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DEVELOPMENT OF A SIMULATION MODEL OF A WEB-ORIENTED SERVO DRIVE FREQUENCY CONTROL SYSTEM BASED ON "DIGITAL TWINS" TECHNOLOGY

The object of this research is the information processes of interaction between virtual components of a WEB-oriented simulation model of a frequency control system for a synchronous servo drive. The research problem lies in the need for a comprehensive solution to the tasks of developing simulation models of control systems for technological objects based on advanced algorithms, procedures, and unified hardware and software tools.

A project of a frequency control system for a SIMOTICS S-1FK2 synchronous servo drive was developed using a PLC S7-1500 and a FC SINAMICS S210 within the TIA Portal environment. Application software for the frequency control system was developed in FBD language with an integrated specialized technological object "SpeedAxis".

During the development of the simulation model, a "Digital Twins" were generated for the frequency converter with an integrated synchronous servo drive. To ensure interaction between the virtual components of the simulation model, procedures for basic parameterization and loading of the TIA Portal project components into the "Digital Twins" were implemented.

Testing and investigation of the information exchange processes between the virtual components of the simulation model were carried out in "on-line" mode using the capabilities of the integrated WEB-server.

The tests were conducted at speeds of 2000 rpm and 4000 rpm, switched periodically every 12 sec. Parameters of the reference and actual speed, as well as the instantaneous voltage, current, torque, and output power of the virtual frequency converter, were measured and analyzed.

Based on the test results, the feasibility and correctness of the joint operation of the simulation model components in an isochronous real-time mode with a 1 ms synchronization cycle were confirmed, demonstrating the effectiveness of the approach based on "Digital Twins" technology.

Keywords: *WEB control system, TIA Portal, Digital Twin, simulation model, PLC, frequency converter Sinamics.*

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1. Introduction

Building automated control systems for technological objects based on modern hardware and software and information technologies involves the use of effective tools to solve the problems of design, modeling, implementation, testing, implementation and maintenance of such systems.

Components of control systems for technological objects are intelligent "smart" sensors and actuators, PLC (Programmable Logic Controller), industrial communications (Industrial NET), HMI (Human Machine Interface), SCADA systems.

One of the directions for solving the problem of modeling and testing control system components at the design and implementation stages is the creation and testing of simulation models, both for individual components and for complete systems.

Taking into account the wide application of electric drive systems in industrial automation, robotics, transport and other areas, the work solves the scientific and technical problem of building a simulation model of a frequency control system based on the "Digital Twins" technology.

"Digital Twins" is a virtual model of a physical object, system or process that uses data from the real environment for modeling, monitoring and analysis in real time. "Digital Twins" allows to simulate the operation of a physical object, detect errors and problems at the design stages, predict functionality, explore operating modes and optimize control processes of technological objects.

"Digital Twins" is actually a virtual component in the form of a digital representation of a physical object (3D model, data set, mathematical or simulation model, or a combination or set of the above).

"Digital Twins" is part of the concept of industrial revolutions (Industry 4.0 and Industry 5.0), as well as an integral part of the latest trends in the development of industrial engineering, information technology and scientific research.

The paper [1] presents an innovative approach to increasing the accuracy of processes with a slow tool servo drive (STS). The work is aimed at solving the problem of dynamic errors that arise due to high-frequency vibrations and inertial effects. The purpose of the research is to create a predictive digital twin for modeling and controlling dynamic errors within and outside the servo control loop in real time.

The developed intelligent model allows predicting the total dynamic error before its manifestation, and then applying feedforward control to compensate for it. The system was implemented on an experimental setup with high-speed real-time signal processing. The advantages of the presented approach are the integration of the "Digital Twins" with the control system in real time, error prediction, a significant increase in accuracy and efficiency without additional mechanical corrections. The proposed approach opens up prospects for creating self-learning error control systems in real time, capable of adapting to changes in the dynamics of the servo control process without operator intervention. The limitations of the study include the complexity of the hardware implementation of the system, the need for a large amount of training data for the correct operation of the model, and the dependence of accuracy on the quality of sensor measurements.

In [2], the use of "Digital Twins" for correction of feedback control parameters in motion control systems of nonlinear dynamic systems is considered. The innovative approach consists in using "Digital Twins" based on a PID controller and has prospects for application in real industrial conditions. The simulation of the control process is carried out using "MATLAB/Simulink" (MathWorks, Inc., USA). This approach allows adapting the control system to changes in the characteristics of the mechanical system, such as wear or changes in technical characteristics. The article is based on simulation processes, but without reference to specific unified hardware and software tools of control systems, which limits the ability to assess the effectiveness of the approach in real conditions. In addition, for the practical application of the specified approach in real conditions, additional experimental studies are required to assess its effectiveness and practical significance.

The purpose of the study [3] is to increase the efficiency and accuracy of technological process control by creating a virtual "Digital Twins" for synchronous interaction with a physical object in real time. The robot has developed a prototype of a portal machine with a PLC Simatic S7-1200 (Siemens, Germany) and an organized infrastructure for communication with the "Digital Twins", which makes it possible to test the concept on real hardware and software. According to the results of experimental studies, minimal latency between physical objects and virtual models has been declared, which is critically important for industrial applications. The virtual environment was created in Unity 3D (Unity Technologies, USA), which provides visualization, monitoring and interaction of the operator with the production process. An important feature is the integration of modern industrial protocols (PROFINET, OPC UA, MQTT, etc.) to ensure compatibility with equipment of different types and manufacturers. However, critical remarks include the use of PLC Simatic S7-1200 (Siemens, Germany), which limits the functionality and scalability of the system to complex production complexes, compared to the more productive PLC Simatic S7-1500T (Siemens, Germany).

In [4], a "Digital Twins" model for electric drives is proposed, which uses EKF (Extended Kalman Filter) to accurately estimate the states of sensorless control. The purpose of the study is to increase the efficiency and accuracy of electric drive control by integrating "Digital Twins" into production and operation processes. The model takes into account the real characteristics of the inverter, including the effects of "dead time" and voltage drop on switching devices, which increases the accuracy of modeling and the adaptability of the system to real operating conditions. The results of simulations performed using "MATLAB/Simulink" (MathWorks, Inc., USA) were compared with experimental data on a 4 kW three-phase electric drive, which confirmed the effectiveness of the proposed model. Integrating the "Digital Twins" of an electric drive with EKF into existing control systems can require significant resources and time for adaptation. The use of EKF requires significant computing resources, which can limit the application of the model in real time, especially for complex systems. The issues of interoperability of simulation model components, such as virtual PLCs and Frequency Converters, remain unresolved.

In [5], the NX MCD 3D modeling system (Siemens, Germany) was used to build, configure, and test the "Digital Twins". This program provides a sequence editor (Gantt Chart) for testing machines and mechanisms at the design stage without implementing PLC program code in automation systems. In parallel, the PLC code was developed in the TIA Portal environment (Siemens, Germany). Then the machine was emulated in synchronous mode of the communication bus via a virtual simulator S7-PLCSIM Advanced (Siemens, Germany) with the downloaded program code. Next, the virtual machine and S7-PLCSIM Advanced were combined in the SIMIT (Siemens, Germany) virtual environment, which simultaneously simulates electric drives, electrical components and 3D machine models in NX MCD 3D. The work does not solve the problem of compatibility of the simulation model with specific Frequency Converter and Motor, which does not fully provide the advantages of the "Digital Twins" technology for use in industrial conditions.

The paper [6] is devoted to the development of a "Digital Twin" for Industry 4.0 production systems. The work is quite voluminous, structured with the possibility of applying individual components of the simulation model on a real technological object (Long Conveyor Belt). Training and demonstration projects have been developed for testing components of robotic control systems based on "Digital Twins" and the design and simulation environments TIA Portal, S7-PLCSIM Advanced, Unit 3D (Unity Technologies, USA). Despite the high level of the research performed, the unsolved problems include the lack of integration of the components of the "Digital Twins" of the frequency control of the electric drive in isochronous mode for highly dynamic "Motion Control" systems into the simulation model.

In the paper [7], the authors implemented two demonstration systems (a production line and a warehouse sorter) with bidirectional interaction between physical and digital components. This concept provides practical solutions, not just theoretical models. The advantage of the research is the use of widely used design environments, such as Unity 3D, Game4Automation (IN2 Engineering GmbH, Germany), TIA Portal, Fischertechnik models (Fischerwerke GmbH & Co. KG, Germany). The work pays attention to a clear classification and differences between "Digital Model", "Digital Shadow" and "Digital Twins" with a justification of what they implement. The article shows in detail how individual components of the virtual model interact with each other. The limitations of the work include dependence on specific environments, for example, the Game4Automation framework may be unsuitable or require significant refinement for specific equipment. In addition, the use of the PLC Simatic S7-1200 has limited application for complex dynamic Motion Control systems and is not supported by the simulator with extended functionality S7-PLCSIM Advanced.

In [8], the results of the development and testing of the built-in MATLAB library for effective real-time communication between the S7-PLCSIM Advanced simulator and MATLAB/Simulink are presented. The library uses Siemens.Simulation.Runtime.API for integration and is structured into three classes: PLCSimAdv, PLCSR (Simulation Runtime) and PLCSW (Simulation Workspace). Integration without the need for S-Function regeneration in TIA Portal unifies and simplifies the interaction procedures between the components of the simulation model. The research results can be used to create "Digital Twins", simulate complex technological processes and virtually commission new systems. Despite the innovative approach, the problem of interaction between virtual "Digital Twins" (PLC, Frequency Converter and various types of electric drive systems) with scaling to specific industrial equipment remains unsolved.

In the paper [9], the problem of applying Virtual Commissioning (VC) methods and "Digital Twins" technology for the Rolling Mill Process is comprehensively solved. The methodology includes mathematical modeling of the rolling mill process (servovalves, hydraulics, rolling shafts, etc.), parameterization and programming of PLC. In this case, "MATLAB/Simulink", TIA Portal/S7-PLCSIM Advanced and HMI are used to implement VC. The work organizes communication between the "Simulink-model" and the virtual PLC using TIA Portal/PLCSIM Advanced, which is a solution to a relatively complex problem.

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Despite the volume and consistency, the work does not fully solve the problem of creating "Digital Twins" of the Frequency Converter and the electric drive and their integration into simulation models of control systems for technological objects.

The results of the analysis of literary sources [1–9] allow to conclude that the problems that need to be solved are related to the complexity of implementing a comprehensive approach when creating simulation models of control systems for technological objects based on the "Digital Twins" technology. At the same time, the problems of unification of design procedures, compatible functionality and adaptation of simulation models for their scaling to real industrial control systems and technological equipment are particularly prominent.

Thus, *the object of research* is the information processes of interaction between the virtual components of the simulation model of the WEB-oriented frequency control system of a synchronous servo drive.

The aim of research is to develop a simulation model of the WEB-oriented frequency control system of a synchronous servo drive based on the "Digital Twins" technology for testing the operating modes of electric drive systems with variable load.

To achieve the aim, the following objectives were set:
- to develop a functional diagram and determine the parameters of the components of the simulation model of the frequency control system of a servo drive;
- to develop a design for a servo drive frequency control system based on PLC S7-1500 and Sinamics S210 (Siemens, Germany);
- to implement interaction procedures between components of the simulation model based on the "Digital Twins" technology;
- to perform testing of the simulation model of the servo drive frequency control system using the "Digital Twins" WEB server.

2. Materials and Methods

The aim of research can be achieved if, within the framework of the developed simulation model, separate "Digital Twins" components are combined, including the communication environment, and their compatible functionality is ensured in real time. In addition, such a model must take into account the need for functioning in the Isochronous Run Time (IRT) mode for highly dynamic "Motion Control" systems.

Before starting the study, the following assumptions were made: the information processes of interaction between the virtual components of the simulation model of the servo drive frequency control system can be reproduced with some limitations compared to real systems.

In the process of the study, the following simplifications were made: the developed simulation model at this stage of the study is a demonstration model with a link to a specific hardware and software and will require improvement for further scaling.

The simulation model will be developed on the basis of unified hardware and software tools for configuration, parameterization, communication setup, programming, visualization and simulation of Simatic S7 (Siemens, Germany) [10]. For the simulation model of frequency control of a synchronous servo drive, a vector control mode is defined.

The following hardware tools are proposed for the implementation of the simulation model of the frequency control system of a servo drive based on the "Digital Twins" technology:
- Operating unit (programmer/personal computer or PG/PC);
- PLC (Programmable Logic Controller Simatic S7-1515T-2 PN) (Siemens, Germany) [11];
- Frequency Converter (Sinamics S210) (Siemens, Germany) [12];
- Motor (Synchronous Motor SIMOTICS S-1FK2) (Siemens, Germany) [13];
- Communication Network (PROFINET/Industrial Ethernet).

The following software was used to implement the tasks:
- MS OS Windows Windows 11 IoT Enterprise LTSC 24H2 (build 26100.6584) (Microsoft, USA);
- TIA Portal V20 software platform (Siemens, Germany) [14];
- Frequency Converters integration module into TIA Portal projects "StartDrive V20" (Siemens, Germany) [15];
- virtual simulator for PLC S7-1500 (S7-PLCSIM Advanced V7.0) (Siemens, Germany) [16];
- "Digital Twins" generation and administration software for Sinamics S210 and SIMOTICS S-1FK2 "DriveSim Engineer V2.0" (Siemens, Germany) [17].

The TIA Portal software platform (Siemens, Germany) includes the following functions:
- creation and management of automation projects for technological objects;
- configuration of hardware for PLC-based control systems;
- parameterization of PLC-based control system hardware;
- creation and parameterization of the project communication environment;
- creation of application software for PLC-based control systems;
- integration of SCADA functions into technological object control systems;
- simulation of PLC and SCADA operation for tasks of simulation modeling and testing of components of technological object control systems.

3. Results and Discussion

3.1. Functional diagram, purpose and parameters of components of the simulation model of a servo drive frequency control system

The tasks of determining the functionality, technical parameters, construction and modeling of control systems for executive mechanisms of control objects based on unified hardware and software Simatic S7 are reflected in [18, 19].

Fig. 1 shows a functional diagram of the frequency-control system of a servo drive via a PLC, based on "SIEMENS_telegram_105".

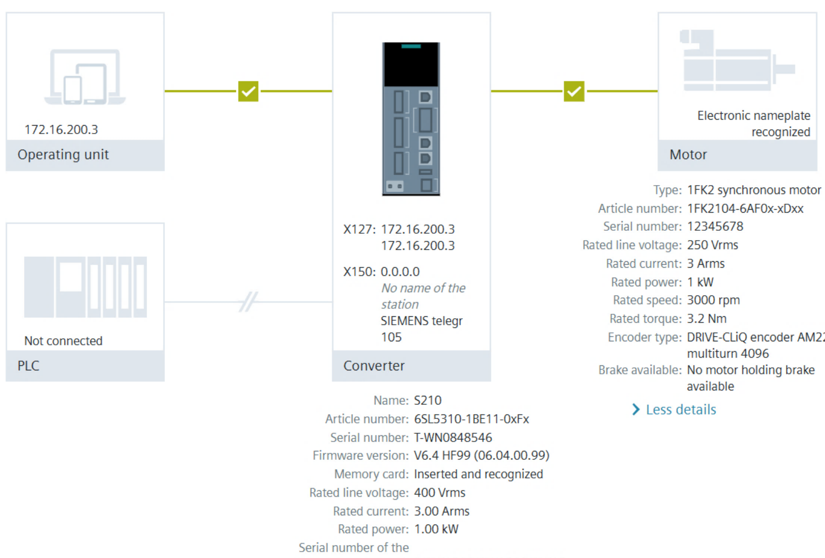

Fig. 1. Functional diagram of the frequency-control system of a servo drive via a PLC, based on "SIEMENS_telegram_105"

The functional diagram includes the following components [13]:

– Operating unit (programmer/personal computer or PG/PC);
– PLC (Programmable Logic Controller Simatic S7-1515T-2 PN) (Siemens, Germany);
– FC (Frequency Converter) Sinamics S210 (Siemens, Germany);
– Motor (Synchronous Motor SIMOTICS S-1FK2) (Siemens, Germany);
– Communication Network (PROFINET/Industrial Ethernet) [20].

The given functional diagram is the basis for developing a simulation model of a WEB-oriented servo drive frequency control system based on "Digital Twins" technology with the possibility of further improvement and expansion of functionality.

3.2. Development of a servo drive frequency control system based on PLC S7-1500 and Sinamics S210

3.2.1. Configuring and parameterizing the project hardware

After creating a new project in the TIA Portal environment (Siemens, Germany), the system hardware is configured and parameterized [14].

Fig. 2 shows the procedure for selecting the Simatic S7-1500 PLC (CPU 1515T-2 PN Version V4.0) in the portal interface (Portal view) of TIA Portal (Siemens, Germany) [10].

After selection, the corresponding PLC Simatic S7-1500 (Siemens, Germany) is added to the project as a component PLC_7 [CPU 1515T-2 PN] with a simultaneous transition to the project interface (Project view) (Fig. 3).

Similarly, FC Sinamics S210, is integrated into the project as a component Drive unit_1 [S210 PN] for servo drive control with a simultaneous transition to the project interface (Project view) (Fig. 4).

In the project interface, the project tree is displayed on the left, the workspace in the center, the hardware catalog on the right, and the command menu and toolbar at the top.

Hardware configuration consists of installing the necessary hardware modules into the project from the (Hardware catalog) according to the actual system configuration.

Parameterization (Properties) of the system hardware consists of setting the appropriate parameters for the PLC Simatic S7-1500, FC Sinamics S210 and other hardware modules, according to their functional purpose and operating modes.

To create a simulation model of frequency control, Sinamics S210 (3AC 200-480 V, 1 kW) was integrated into the project as a frequency converter, and a synchronous electric drive Simotics 1FK2 synchronous motor (3000.00 r/min, 1 kW, DRIVE-CLiQ encoder AM22, Multiturn 4096) (Siemens, Germany) was integrated as a servo drive (Fig. 4) [12].

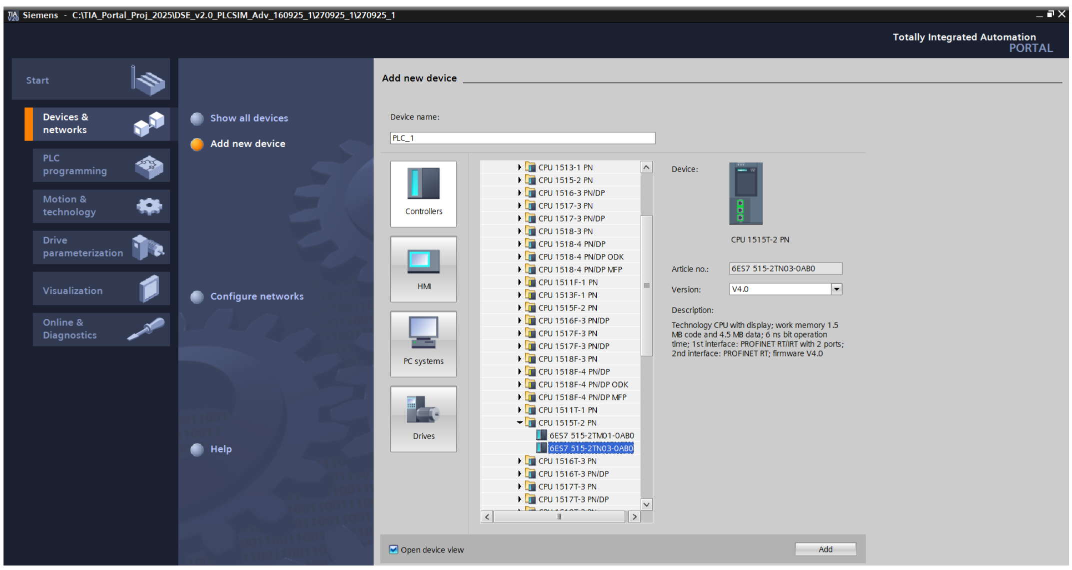

Fig. 2. Procedure for selecting PLC Simatic S7-1500 (CPU 1515T-2 PN Version V4.0) in the portal interface (Portal view)

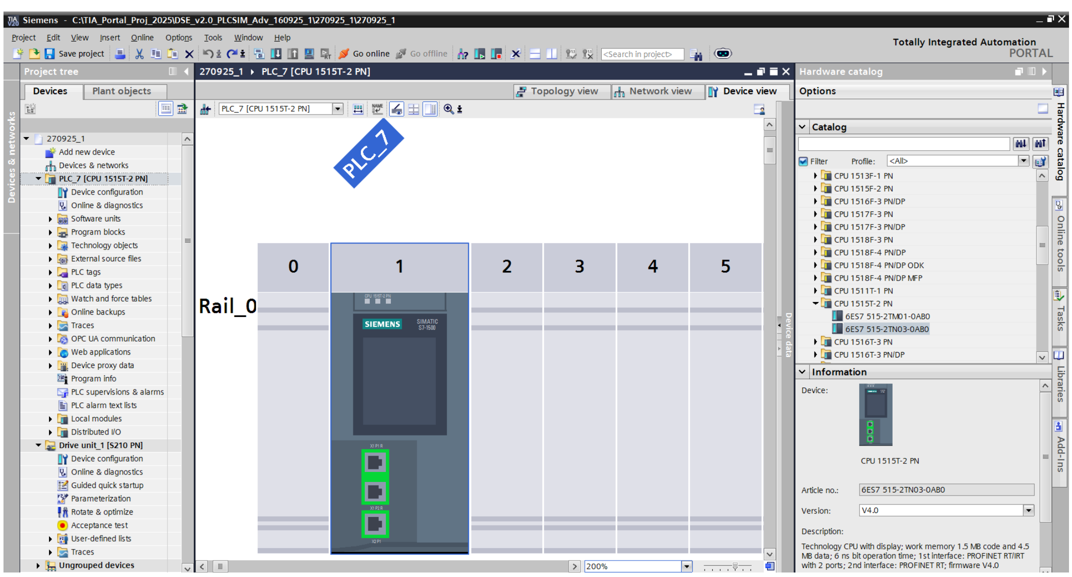

Fig. 3. PLC Simatic S7-1500 and FC Sinamics S210 in the project interface (Project view)

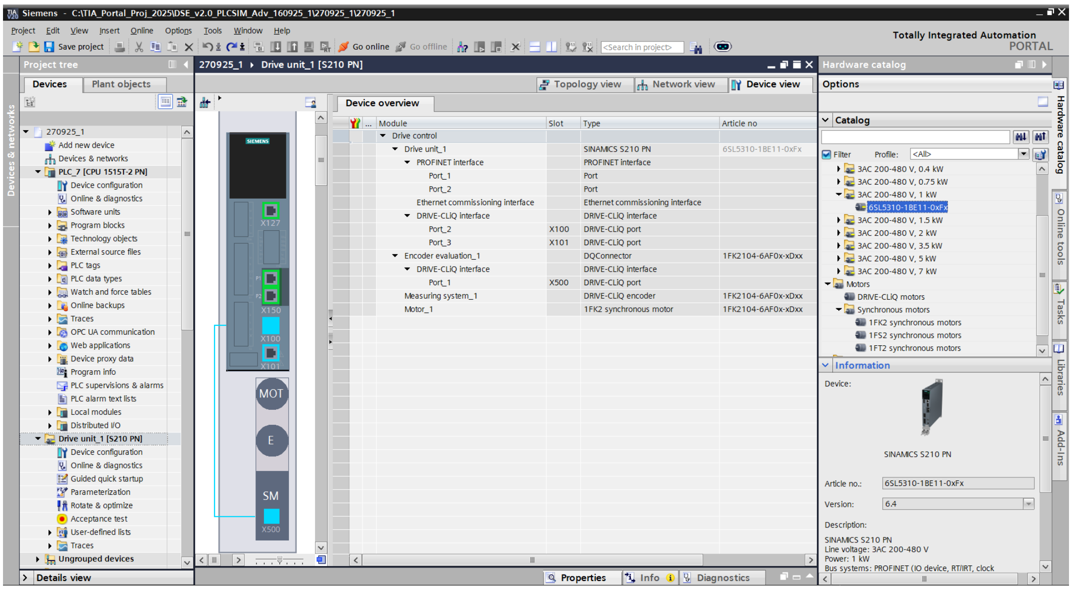

Fig. 4. Procedure for integrating FC Sinamics S210 and SIMOTICS S-1FK2 servo drive into a project

For interaction between the hardware components of the project, it is necessary to configure communication connections. Fig. 5 shows the developed communication environment of the system between PLC Simatic S7-1500 and FC S210 based on industrial communication PROFINET/Industrial Ethernet [20].

3.2.2. Development of the system application software

The next stage of design is the development of application software in the FBD (Function Block Diagram) language of the IEC 61131-3 standard [10] for the implementation of the SIMOTICS S-1FK2 servo drive frequency control algorithm based on PLC Simatic S7-1500 and FC Sinamics S210.

To unify the design procedures when developing the control system application program, a specialized technological object "SpeedAxis" [12] was used, which implements, as the main function, the servo drive speed control function, as well as setting and monitoring other parameters (Fig. 6).

Fig. 7 shows the section of basic parameters (Basic parameters) of technological object "SpeedAxis_1 [DB2]", which connect PLC (User program and Technology object Speed axis), frequency converter (Drive) and servo drive (motor).

In addition, when integrating into the project of technological object "SpeedAxis", Motion Control interrupt OBs are automatically generated: "MC_Servo [OB91]" and "MC_Interpolator [OB92]".

The "MC-Servo [OB91]" organizational unit is an internal (system) organizational block that performs servo control in a closed loop (feedback control). Provides functions for processing data from servo encoders, calculating control signals (speed, position, etc.), provides position/movement control in accordance with the tasks defined by the "Motion Control" program instructions [11, 12]. The [OB91] organizational unit is executed in a special cycle (Application cycle), which can be synchronized with the communication bus (Isochronous mode) or run cyclically with a specified interval.

The "MC_Interpolator [OB92]" organizational unit provides interpolation of motion/movement parameters (calculates intermediate "setpoint" values for technological objects "Motion Control"). The "MC-Servo [OB91]" and "MC_Interpolator [OB92]" organizational units form the core of "Motion Control" data processing in the PLC Simatic S7-1500. To organize data exchange between PLC Simatic S7-1500 and FC Sinamics S210, the project performed parameterization based on the communication telegram "SIEMENS_telegram_105" (Siemens, Germany) [21].

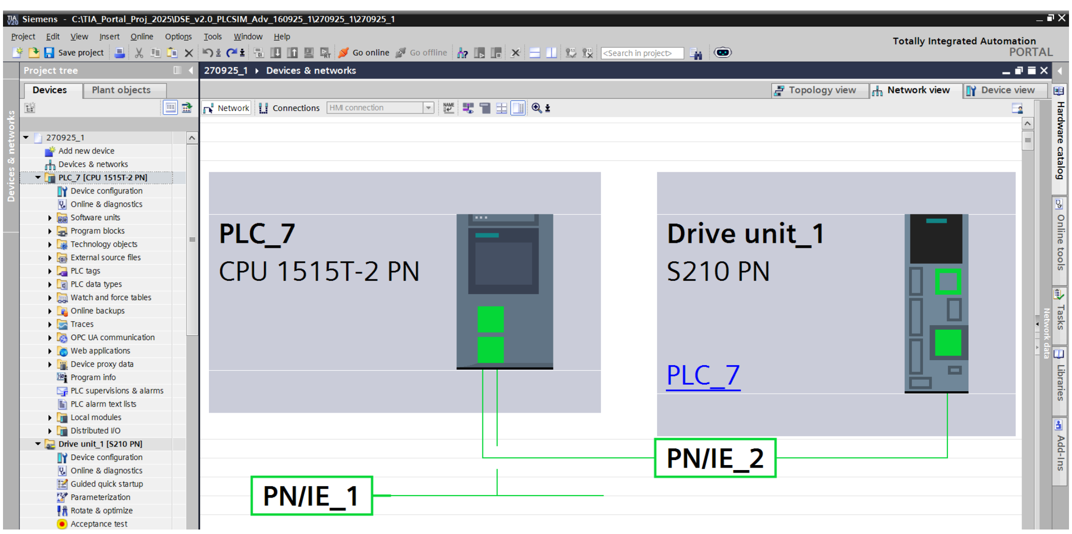

Fig. 5. Communication environment of the servo drive frequency control system based on PLC Simatic S7-1500 and FC Sinamics S210

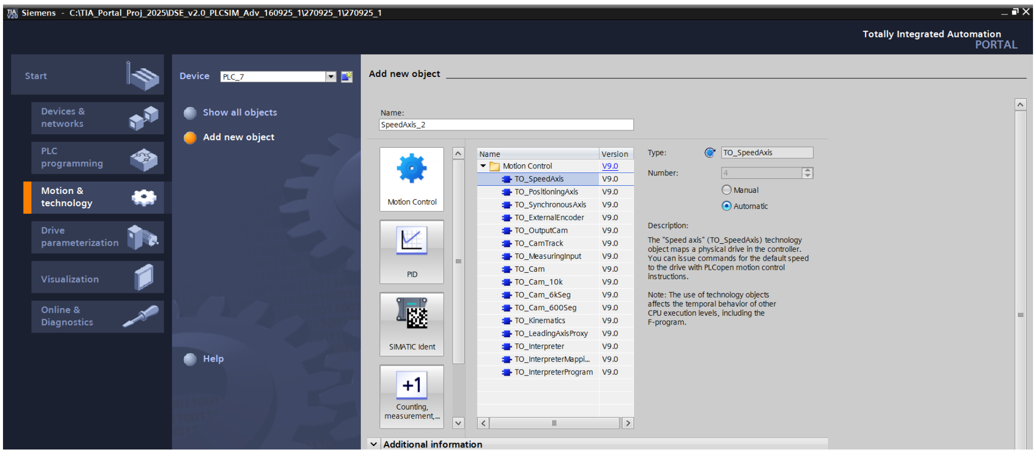

Fig. 6. "SpeedAxis" technological object for parameterization and implementation of servo frequency control functions

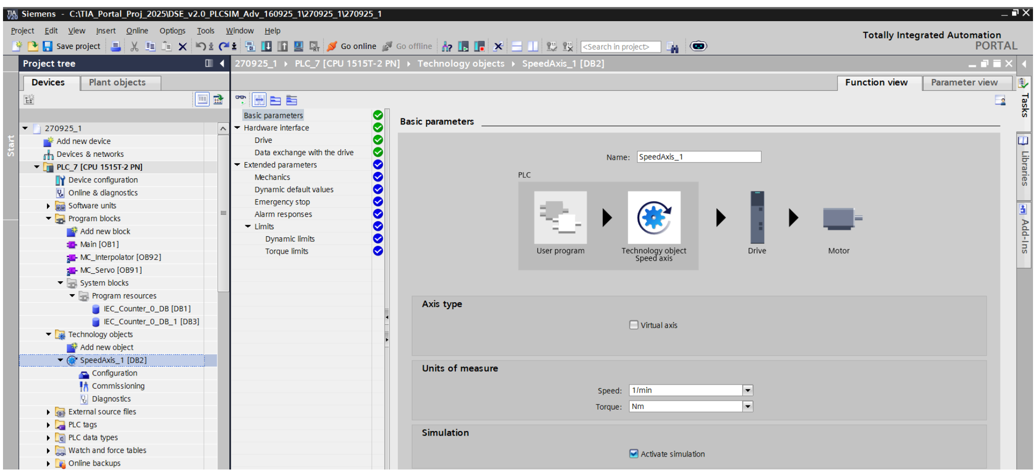

Fig. 7. "SpeedAxis" technological object for parameterization and implementation of frequency control functions of the servo drive

To build a simulation model of servo drive control based on the "Digital Twins" technology (PLC S7-1500 and Sinamics S210), "SIEMENS_telegram_105" was used. The choice of this type of communication connection is determined by the fact that only starting from the DriveSim Engineer V2.0 version – "Digital Twins" communication is supported, both with hardware PLCs and with PLCSIM Advanced [17].

The project, in addition to the main cycle block "Main [OB1]", includes the organizational blocks "MC_Servo [OB91]" and "MC_Interpolator [OB92]". Additionally, in "Main [OB1]" of PLC_7 [CPU 1515T-2 PN], a control algorithm for two servo speed values in revolutions per minute (2000 r/min and 4000 r/min) is implemented in the FBD language (Fig. 8).

In the line "Network 3:" the operator "MOVE" sends the control word (Control Word 1) from the PLC S7-1500 at the address "%QW256:P" to the FC Sinamics S210.

In the lines "Network 4:" and "Network 5:" the values of the set servo speed (2000 r/min and 4000 r/min) are formed in relative units (16#10000000 and 16#20000000), respectively, which are alternately (via the comparison operators "= =" and "MOVE") sent to the address "%QD258:P" to the FC Sinamics S210.

3.3. Implementation of interaction procedures between components of the simulation model based on the "Digital Twins" technology

To implement interaction between components of the simulation model of the servo drive frequency control system based on the "Digital Twins" technology, the following procedures must be performed:

– apply, create or generate virtual "Digital Twins" for the PLC Simatic S7-1500, the frequency converter FC Sinamics S210 and the servo drive SIMOTICS S-1FK2 (Siemens, Germany);

– perform basic parameterization of "Digital Twins" for the PLC Simatic S7-1500, the frequency converter FC Sinamics S210 and the servo drive SIMOTICS S-1FK2 (Siemens, Germany);

– load the components of the TIA Portal project (Siemens, Germany) into the corresponding virtual simulators "Digital Twins" and perform their parameterization for interoperability;

– test the operability of the developed simulation model of frequency control of a servo drive based on the "Digital Twins" technology in the "on-line" mode.

As a digital twin "Digital Twin" for the PLC Simatic S7-1500, a simulator with extended functionality S7-PLCSIM Advanced V7.0 with a loaded project in the "STOP" and "RUN" modes (Fig. 9) [16].

For the simulation of FC Sinamics S210 with integrated servo drive SIMOTICS S-1FK2, the procedure for generating their "Digital Twins" was performed using DriveSim Engineer V2.0 → DriveSim Engineer AddIn Generator (Siemens, Germany) (Fig. 10) [15, 17].

The basic parameterization of "Digital Twins" for PLC Simatic S7-1500, frequency converter FC Sinamics S210 and servo drive SIMOTICS S-1FK2 (Siemens, Germany) consists in determining and setting their basic parameters. Additionally, communication connections of the frequency control system of the servo drive based on "Digital Twins" technology are organized and parameterized for the correct functioning of the simulation model on a separate PG/PC.

Fig. 11 shows the procedure for parameterizing the communication mode of the virtual simulator S7-PLCSIM Advanced V7.0 (Siemens, Germany):

– S7-PLCSIM Softbus (internal only) without support for OPC UA and Webserver functions;

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– TCP/IP Single Adapter with support for OPC UA and Webserver functions;
– TCP/IP Multiple Adapter Adapter with support for OPC UA and Webserver functions.

For TCP/IP modes, virtual Ethernet communication (PLCSIM Virtual Adapter) is automatically enabled on the PG/PC workstation.

Fig. 12 shows the procedure for basic parameterization of the FC Sinamics S210 (Siemens, Germany) "Digital Twin":
– Connection to PLC (communication with the virtual simulator S7-PLCSIM Advanced (Siemens, Germany));
– Limits (limit values of the main parameters of FC Sinamics S210 (Siemens, Germany));
– I/O configuration (parameterization of digital and analog inputs/outputs);
– Telegrams (parameterization of communication telegrams);
– Summary (completion of the procedure and generation of a report on the parameterization results).

Fig. 13 shows the basic parameterization procedure for the "Digital Twin" servo drive SIMOTICS S-1FK2 (Siemens, Germany) which consists of:
– Encoder (DRIVE-CLiQ AM22 Multiturn 4096);
– Rated current (3.00 Ams);
– Rated speed (3000 prm);
– Rated voltage (250 Vms);
– Rated power (1.00 kW);
– Rated torque (3.20 Nm);
– Supply voltage (400 V);
– Motor ambient temperature (40°C);
– Direction of rotation (Clockwise);
– Positive speed limit (8000 rpm);
– Negative speed limit (–8000 rpm);
– Torque limit upper (11.55 Nm);
– Torque limit lower (–11.55 Nm);
– OFF1 ramp-down time (1.000 s).

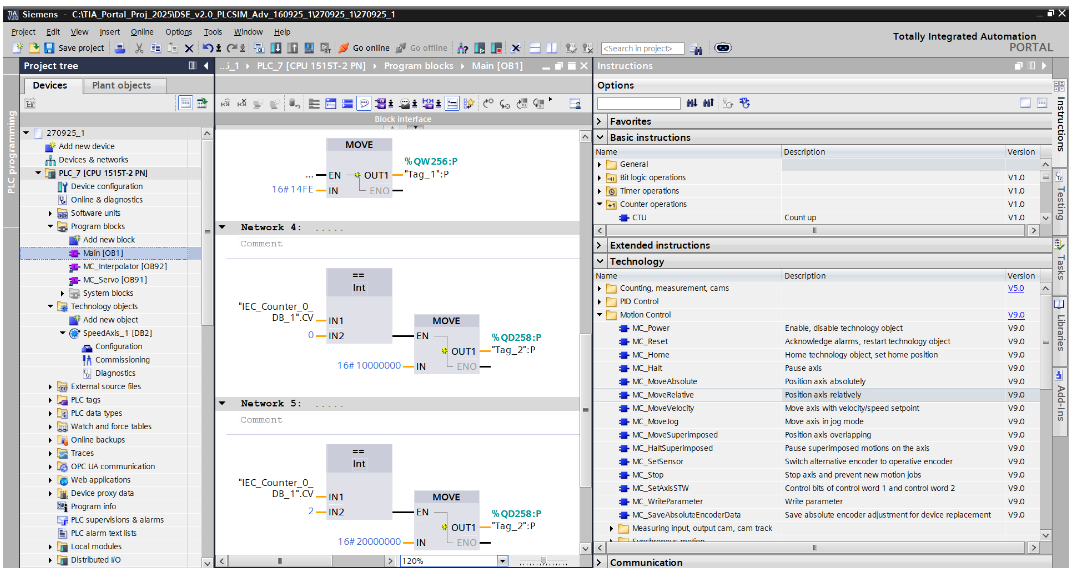

Fig. 8. Fragment of the application program for controlling two values of the set speed of the servo drive in revolutions per minute (2000 r/min and 4000 r/min)

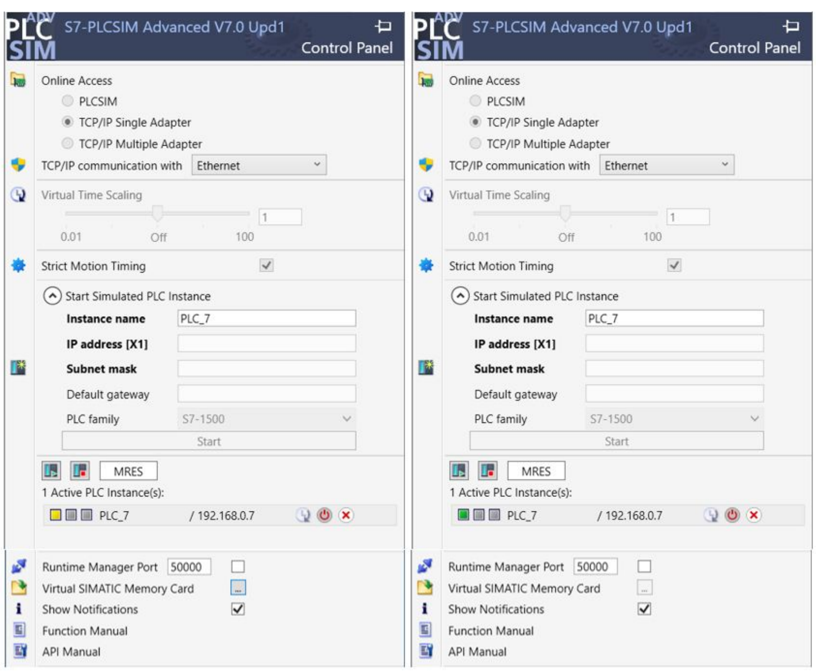

Fig. 9. "Digital Twin" for PLC Simatic S7-1500 – S7-PLCSIM Advanced V7.0 simulator with a loaded project in "STOP" and "RUN" modes

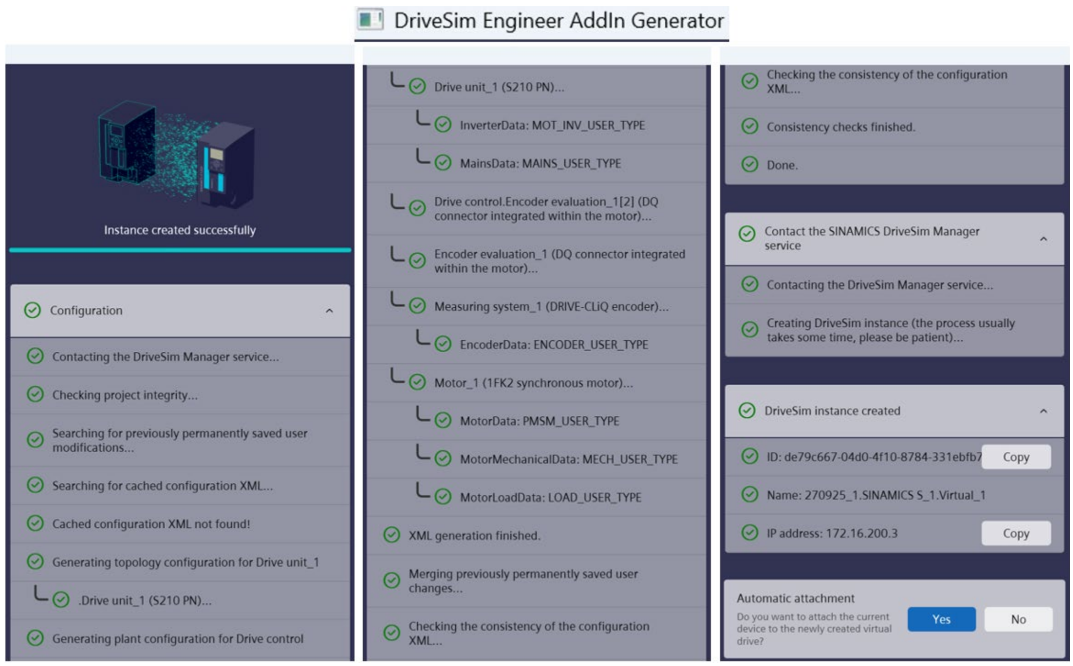

Fig. 10. Procedure for generating "Digital Twins" FC Sinamics S210 with integrated servo drive SIMOTICS S-1FK2 using DriveSim Engineer V2.0 → DriveSim Engineer AddIn Generator

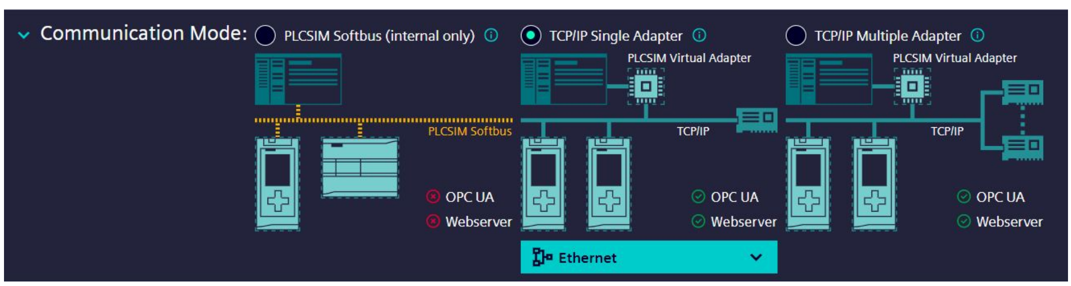

Fig. 11. Procedure for parameterizing the communication mode of the virtual simulator S7-PLCSIM Advanced V7.0

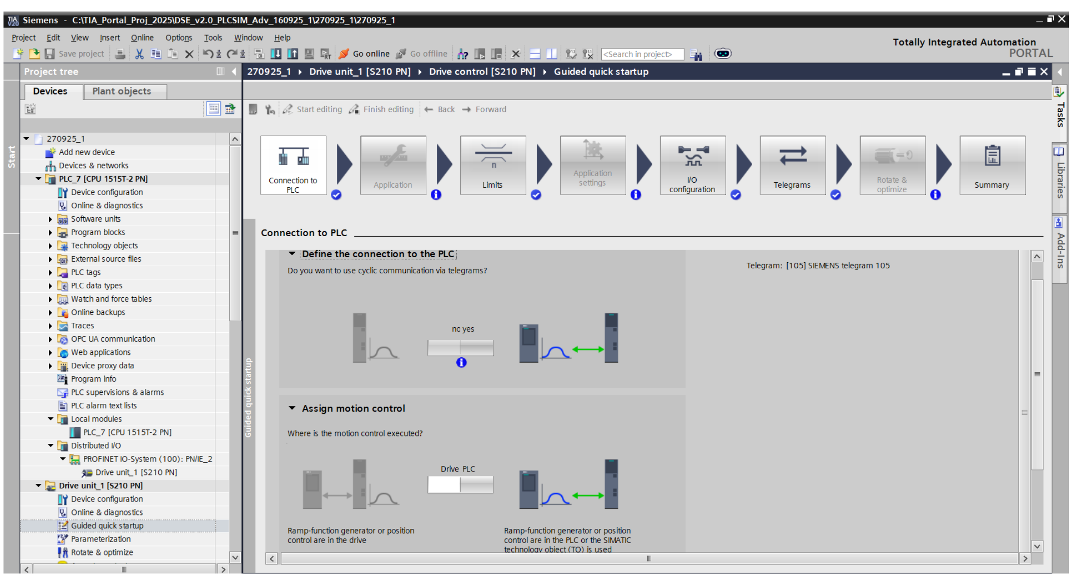

Fig. 12. Basic parameterization procedure for the "Digital Twin" for the FC Sinamics S210 frequency converter

The parameterized components of the simulation model are loaded into the corresponding virtual simulators "Digital Twins" using the TIA Portal tool software for interoperability.

Fig. 14 shows the procedure for loading the Simatic PLC S7-1500 into the virtual simulator S7-PLCSIM Advanced V7.0 in the "on-line" mode via the PG/PC interface "Siemens PLCSIM Virtual Ethernet Adapter" [16, 22]. Fig. 15 shows the procedure for loading FC Sinamics S210 with integrated servo drive SIMOTICS S-1FK2 in the "on-line" mode into their virtual "Digital Twins" via the PG/PC interface "SINAMICS DriveSim Virtual Network Interface".

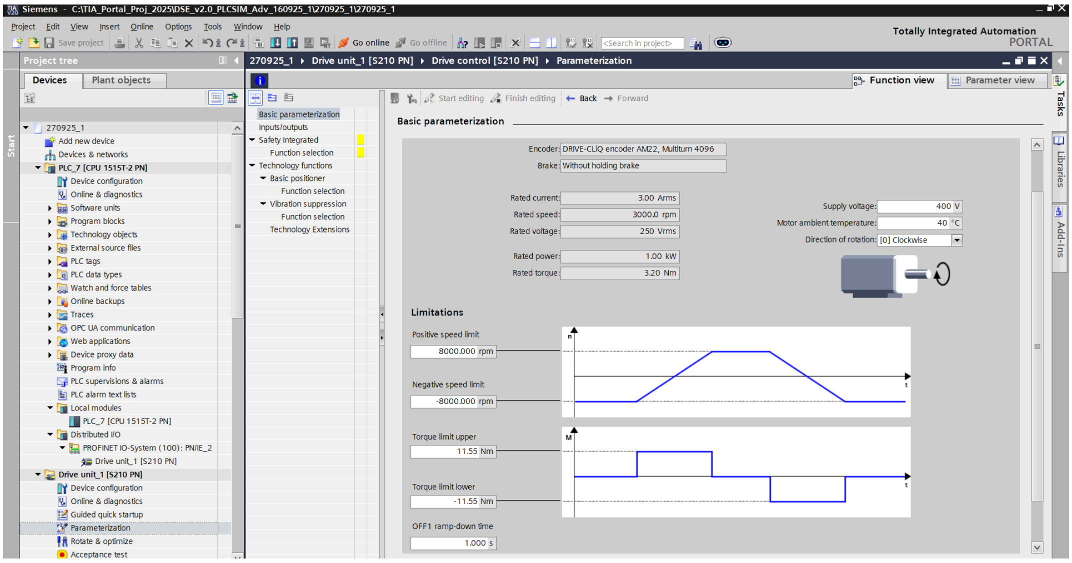

Fig. 13. Basic parameterization procedure for the SIMOTICS S-1FK2 servo drive

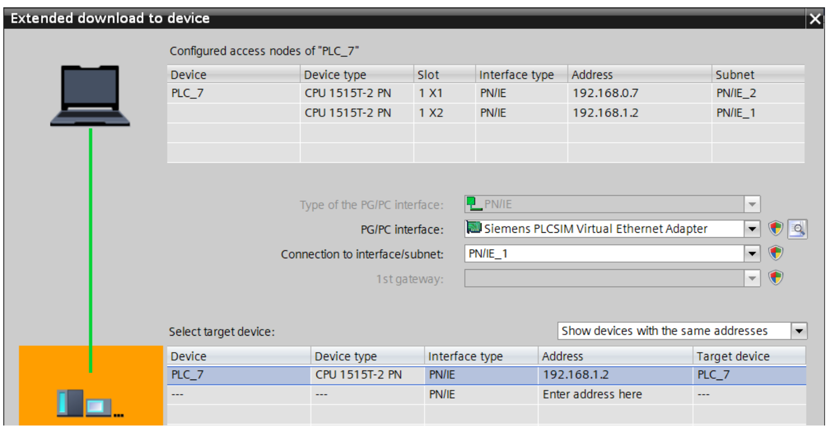

Fig. 14. Procedure for loading PLC Simatic S7-1500 into the virtual simulator PLCSIM Advanced V7.0 in the "on-line" mode via the PG/PC interface "Siemens PLCSIM Virtual Ethernet Adapter"

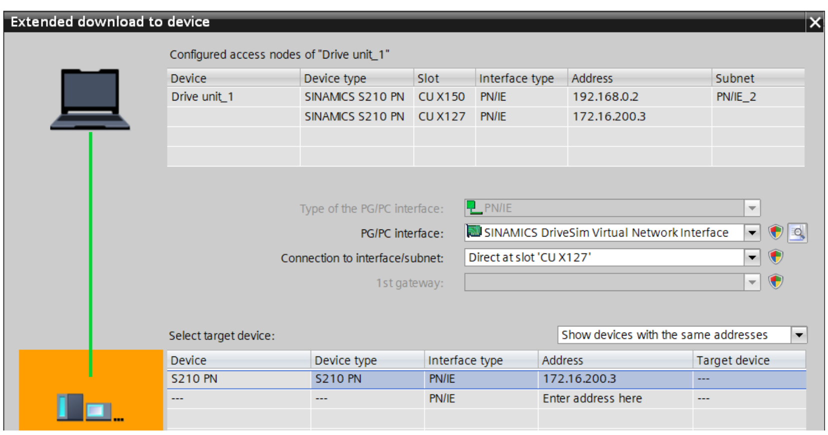

Fig. 15. Procedure for loading FC Sinamics S210 with integrated servo drive SIMOTICS S-1FK2 in the "on-line" mode into their virtual "Digital Twins" via the PG/PC interface "SINAMICS DriveSim Virtual Network Interface"

The result of testing in the "on-line" mode the operability of the developed simulation model of frequency control of the servo drive based on the "Digital Twins" technology is shown in Fig. 16 and Fig. 17, respectively.

In the TIA Portal project tree, PLC_7 [CPU 1515T-2 PN] and Drive_Unit_1 [S210 PN] function correctly in the "on-line" mode (all project components are indicated by green markers) (Fig. 16). In the toolbar "Online tools → Options → CPU Operator panel → Cycle time" PLC_7 [CPU 1515T-2 PN] executes in the "RUN" mode the current cycle "Current/last" equal to 1.055 ms.

"Digital Twins" FC Sinamics S210 with integrated SIMOTICS S-1FK2 was tested in the "Stop/Start Servise" and "Stop/Start Fieldbus Connector" modes using the "DriveSim Manager" module of the DriveSim Engineer V2.0 software package (Siemens, Germany) (Fig. 17) [17, 23]. At the same time, stable compatible operation of the components of the simulation model with the specified functionality was recorded.

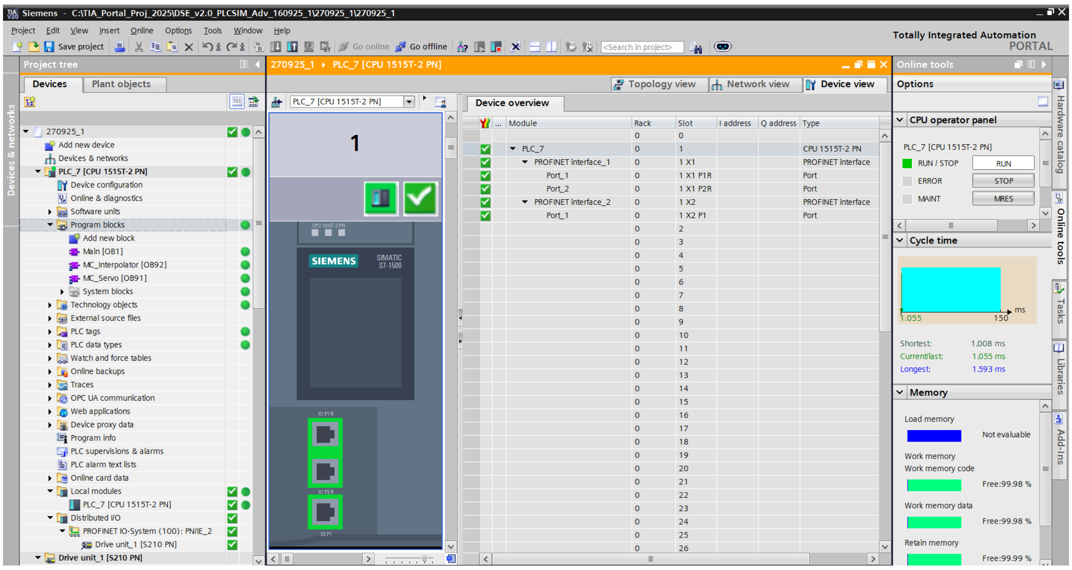

Fig. 16. Result of "on-line" testing of the PLC_7 [CPU 1515T-2 PN] operability based on the "Digital Twins" technology

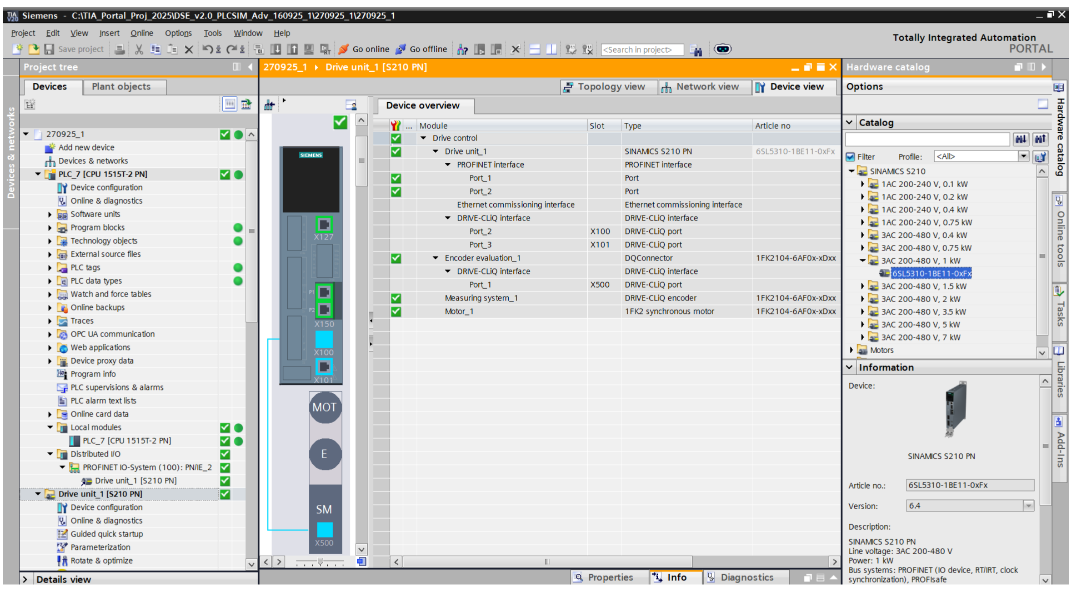

Fig. 17. Result of "on-line" testing of the Drive_Unit_1 [S210 PN] operability based on the "Digital Twins" technology

In addition, Fig. 18, *a* shows the correct interoperability of the virtual "Digital Twins" PLC_7 [CPU 1515T-2 PN] and Drive_Unit_1 [S210 PN] in the "DriveSim Manager" tool panel of the DriveSim Engineer V2.0 software package (Siemens, Germany).

The virtual FC Sinamics S210 with the integrated servo drive SIMOTICS S-1FK2 is displayed in the "DriveSim Manager" as "270925_1.SINAMICS S_1.Virtual_1". Additionally, the cyclic data exchange mode "CONNECT" is displayed (cyclical display of the icon in the upper left corner) (Fig. 18, *a*).

Fig. 18, *b*, *c*, *d* show the functioning of the virtual component "270925_1.SINAMICS S_1.Virtual_1" in the "STOP", "DOWNLOAD" and "RUN" modes, respectively.

3.4. Testing the simulation model of the servo drive frequency control system using the "Digital Twing" Web server

The hardware used in the project to create a simulation model of the servo drive frequency control system based on the "Digital Twins" technology supports the built-in WEB server [13].

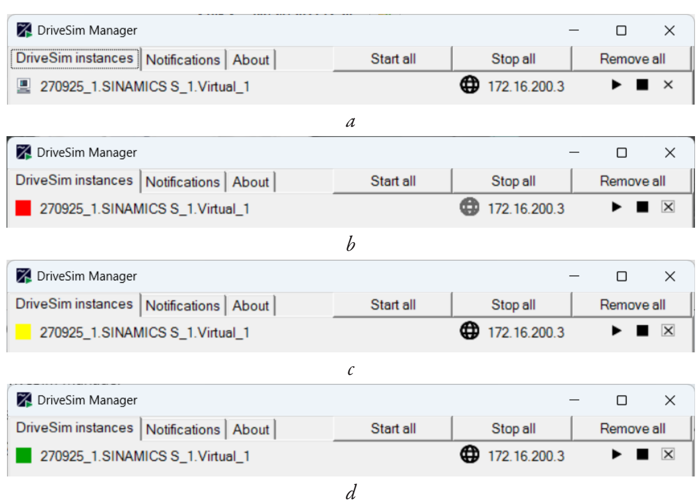

Fig. 18. Functioning and display states of the "270925_1.SINAMICS S_1.Virtual_1" virtual component in the following modes: *a* – "CONNECT"; *b* – "STOP"; *c* – "DOWNLOAD"; *d* – "RUN"

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For testing and studying the operating modes of the frequency-controlled servo drive, the built-in WEB server FC Sinamics S210 is of considerable interest.

To test the simulation model of the servo frequency control system using the built-in WEB server, it is necessary to activate this function when parameterizing the FC Sinamics S210 in the TIA Portal project.

For communication with the "Digital Twins" FC Sinamics S210 via the built-in WEB server (Siemens, Germany), a secure communication connection "X127: Web server access via HTTPS (port 443)" is used.

The FC Sinamics S210 WEB server (Siemens, Germany) provides the following functions, some of which will be used in the process of testing the simulation model (Fig. 19):

– commisioning (Quick setup, Advanced setup, Optimization, Safety integrated);
– monitoring and operation (Drive status, Inputs/outputs);
– diagnostics (Messages, Diagnostics buffers, Safety Integrated, Connection Overview, Communication, Control/status word);
– parameter (Parameter list);
– backup and restore;
– system (Settings, Protection & Security, Licenses, Firmware update, About Web server).

In addition to generating "Digital Twins" FC Sinamics S210 with integrated servo drive SIMOTICS S-1FK2, DriveSim Engineer V2.0 has the functionality to create and manage simulation parameter sets [17].

These parameters include (default values), Fig. 20:

– Device supply voltage, 400 V;
– Total moment of inertia, 7.6E-05... kg · m^2;
– Inertia factor, 5 p. u.;
– Enable mechanical load, 1:Yes;
– Constant load torque, 0.01 p. u.;
– Linear load torque, 0.01 p. u.;
– Quadratic load torque, 0 p. u.;
– Load oscillation: load inertia 1, 0 kg · m^2;
– Load oscillation: spring rate 1, 0 Nm/rad;
– Load oscillation: damping, 0 Nms/rad.

The notation p. u. (per unit) is a way of representing physical quantities as a fraction of a base value (for compatibility of characteristics of machines and mechanisms and simplification of calculations in electrical systems).

The above parameters are shown in (Fig. 20).

Fig. 21 shows the process of testing the simulation model of the servo drive frequency control system according to the "Monitoring and operation (Drive status)" function using the WEB server (for the default values of the simulation parameters).

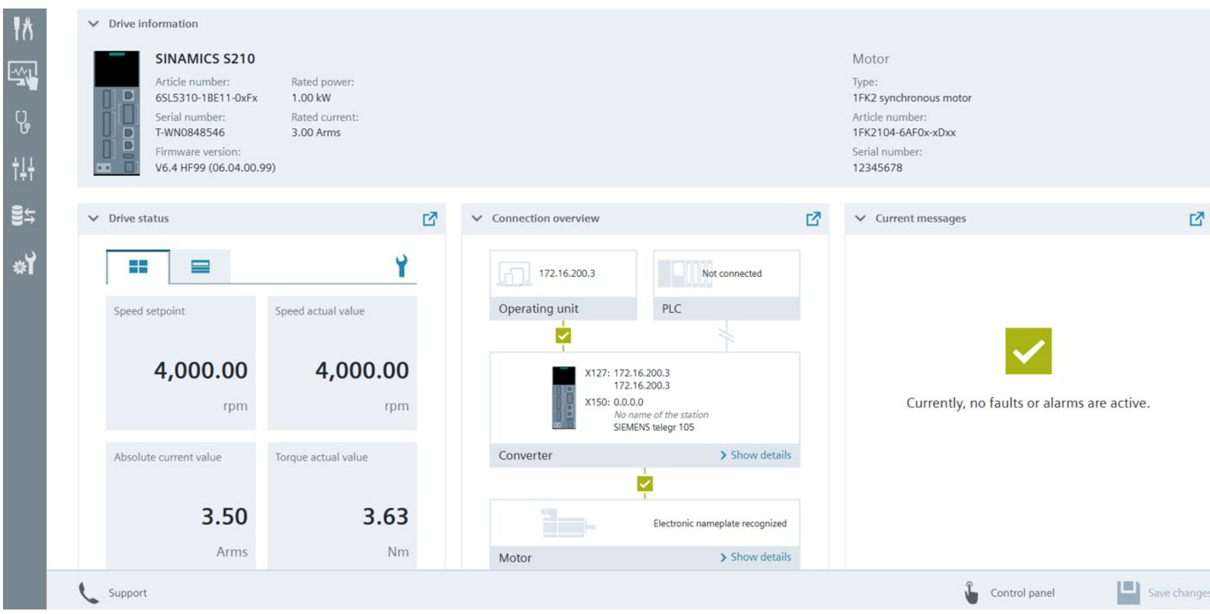


Fig. 19. WEB server "Digital Twin" FC Sinamics 210 with integrated servo drive SIMOTICS S-1FK2 in simulation model mode

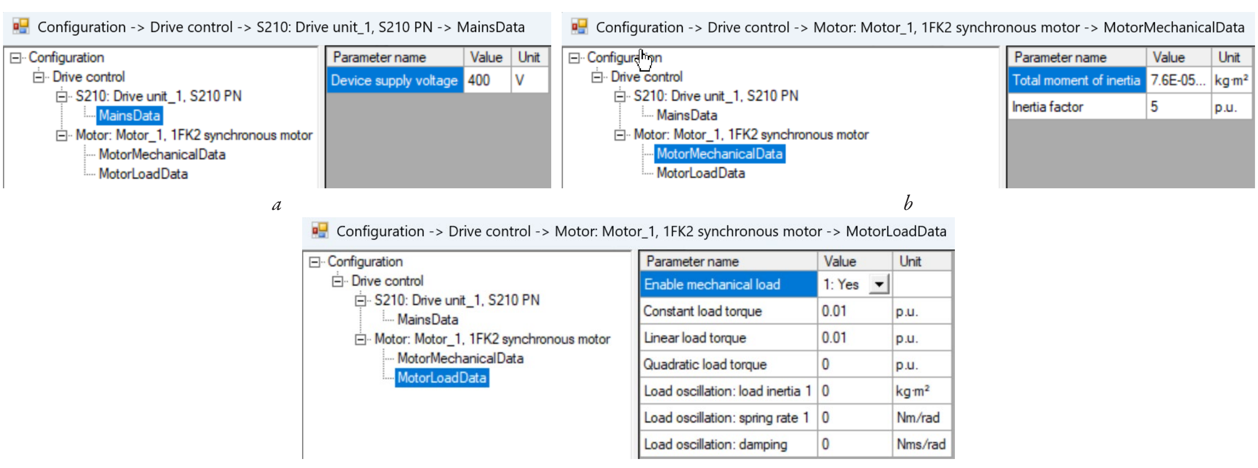
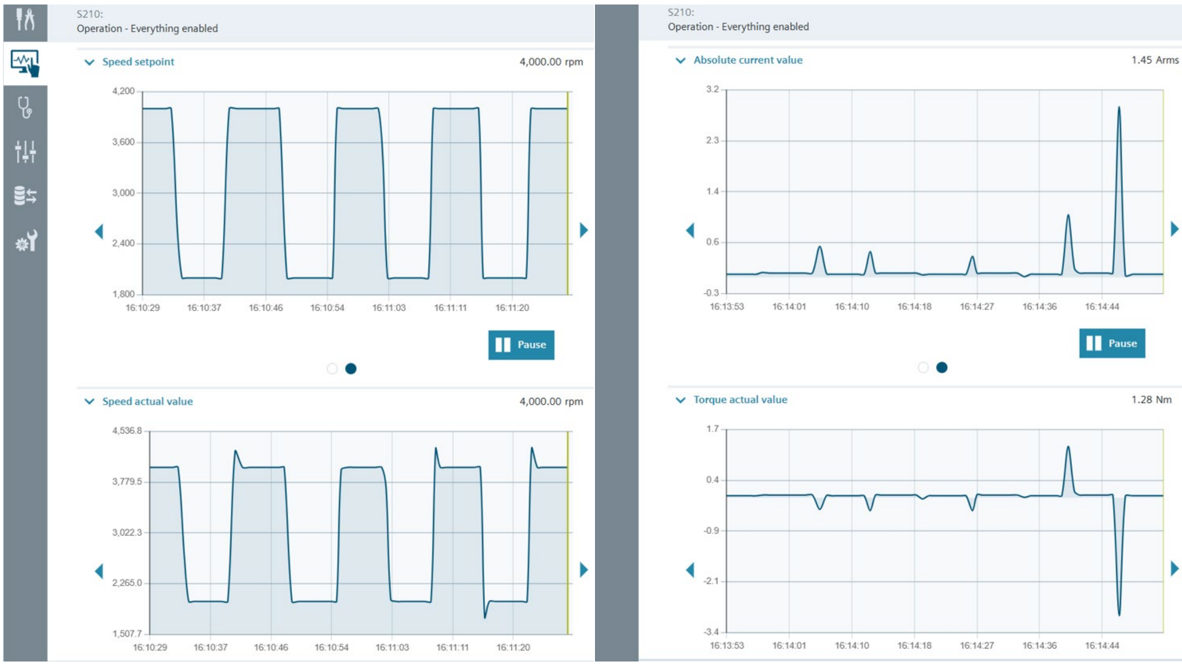


Fig. 20. DriveSim Engineer V2.0 functionality for creating and managing simulation parameter sets (default values):
a – MainsData; *b* – MotorMechanicalData; *c* – MotorLoadData



a *b*

Fig. 21. The process of testing the simulation model using the WEB server "Digital Twin" FC Sinamics S210 (basic values of simulation parameters): *a* – Speed setpoint and Speed actual value; *b* – Absolute current value and Torque actual value

The time dependences of the servo drive rotation speed in rpm for the parameters "Speed setpoint" and "Speed actual value" (Fig. 21, *a*) and "Absolute current value" and "Torque actual value" (Fig. 21, *b*) are shown.

Fig. 22, 23 shows the process of testing the simulation model of the servo drive frequency control system according to the "Monitoring and operation (Drive status)" function using the WEB server. In this case, modified simulation parameters were applied:

– Inertia factor, 1 p. u.;
– Constant load torque, 0.5 p. u.;
– Linear load torque, 0.5 p. u.

Visual analysis of the test results in Fig. 21 and Fig. 23 shows that the control system responds appropriately to changes in load parameters (Inertia factor, Constant load torque, Linear load torque). At the same time, the operating mode recorded in Fig. 23 (with modified mechanical load parameters) is more stable and corresponds to the algorithm of dynamic frequency control of the servo drive.

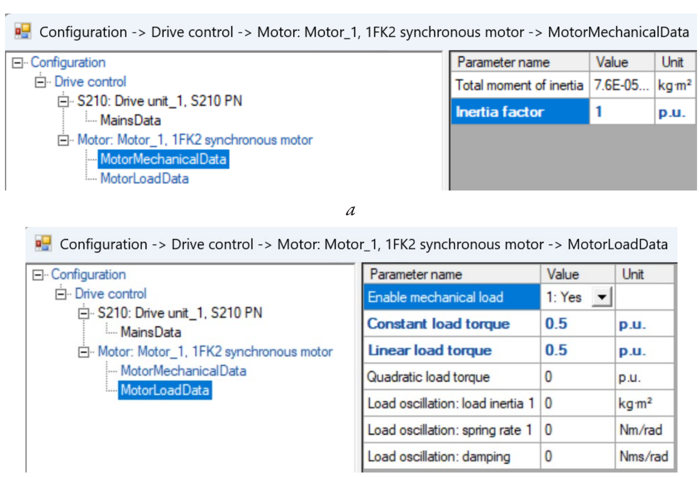
Thus, the WEB server of the simulation model can be used for parameterization, control of technological parameters, diagnosis of defects, maintenance and commissioning of FC Sinamics S210 with a servo drive of the SIMOTICS S-1FK2 type.

The main criterion in the development of the simulation model of the WEB-oriented servo frequency control system was the comprehensive solution of the tasks based on the developed functional diagram (Fig. 1) and the project in the TIA Portal environment (Siemens, Germany) (Fig. 2–5).

The following variants of the frequency control system based on PLC Simatic S7-1500 and FC Sinamics S210 are possible (fully hardware, combined, or fully virtual configurations):

– hardware PLC Simatic S7-1500 ↔ hardware FC Sinamics S210;
– hardware PLC Simatic S7-1500 ↔ virtual FC Sinamics S210;
– virtual PLC Simatic S7-1500 ↔ hardware FC Sinamics S210;
– virtual PLC Simatic S7-1500 ↔ virtual FC Sinamics S210.

The fully virtual configuration of the system is, from the authors' point of view, the most complex, which is associated with certain functional limitations regulated by the technical specifications for the software for creating "Digital Twins" [16, 17].



b

Fig. 22. Modified simulation parameters: *a* – MotorMechanicalData; *b* – MotorLoadData

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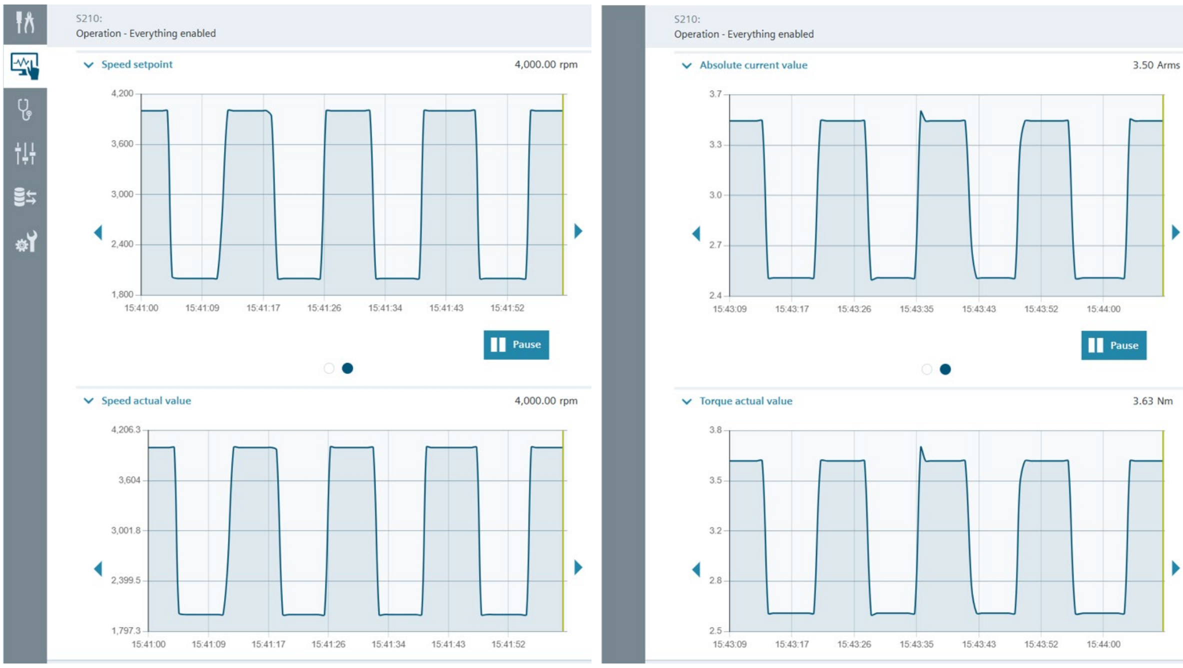

a *b*

Fig. 23. The process of testing the simulation model using the WEB server "Digital Twins" FC Sinamics S210 (modified simulation parameter values): *a* – Speed setpoint and Speed actual value; *b* – Absolute current value and Torque actual value

The system project in the TIA Portal includes the technological PLC Simatic S7-1515T [11], optimized for operation with the drive systems "Motion Control", frequency convertor Sinamics S210 [12] and the synchronous servo drive SIMOTICS S-1FK2 [13] (Siemens, Germany). The project also includes application software in the FBD language of the IEC 61131-3 standard for implementing the frequency control algorithm of the SIMOTICS S-1FK2 servo drive based on the PLC Simatic S7-1500 and FC Sinamics S210 (Siemens, Germany).

The developed application program includes a specialized technological object "SpeedAxis" [24, 25], which implements, in addition to the main function of controlling the speed of the servo drive, the function of setting and controlling other parameters, including the parameters of the built-in encoder (Fig. 6). The implementation of the procedure (Basic parameters) of the technological object "SpeedAxis" creates cross-connections between the hardware and software components of the TIA Portal project (Siemens, Germany) for optimal interaction. When integrating the "SpeedAxis" technological object into the project, the "MC_Servo [OB91]" and "MC_Interpolator [OB92]" organizational blocks are automatically generated, which form the "Motion Control" core of data processing in the PLC Simatic S7-1500 (Fig. 7). Additionally, the "MC_Servo [OB91]" organizational block ensures the functioning of the PLC and FC in isochronous real-time mode.

To organize data exchange between PLC Simatic S7-1500 and FC Sinamics S210, the project has been parameterized based on the communication telegram "SIEMENS_telegram_105" (Siemens, Germany). The choice of this type of communication connection is determined by the fact that only starting from the DriveSim Engineer V2.0 version, "Digital Twins" communication is supported, both with hardware PLCs and with PLCSIM Advanced [17].

In the organizational block of the main cycle "Main [OB1]" PLC_7 [CPU 1515T-2 PN], a control algorithm is implemented for two values of the set servo speed in revolutions per minute (2000 r/min and 4000 r/min) with a switching period of 12 s (Fig. 8).

To enable interaction between components of the simulation model of the servo drive frequency control system based on the "Digital Twins" technology, the following procedures were implemented:

– virtual "Digital Twins" were applied, created or generated for PLC Simatic S7-1500, FC Sinamics S210 and SIMOTICS S-1FK2 (Siemens, Germany) (Fig. 9–11);
– basic parameterization of "Digital Twins" was performed for PLC Simatic S7-1500, FC Sinamics S210 and SIMOTICS S-1FK2 (Siemens, Germany) (Fig. 12, 13);
– components of the TIA Portal project (Siemens, Germany) were loaded into the corresponding virtual simulators "Digital Twins" and their parameterization for interoperability was performed (Fig. 14, 15);
– the operability of the developed simulation model of frequency control of a servo drive based on the "Digital Twins" technology was tested in the "on-line" mode (Fig. 16–18).

According to the results of the "on-line" testing, the compatible functionality of the components of the simulation model was confirmed by the execution time of the main PLC cycle "Main [OB1]" within 1 ms (Fig. 16).

The advantage of the developed simulation model is the support at the "Digital Twin" level of the built-in WEB server FC Sinamics S210 (Siemens, Germany), for which the activation and parameterization procedures were performed. For communication with the "Digital Twins" FC Sinamics S210 (Siemens, Germany) through the built-in WEB server, a secure virtual communication connection "X127: Web server access via HTTPS (port 443)" was used, similar to the corresponding real connection.

The organization of a virtual WEB server at the level of "Digital Twins" FC Sinamics S210 (Siemens, Germany) expands the functionality of the developed simulation model for the tasks of parameterization, testing and control of technological parameters of a frequency-controlled servo drive (Fig. 19–23).

The limitations of research performed at this stage include the binding of the simulation model to specific hardware and software tools Simatic S7 (Siemens, Germany), as well as the power of SIMOTICS S-1FK2 servo drives (Siemens, Germany) within the limits of 7 kW.

The disadvantages of the work include the fact that not all the functional capabilities of "Digital Twins" were implemented in terms of dynamic changes in time of servo drive parameters (axis load, torque, inertia, etc.).

Continuation of research in this direction may concern the creation of new, improved simulation models based on the "Digital Twins" technology with the functions of regulators [26], vibration control [27] and other technological parameters. At the same time, methods and hardware and software tools, algorithms and application software can be improved, including on the basis of practical testing of research results.

4. Conclusions

1. A functional diagram has been developed and the technical characteristics of the components and hardware and software of the simulation model of a WEB-oriented servo drive frequency control system based on the "Digital Twins" technology have been determined. The functional diagram includes the technological PLC Simatic S7-1515T, optimized for work with "Motion Control" drive systems, Frequency Convertor Sinamics S210 and synchronous servo drive SIMOTICS S-1FK2 (Siemens, Germany).

2. A project of a servo drive frequency control system based on PLC Simatic S7-1500, FC Sinamics S210 and servo drive SIMOTICS S-1FK2 (Siemens, Germany) has been developed in the TIA Portal environment. The hardware of the project has been configured and parameterized. The algorithm and application software of the system based on the technological object "SpeedAxis" and the FBD language of the IEC 61131-3 standard for the integration of components, parameterization and implementation of frequency control functions of the servo drive have been developed.

3. The interaction procedures between the components of the simulation model based on the "Digital Twins" technology have been implemented, which include the use, creation and generation of virtual PLCs Simatic S7-1500 and FC Sinamics S210 with an integrated servo drive SIMOTICS S-1FK2 (Siemens, Germany). The basic parameterization of the components of the simulation model and their loading from the TIA Portal project (Siemens, Germany) into the corresponding virtual "Digital Twins" has been performed. The operability of the developed simulation model in isochronous real-time mode with the execution time of the main cycle of the virtual PLC within 1 ms was tested in the "on-line" mode.

4. Testing and research of information processes of interaction between virtual components of the simulation model in the "on-line" mode and by means of the built-in WEB-server have been performed. Testing was carried out at speeds of 2000 and 4000 rpm. switched with a period of 12 s with basic and modified simulation parameters. Parameters of the set and actual rotation speeds, the current and torque at the output of the virtual frequency converter have been determined.

Conflict 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 article.

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Data availability

The manuscript has no related data.

Use of artificial intelligence

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

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For their part, they are ready for further cooperation by conducting scientific research, popularization in publications, and application for educational and industrial purposes of hardware and software based on the latest technologies of "Siemens AG".

Authors' contributions

Leonid Zamikhovskyi: formation of research aim and objectives, development of an algorithm for the functioning of a simulation model, study of the operating modes of a simulation model of a control object, testing and verification of the reliability of the results obtained; ***Mykola Nykolaychuk***: development of individual components of a simulation model, development of an algorithm and application software for a simulation model, study of the operating modes of a simulation model of a control object, testing and testing of the development results; ***Ivan Levitskyi***: development of individual components of a simulation model, development of an algorithm and application software for a simulation model, study of the operating modes of a simulation model of a control object, testing and testing of the development results.

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