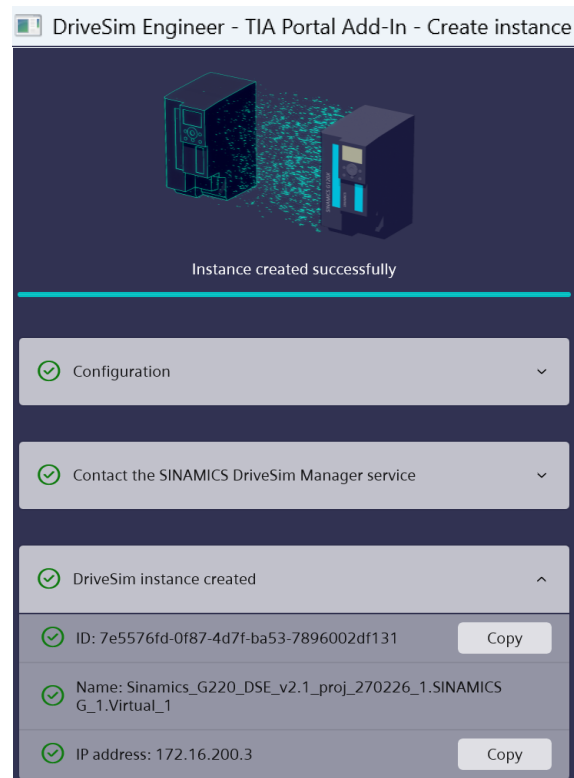


Fig. 5. Procedure for generating a "Digital Twin" of the FC Sinamics G220 PN with integrated induction motors using DriveSim Engineer V2.1

The following system parameters of the "Digital Twin" were generated:

- ID: 7e5576fd-0f87-4d7f-ba53-7896002df131;
- Name: Sinamics_G220_DSE_v2.1_proj_270226_1.SINAMICS G_1_Virtual_1;
- IP address: 172.16.200.3.

Fig. 6 shows the DriveSim Manager panel with the active instance "Sinamics_G220_DSE_v2.1_proj_270226_1.SINAMICS G_1_Virtual_1".

Thus, the active instance of the "Digital Twin" FC Sinamics G220 PN "Sinamics_G220_DSE_v2.1_proj_270226_1.SINAMICS G_1_Virtual_1" interacts with the project in TIA Portal V20 in the same way as real equipment and is the basis of the simulation model.

3.2.3. Activation and parameterization of the WEB server "Digital Twin" FC Sinamics G220 PN

The integration of WEB servers into the hardware and software tools of the ACS TO [9, 25] (PLC, Frequency Converters, Smart Sensors and Actuators, SCADA) is a modern trend and corresponds to the concepts of "Industry 4.0" and "Industry 5.0". The integration of WEB servers into the ACS TO provides the following functionality:

- remote monitoring of technological processes via the WEB interface in real time;
- visualization of equipment operating parameters (time trends, tables, information panels);
- control of technological objects via standard browsers without the need to install specialized software;
- collection, storage and processing of technological data from sensors, actuators, PLC and other devices;
- administration, diagnostics and maintenance of technological equipment based on network technologies.

WEB servers are especially useful in solving simulation modeling problems of ACS TO components based on "Digital Twin" technologies, where on the one hand unified hardware and software tools are used, and on the other hand there is no physical interface. At the same time, there are various ways to organize a virtual interface in simulation modeling problems [14, 34, 39]:

- by means of tool software based on internal virtual data exchange protocols;
- based on virtual interfaces and I/O of individual "Digital Twin" ACS TO components;
- based on integrated WEB servers "Digital Twin" ACS TO components.

The developed methodology is based on the application of all the above methods. Fig. 7 shows the procedure for activating the integrated WEB server "Digital Twin" FC Sinamics G220 PN.

FC Sinamics G220 PN uses two independent networks:

- PROFINET interface [X150]: Web server access via HTTPS (port 443);
- Ethernet commissioning interface [X127]: Web server access via HTTP (port 80);
- Ethernet commissioning interface [X127]: Web server access via HTTPS (port 443).

Fig. 8 shows the result of accessing the integrated WEB server "Digital Twin" FC Sinamics G220 PN in the sections "Diagnostics" → "Connection overview".

The section "Diagnostics" → "Connection overview" of the WEB server "Digital Twin" FC Sinamics G220 PN displays the current structure of all components of the simulation model (Operation unit ↔ Converter ↔ Motor) with the corresponding parameters and communication connections.

3.3. Implementation of the functionality of the operating modes "Digital Twin" Sinamics G220 with an asynchronous drive

The functionality of the operating modes "Digital Twin" Sinamics G220 PN with an integrated induction motor is determined by the parameters in the section "Guided quick startup" for the object "Drive unit_1 [G220]" [40].

Fig. 9 shows the sequence of parameterization of the operating modes "Digital Twin" Sinamics G220 PN with an integrated induction motor.

The sequence of parameterization of the functionality of the operating modes "Digital Twin" Sinamics G220 PN with integrated induction motor includes:

- Connection to PLC: operating mode Sinamics G220 PN with PLC, or without PLC;
- Application: modes "Speed control", "Positioning" or "PID controller";
- Operation mode: modes "Standard Drive Control – SDC", "Dynamic Drive Control – DDC", or "Selecting other closed-loop control mode";
- Limits: "Maximum speed", "Minimum speed", "Rump-up time", "OFF1 rum-down time", "Quick stop – OFF3 rum-down time", "Motor current limit", "Supply voltage";
- I/O configuration: "Select I/O presetting";
- Telegrams: "Communication telegrams for the PLC", "No telegram";
- Rotate & optimize: "Define the criteria for optimization";
- Summary: "Configuration summary".

The individual parameters of the "Digital Twin" Sinamics G220 PN with integrated induction motor are defined in the "Parameterization" section for the "Drive unit_1 [G220]" object.

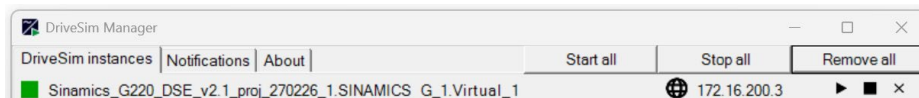


Fig. 6. DriveSim Manager panel with active instance "Sinamics_G220_DSE_v2.1_proj_270226_1.SINAMICS G_1_Virtual_1"

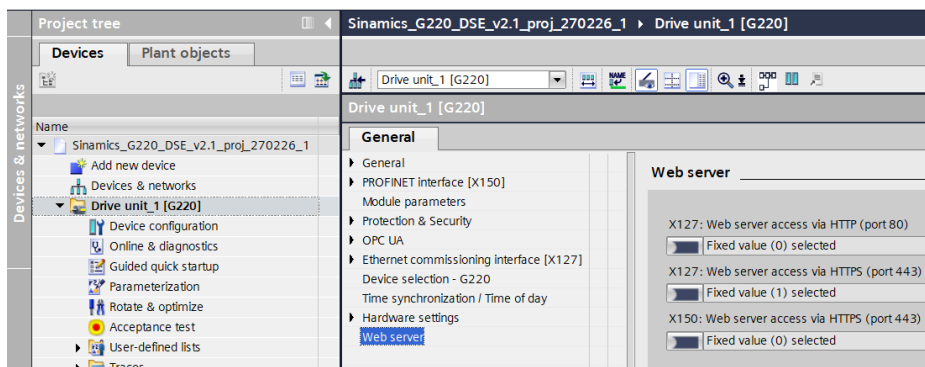


Fig. 7. Procedure for activating the integrated WEB server "Digital Twin" FC Sinamics G220 PN

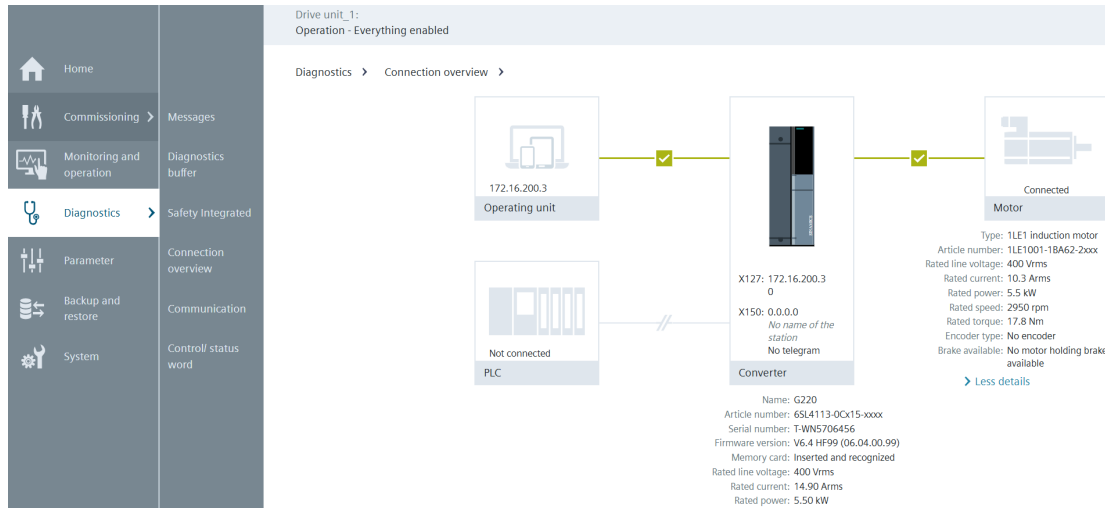


Fig. 8. Result of accessing the integrated WEB server "Digital Twin" FC Sinamics G220 PN in the sections "Diagnostics" → "Connection overview"

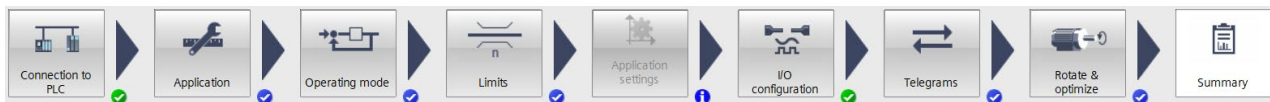


Fig. 9. Sequence of parameterization of the operating modes "Digital Twin" Sinamics G220 PN with integrated induction motor

Fig. 10 shows the "Operation mode" parameterization procedure for the standard operating mode of the "Digital Twin" Sinamics G220 PN with parabolic amplitude-frequency characteristic.

The procedure is performed through the section "Parameterization" → "Basic parameterization" → "Operation mode" → "Speed set-

point" → "Standard Drive Control (SDC)" → "Speed dependent (parabolic characteristic)".

The next required functional parameter is "Setpoint channel", which defines the source of the control signal for the "Digital Twin" Sinamics G220 PN (Fig. 11).

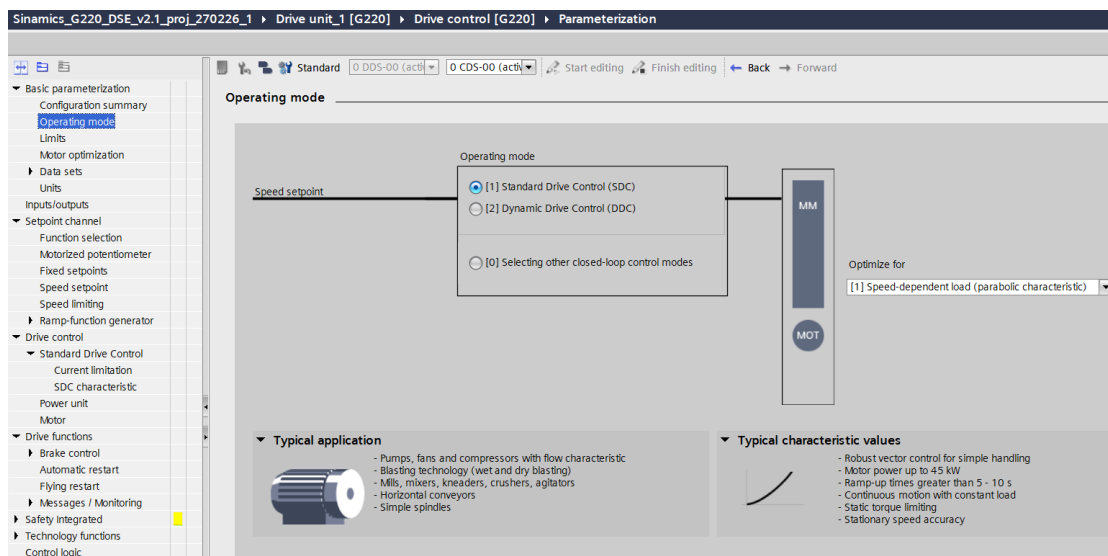


Fig. 10. Procedure for parameterizing "Operation mode" for the standard operating mode "Digital Twin" Sinamics G220 PN with parabolic amplitude-frequency characteristic

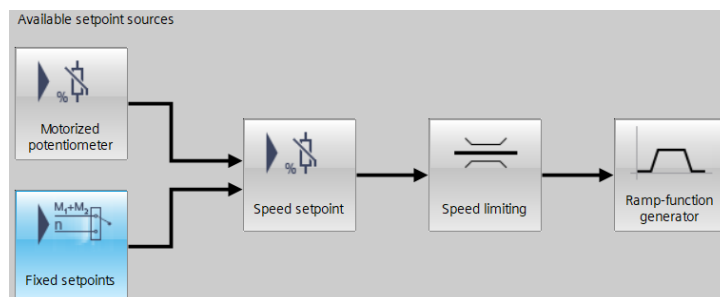


Fig. 11. Procedure for determining "Setpoint sources" for "Digital Twin" Sinamics G220 PN

For the developed simulation model, it is assumed that the induction motor rotation speed is set via Digital Inputs (DI) for "Setpoint channel" → "Fixed setpoint" of the FC Sinamics G220 PN [41]. Fig. 12 shows the procedure for parameterizing "Setpoint channel" for "Digital Twin" Sinamics G220 PN in "on-line" mode.

The procedure is performed through the section "Parameterization" → "Setpoint channel" → "Fixed setpoint" → "Fixed speed setpoint select mode" → "Binary" and allows to set 16 predefined speeds of the induction motor via 4 DI [42]. Fig. 12 shows the activation of "Bit 0" and "Bit 1", which corresponds to the code combination "0011", which sets the output speed for the "Digital Twin" Sinamics G220 PN – 3000 rpm.

3.4. Testing the Sinamics G220 Digital Twin with an asynchronous drive for variable speed and mechanical load modes

The testing process of the Sinamics G220 PN Digital Twin with integrated induction motors will include the following:

- parameterization of the Digital Inputs/Outputs (I/O) of the Sinamics G220 PN Digital Twin (Fig. 13);
- activation of the ON/OFF(OFF1) mode via the virtual Digital Input "DI0" in "DriveSim Manager" → "Controls" → "Digital input" → "DI0 (FDI: 1)" → "Set/Reset" (Fig. 14, a);
- setting one of two different speeds (1000 rpm) via the virtual Digital Input "DI1" in "DriveSim Manager" → "Controls" → "Digital input" → "DI1 (FDI: 1)" → "Set/Reset" (Fig. 14, a);
- setting the other of two different speeds (3000 rpm) via virtual Digital Inputs "DI2–DI3" in "DriveSim Manager" → "Controls" → "Digital input" → "DI2 (FDI: 2)" and "DI3 (FDI: 2)" → "Set/Reset" with a period of 20 s (Fig. 14, a);
- parameterizing the change of mechanical load "Load settings" on the "Digital Twin" Sinamics G220 PN with integrated induction motor (Fig. 14, b).

As a result of parameterization of virtual Digital Inputs, the operating modes and speed of the Digital Twin Sinamics G220 PN are set (Fig. 14, a):

- DI 0 (X131.1) activates parameter c840[0] "ON/OFF (OFF1)", which activates the three-phase power supply of the "Digital Twin" Sinamics G220 PN power unit;
- DI 1 (X131.2) activates parameter c1022[0] "Fixed speed setpoint selection bit 2", which sets the speed setpoint of Sinamics G220 PN – 1000 rpm (Fig. 10);

- DI 2 (X131.5) activates parameter c1020[0] "Fixed speed setpoint selection bit 0", which sets the speed setpoint of Sinamics G220 PN – 1500 rpm (Fig. 10);
- DI 3 (X131.6) activates parameter c1021[0] "Fixed speed setpoint selection bit 1", which sets the speed setpoint of Sinamics G220 PN – 2000 rpm (Fig. 10).

The following basic mechanical load parameters are available in "DriveSim Manager" that can be changed (Fig. 14, b):

- constant load torque, 0.01 p. u.;
- linear load torque, 0.01 p. u.;
- quadratic load torque, 0 p. u.

Dimension p. u. (per unit) – representation of physical quantities as a fraction of the base value (used to simplify calculations in electrical systems for machines and mechanisms).

In addition, for testing the "Digital Twin" Sinamics G220 PN, it is possible to "Import" from the available database [34] additional mechanical load parameters (Fig. 14, b):

- intrinsic moment of inertia, $\text{kg} \cdot \text{m}^2$;
- external moment of inertia, $\text{kg} \cdot \text{m}^2$;
- torsional stiffness, Nm/rad ;
- damping constant, Nms/rad .

Set of parameters "Digital Twin" Sinamics G220 PN No. 1:

- frequency converter: SINAMIC G220 PN (6SL4113-0Cx15-xxxx, 5.5 kW);
- electric drive: Induction Motor (1LE1001-1BA62-2xxx, 5.5 kW);
- device supply voltage: 400 V;
- speed control mode: "Setpoint channel" → "Fixed setpoint" → "Binary";
- speed parameters: two speed values with a period of 20 s (1000 rpm and 2950 rpm);
- constant load torque, 0.95 p. u. (Fig. 15).

Fig. 16 shows the results of testing the "Digital Twin" Sinamics G220 PN with an integrated induction motor for parameter set No. 1 using the WEB server. The time dependences of the servo rotation speed in rpm for the parameters "Speed setpoint" and "Speed actual value" (Fig. 16, a) and "Output voltage" and "Absolute current value" (Fig. 16, b) are shown.

Fig. 17 shows the results of testing the "Digital Twin" Sinamics G220 PN with integrated induction motor for parameter set No. 1 using the WEB server. The time dependences for the parameters "Torque actual value" and "Active power value" are shown.

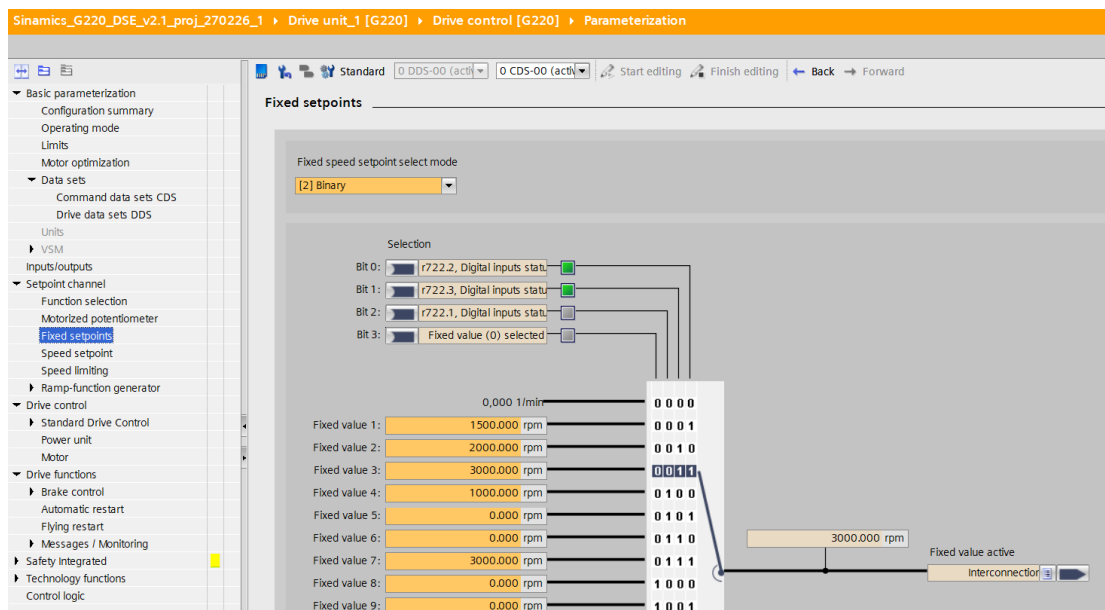


Fig. 12. Procedure for parameterizing the "Setpoint channel" for the "Digital Twin" Sinamics G220 PN in the "on-line" mode

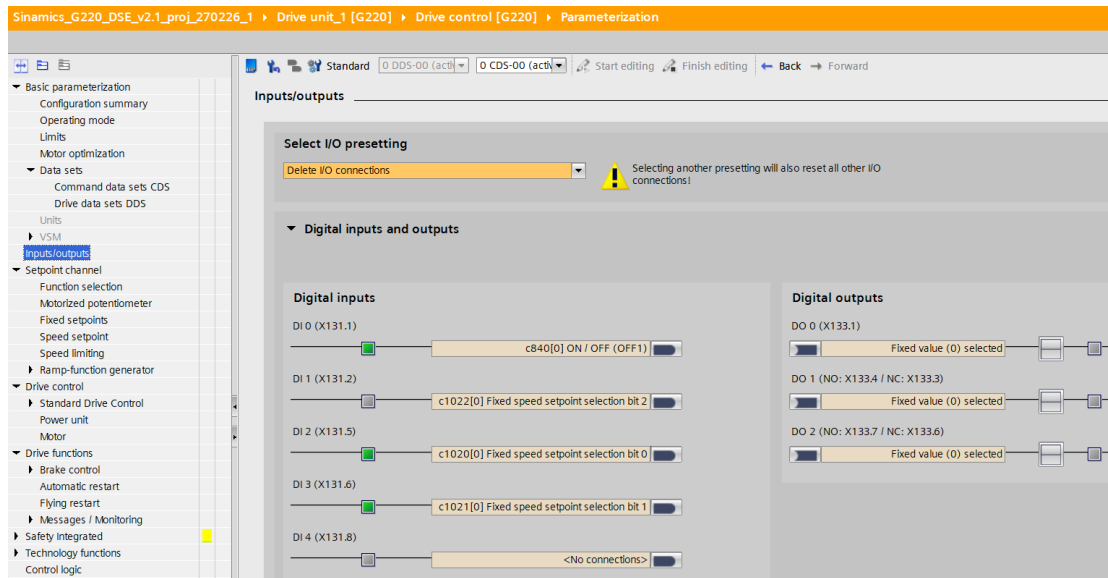


Fig. 13. Parameterization of Digital Inputs/Outputs (I/O) "Digital Twin" Sinamics G220 PN) – "on-line" mode

Parameter set No. 2 "Digital Twin" Sinamics G220 PN No. 2 differs from parameter set No. 1 by the Constant load torque value equal to 0.75 p. u. (Fig. 18).

Fig. 19 and Fig. 20 show the results of testing the Sinamics G220 PN Digital Twin with integrated induction motor for parameter set No. 2.

Fig. 21 and Fig. 22 show a comparison of the results of testing the "Digital Twin" Sinamics G220 PN with an integrated induction motor for parameter set No. 1 and No. 2 at "Speed setpoint" speeds of 1000 rpm and 2950 rpm.

From the comparative analysis of the test results, it follows that the simulation model "Digital Twin" FC Sinamics G220 PN adequately responds to changes in the parameters of the speed of rotation "Speed setpoint" and the mechanical load "Constant load torque equal to". Thus, the developed simulation model and testing methodology for Sinamics G220 PN frequency converters with an asynchronous drive based on "Digital Twin" technology can be effectively used to study the operating modes of components of control systems for technological objects.

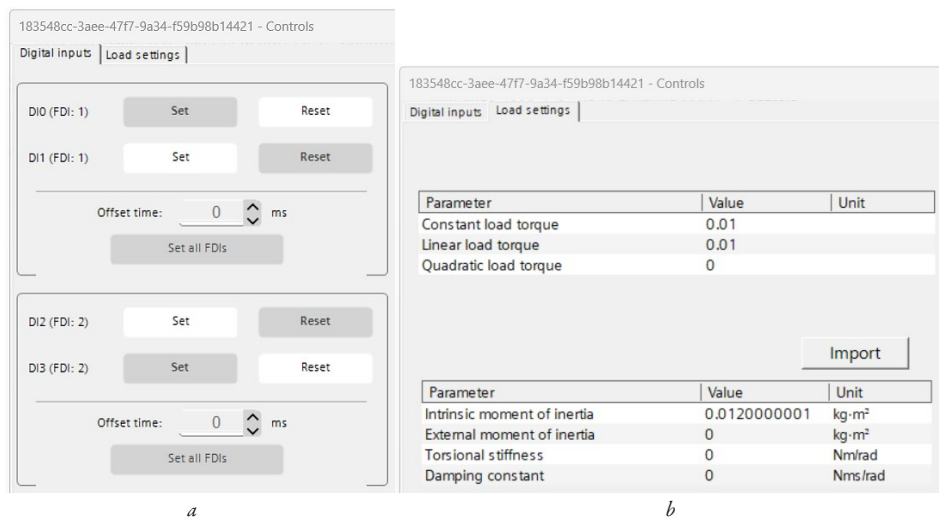


Fig. 14. Parameterization of the "Digital Twin" Sinamics G220 PN in "DriveSim Manager":

a – activation of the "ON/OFF(OFF1)" mode and setting the speed of rotation of the "Digital Twin" Sinamics G220 PN via virtual Digital Inputs;
b – changing the mechanical load in "Load settings"

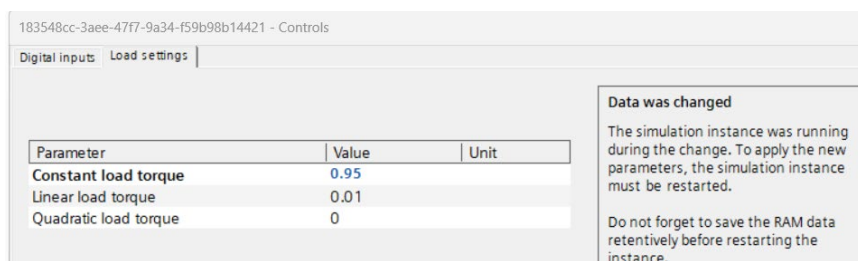


Fig. 15. Parameterization of the "Digital Twin" Sinamics G220 PN in "DriveSim Manager" (Constant load torque equal to 0.95 p. u.)

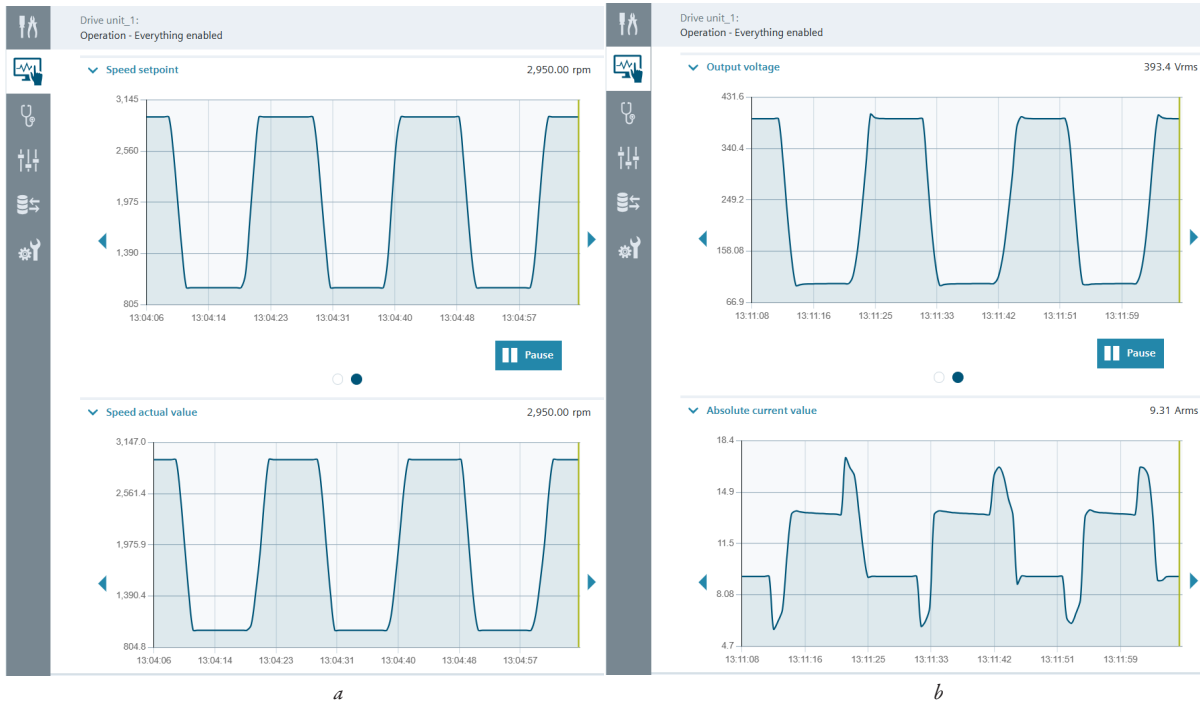


Fig. 16. Results of testing the "Digital Twin" FC Sinamics G220 PN using the WEB server for parameter set No. 1:
a – Speed setpoint and Speed actual value; b – Output voltage and Absolute current value

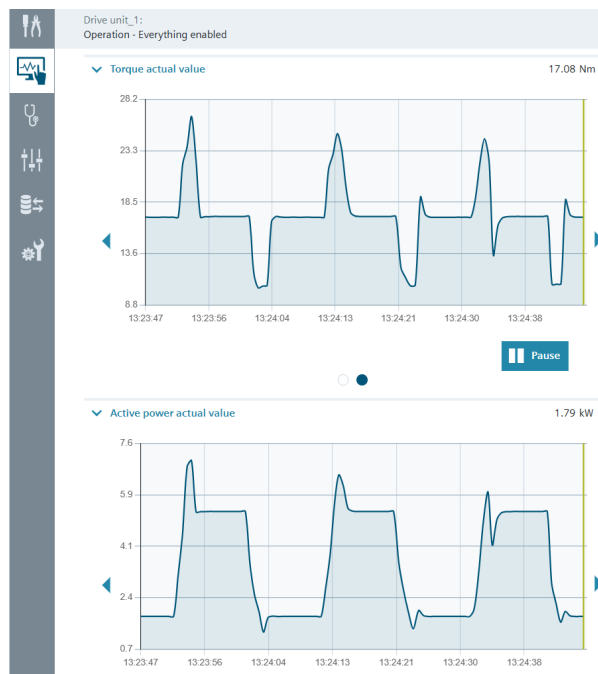


Fig. 17. Results of testing "Digital Twin" FC Sinamics G220 PN by WEB-server means for parameter set No. 1 (Torque actual value and Active power value)

183548cc-3aee-47f7-9a34-f59b98b14421 - Controls

Digital inputs | **Load settings**

Parameter	Value	Unit
Constant load torque	0.75	
Linear load torque	0.01	
Quadratic load torque	0	

Data was changed

The simulation instance was running during the change. To apply the new parameters, the simulation instance must be restarted.

Do not forget to save the RAM data retentively before restarting the instance.

Fig. 18. Parameterization of the Sinamics G220 PN Digital Twin in DriveSim Manager (Constant load torque equal to 0.75 p. u.)

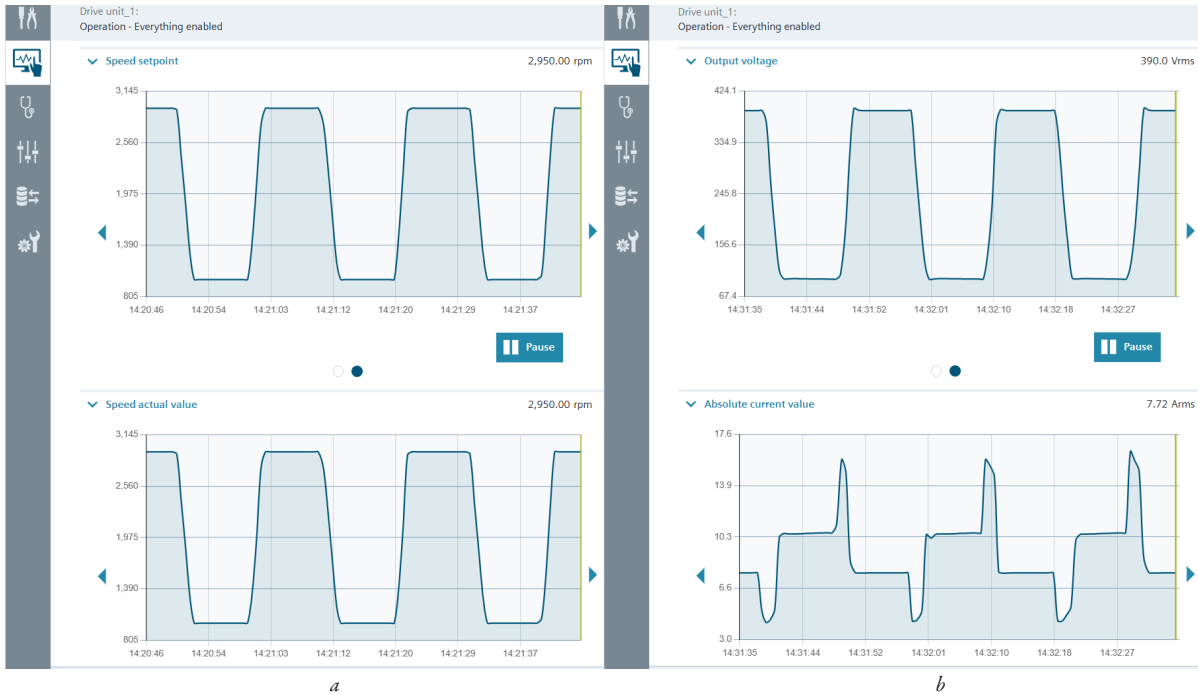


Fig. 19. Results of testing the "Digital Twin" FC Sinamics G220 PN using the WEB server for parameter set No. 2:
a – Speed setpoint and Speed actual value; b – Output voltage and Absolute current value

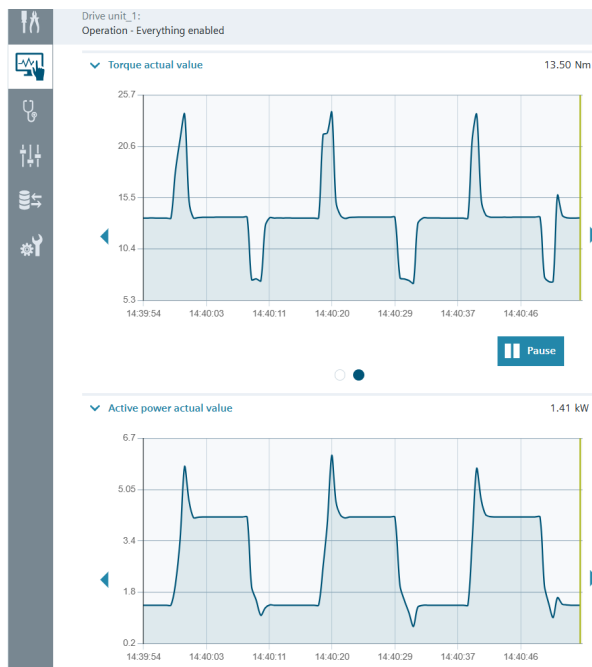


Fig. 20. Results of testing the "Digital Twin" FC Sinamics G220 PN using the WEB server for parameter set No. 2 (Torque actual value and Active power value)

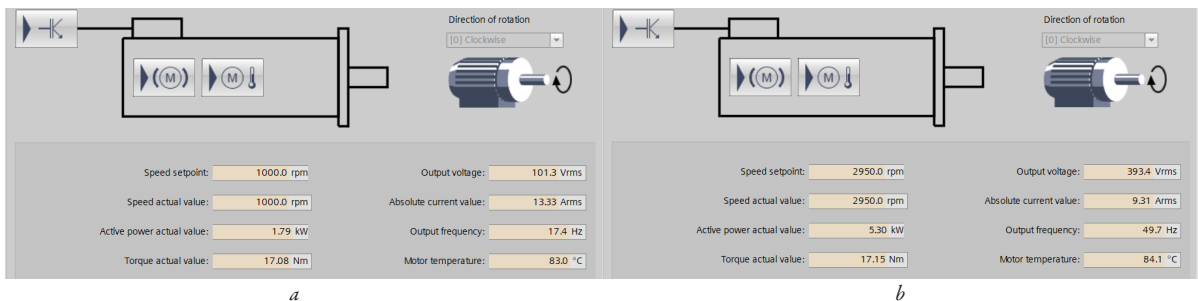


Fig. 21. Results of testing "Digital Twin" FC Sinamics G220 PN for parameter set No. 1 (Constant load torque equal to 0.95 p. u.):
a – "Speed setpoint" equal to 1000 rpm; b – "Speed setpoint" equal to 2950 rpm

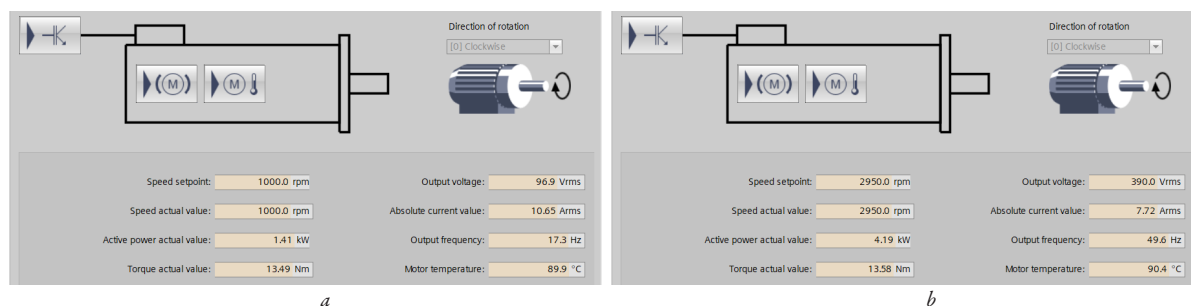


Fig. 22. Results of testing "Digital Twin" FC Sinamics G220 PN for parameter set No. 2 (Constant load torque equal to 0.75 p. u.):
a – "Speed setpoint" equal to 1000 rpm; *b* – "Speed setpoint" equal to 2950 rpm

3.5. Discussion of the results

The main criterion in developing a simulation model and testing methodology for frequency converters "Sinamics G220 PN" with an asynchronous drive for control systems based on "Digital Twin" technology was the creation of a functionally adequate simulation model and a comprehensive solution to the formulated problems.

Before starting the research, an analysis of scientific publications [1–8] was conducted, which highlight the basic principles of construction, relevance and prospects for the use of "Digital Twins" technology in the design, modeling, creation and maintenance of the life cycle of the ACS TO. In addition, the implementation of research in the above direction closely correlates with modern concepts and examples of building ACS TO "Industry 4.0" and "Industry 5.0" [9–12].

A feature of the developed simulation model and testing methodology is the use of the TIA Portal tool environment (Siemens AG, Germany), which provides simulation modeling modes with an approximation to real time [13–15].

The widespread use of frequency control systems for electric drives in modern industrial production conditions is closely related to the need to optimize production through maximum automation of technological processes and saving energy resources [16–19].

The results of the analysis [20–27] allow to conclude that further solutions are needed to improve the topologies and methods for modeling components of the ACS TO and systems as a whole based on their "Digital Twins". Solving such problems is aimed at creating simulation models based on "Digital Twins" with their maximum approximation to real control systems and technological equipment operating in real time.

Considering that modern industrial production massively uses frequency-controlled electric drives [28–30], it is advisable to integrate the latest tools for creating "Digital Twins" into the modeling systems of ACS TO, for example, based on the "DriveSim Engineer" toolkit (Siemens, Germany) [35].

As a toolkit for conducting research, a modern software platform and unified hardware and software tools "Simati S7" (Siemens AG, Germany) were used [31–36].

Based on the functional diagram (Fig. 1), a project was developed in "TIA Portal V20", which includes the implementation of procedures for configuring and parameterizing the Sinamics G220 PN frequency converter with an integrated asynchronous drive "SIMOTICS 1LE1" (Fig. 2–4). The simulation model and testing methodology involve the use of the virtual interface "SINAMICS DriveSim Virtual Network Interface" for interaction between the TIA Portal project and the "Digital Twins" of the system (Fig. 1). The advantage here is that the project is first developed based on real hardware in the "TIA Portal" tool environment, and then this project is transferred to the "Digital Twin" of the Sinamics G220 PN (Fig. 1). To generate the "Digital Twin" of the Sinamics G220 PN frequency converter with an integrated asynchronous drive and specified parameters, the "DriveSim Engineer V2.1" toolkit [34] was used. This toolkit allows, in addition to generating "Digital Twins" (Fig. 5, 6), to simulate various types of mechanical loads on the virtual asynchronous drive (Fig. 14, *b*). Despite the binding of the proposed solutions to

frequency converters of the "Sinamics G220" type, such converters have a fairly wide range of output powers within (0.55–160 kW) [32].

In the research, for the tasks of parameterization and visualization of the system operating modes, an integrated WEB server of the frequency converter "Sinamics G220" was used, which functions both on the physical converter and on "Digital Twins" [14, 34, 39]. Integration of WEB servers into hardware and software tools of the ACS TO is a modern trend and provides the following functionality:

- remote monitoring of technological processes via the WEB interface in real time;
- visualization of equipment operating parameters (time trends, tables, information panels);
- control of technological objects via standard browsers without the need to install specialized software;
- collection, storage and processing of technological data from sensors, actuators, PLC and other devices;
- administration, diagnostics and maintenance of technological equipment based on the latest network technologies.

WEB servers are especially useful when solving problems of simulation modeling of ACS TO components based on "Digital Twin" technologies, where unified hardware and software tools are used, but there is no physical interface (Fig. 7, 8).

For the simulation model and testing methodology, the research implemented the "Operation mode" parameterization procedures for the standard operating mode of the "Sinamics G220 PN" frequency converter with a parabolic amplitude-frequency characteristic (Fig. 9, 10). Such a characteristic is typical for pumping units, fans, compressors, mixers, grinders, conveyors and other technological equipment with variable mechanical load [43–47].

One of the functional tasks when creating simulation models of ACS TO components is the implementation of virtual methods for specifying input parameters. For the developed simulation model, in contrast to the research with speed setting via the communication bus [14], a method of setting the speed of the asynchronous drive via Digital Inputs (DI) "Sinamics G220" [41, 42] was defined. The procedure "Setpoint channel" → "Fixed setpoint" of the FC Sinamics G220 PN was implemented (Fig. 12).

Testing of the simulation model "Digital Twins" of the frequency converter "Sinamics G220" with an asynchronous drive was carried out for operating modes with variable speed and mechanical load. The corresponding parameters "Digital inputs" and "Load settings" were set via the virtual panel (Fig. 14) in "DriveSim Manager" with the active instance "Sinamics_G220_DSE_v2.1_proj_270226_1.SINAMICS G_1_Virtual_1" (Fig. 6).

As a result of testing, transient processes were investigated during the interaction between virtual components of the simulation model in the "on-line" mode. Testing was carried out for two sets of input parameters (Fig. 15–20):

- "Speed setpoint" (1000 rpm and 2950 rpm), which were switched with a period of 20 s;
- "Constant load torque" (0.95 p. u. and 0.75 p. u.).

Time trends of transient processes were constructed and absolute values of technological parameters were obtained: "Speed setpoint", "Speed actual value", "Output voltage", "Absolute current value", "Torque actual value and" and "Active power value". The results of testing the simulation model of the frequency converter "Sinamics G220" with an asynchronous drive based on "Digital Twins" technology confirm the operability, functionality and adequacy of the model's behavior.

The simulation model did not use a PLC, and to control the operating modes of the frequency converter and the asynchronous drive, virtual discrete inputs "DI0–DI3" of Sinamics G220 PN were used (Fig. 11–14, a). The TIA Portal V20 project, which includes the parameterized Sinamics G220 PN frequency converter and the asynchronous drive, is an integral part of the simulation model and can be transferred to real hardware. In this case, the virtual interface "SINAMICS DriveSim Virtual Network Interface" for communication of the TIA Portal project with the "Digital Twin" (Fig. 1) must be switched to hardware. Similarly, in a real system, instead of virtual discrete inputs for controlling the operating modes of Sinamics G220 PN, real inputs with control signals from hardware PLCs or other control devices must be used.

The limitations of research include the fact that only some of the available parameters of the virtual mechanical load were involved in the process of testing the simulation model. In addition, Restrictions are defined for the "DriveSim Engineer V2.1" toolkit [48].

The TIA Portal development environment also supports the integration of MATLAB Simulink models based on the "SIMATIC Target" technology [49]. At the same time, the "SIMATIC Target" technology requires a PLC with ODK (Open Development Kit) support: Software PLC SIMATIC S7-1500 or CPU 1518 ODK. This approach complicates the implementation of the simulation model due to additional components and procedures, and the integrated MATLAB-Simulink models may require additional correction and research for their practical application.

The research can be continued in the direction of creating new improved and promising simulation models based on the "Digital Twins" technology with the functions of regulators and control of additional technological parameters.

4. Conclusions

1. Based on the proposed functional scheme, a simulation model and a methodology for testing and studying the operating modes of the frequency control system for an asynchronous drive based on the "Digital Twins" technology have been developed. The functional scheme of the simulation model includes virtual frequency converters Sinamics G220 PN, asynchronous drive SIMOTICS 1LE1 and SINAMICS DriveSim Virtual Network Interface, which interact with each other in real time.

2. A project for a frequency control system for an asynchronous drive has been developed in the TIA Portal tool environment. The hardware and communication environment of the project have been parameterized. "Digital Twins" of the Sinamics G220 PN frequency converter with integrated asynchronous drive SIMOTICS 1LE1 and WEB server have been parameterized and generated using the DriveSim Engineer V2.1 tool for 5.5 kW. This makes it possible to test and study the operating modes of the system based on the time trends of transient processes and absolute values of technological parameters.

3. The functionality of the simulation model and testing methodology "Digital Twin" Sinamics G220 PN with an asynchronous drive was implemented by integrating the procedures:

- parameterization of the operating mode with a parabolic amplitude-frequency characteristic: Parametrization → Basic parametrization → Operation mode → Speed setpoint → Standard Drive Control (SDC) → Speed dependent (parabolic characteristic);

- parameterization of the setpoint source for up to 16 predefined speeds of the asynchronous drive via Digital Inputs (DI) of the frequency converter: Parametrization → Setpoint channel → Fixed setpoint → Fixed speed setpoint select mode → Binary.

4. The transient processes during the interaction between the virtual components of the simulation model in the "on-line" mode were tested and studied. Testing was carried out for two sets of input parameters:

- speed setpoint (1000 rpm and 2950 rpm), which were switched with a period of 20 s;
- constant load torque (0.95 p. u. and 0.75 p. u.).

Time trends of transient processes were constructed and absolute values of technological parameters were obtained: Speed setpoint, Speed actual value, Output voltage, Absolute current value, Torque actual value and, Active power value.

The results of testing the simulation model of the frequency control system based on the "Digital Twins" technology allow to draw a conclusion about the operability, functionality and adequacy of the development.

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Conflicts of interest

The authors declare that they have no conflict of interest regarding this research, including financial, personal, authorship or other nature, which could affect the research and its results presented in this paper.

Financing

The research was conducted without financial support.

Data availability

The manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the presented paper.

Authors' contributions

Leonid Zamikhovskiy: Conceptualization, Methodology, Validation, Writing – review and editing, Project administration;
Mykola Nykolaychuk: Methodology, Software, Validation, Formal analysis, Writing – original draft;
Ivan Levitskiy: Methodology, Software, Validation, Writing – original draft, Visualization.

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