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RESULTS OF DEVELOPING A LABORATORY TESTBENCH FOR REMOTE CONTROL OF A COMPRESSOR INSTALLATION BASED ON WEBHMI

Purpose. To develop and carry out experimental testing of a laboratory testbench for remote control of a diaphragm compressor with PID control capability, integrated into the architecture of a WebHMI-based SCADA system, suitable for educational and research purposes in the field of automated electric drive and control engineering.

Methodology. Methods of critical analysis and logical generalisation of research results in the field of remote control, automatic control theory, computer modelling, and experimental verification of the functional characteristics of the system were used. The developed methodology included architecture design, integration of hardware and software components, tuning of PID controller parameters, and verification of system performance under remote access conditions.

Findings. The structural architecture of the stand was implemented, combining a programmable logic controller, frequency converter, Raspberry PI, video cameras and WebHMI into a single information environment. Real-time monitoring and control, data archiving and experimental scenario playback were provided. Verification tests confirmed the correctness of data exchange, the stability of PID control to changes in settings and external disturbances, as well as the operability of the web interface in conditions of global access.

Originality. An architectural solution has been proposed that integrates a web-oriented SCADA platform with industrial-level control algorithms, enabling the implementation of a remote laboratory complex for compressor units and other similar systems with the ability to control and visualise the process in a multi-user environment.

Practical value. The developed testbench can be used in the educational process to develop practical skills in the field of automated electric drive, control engineering, as well as in scientific research to test control algorithms and analyse the characteristics of compressor systems. The results obtained create the prerequisites for further scaling of the system and expanding its functionality.

Keywords: *membrane compressor, SCADA, WebHMI, PID controller, remote access, Industry 4.0, cyber-physical system*

Introduction. The fourth industrial revolution, or Industry 4.0, is radically changing production processes by introducing total digitalisation and automation at all levels [1]. The key elements of this paradigm are cyber-physical systems, the Industrial Internet of Things (IIoT) [2] and cloud technologies, which enable flexible, scalable and efficient solutions for the automation of production processes. In such conditions, there is a critical increase in demand for engineering specialists who possess not only in-depth theoretical knowledge in the field of automation, but also practical skills in working with modern Supervisory Control and Data Acquisition (SCADA) systems, remote monitoring and control systems for technological processes [3].

Such systems are particularly important in the context of distance learning, which has become a necessity due to the COVID-19 pandemic and subsequent geopolitical challenges, particularly in Ukraine, due to full-scale military operations [4]. In this regard, the higher technical education system has faced unprecedented challenges that require immediate adaptation of the educational process [5]. This exposed an acute problem, namely the inability to provide students with full access to laboratory equipment. While theoretical disciplines have been successfully adapted to the online format, the acquisition of practical skills, which form the basis of engineering education, has been threatened. Simulation modelling, although a useful tool, cannot completely replace experience working with real physical equipment, with its inertia, non-linearities and external disturbances.

Thus, there is an urgent need to create and implement laboratory complexes with full remote access capabilities in the educational process [6]. This will ensure the continuity of the educational process for future specialists in difficult socio-economic conditions, allowing them to acquire practical skills regardless of their physical presence at the higher education institution.

Literature review. The problem of creating remote laboratories for engineering education is not new and is being actively researched by the scientific community. An analysis of publications in the Scopus and Web of Science databases has identified several key areas of research and existing solutions.

The first significant body of work is devoted to the development of remote laboratory architectures in the context of the transition to Industry 4.0. Such laboratories are considered an essential element in training specialists capable of working with cyber-physical systems [7]. Publications [8, 9] present various approaches to creating remote laboratory complexes based on the use of programmable logic controllers (PLCs), microcontrollers (Arduino, Raspberry Pi) and communication with the client side via web servers. The main focus of these studies is on hardware integration and the development of basic software for data transmission.

The authors in [10] proposed a laboratory testbench for online temperature monitoring in classrooms based on LoRaWAN. The system allows researching daily temperature fluctuations, optimising the operation of climate control systems, and displaying data in a web interface. Using the testbench helps students build practical skills in working with IoT technologies, and the authors have plans for further hardware and software improvements. In [11], a hardware and software complex was proposed for researching control systems for electro-pneumatic mechatronic systems based on Festo equipment and a Siemens S7-1200 controller. Relay-contactor and software control of technological processes using TIA Portal, FluidSIM and SCADA WinCC were implemented. The use of the testbench in the educational process develops students' practical skills and allows them to practise automatic control algorithms. A laboratory testbench for remote control of an electromechanical lift installation using modern web technologies and digital automation tools was proposed in [12]. Hardware and software for web access were implemented, allowing experimental research to be conducted in real time. Recent work [13] has shown that the integration of open-source platforms such as Node-RED and WebSocket proxy servers can provide a flexible and secure architecture for seamless interconnection of industrial hardware and educational tools, thereby enhancing students' hands-on learning experience in process control systems (Nelson Mandela University case study). Moreover, such approaches highlight the potential of combining physical experimental setups with digital twin models, enabling not only remote operation but also performance optimization and deeper knowledge retention in engineering education.

The second area focuses on the use of specific software for organising remote access, such as LabVIEW and MATLAB/Simulink [14, 15]. These platforms provide powerful visualisation and control tools, allowing for the creation of complex interfaces and the implementation of sophisticated algorithms. They have proven their effectiveness, but they have significant limitations: high licence costs, requirements for installing client software or plugins, which limits accessibility and creates platform dependency.

As part of the ELLI project – Excellent Teaching and Learning in Engineering Science – German universities have developed a series of remote and virtual laboratories for engineering education with a focus on manufacturing technologies [16]. Equipment for materials testing and pipe forming were implemented, as well as a Massive Open Online Course (MOOC) using remote laboratories. Virtual models and laboratories allow students to explore complex processes visually. Further development includes AR and additive manufacturing. Robotarium was presented in [17], a remote multi-robot research platform that provides access to hardware testbenches for academic and educational purposes free of charge. The system includes a server, user interface, tracking, virtualisation and local simulation modules (MATLAB/Python) that provide robot control, experimental data processing and code validation. The use of the testbench allows students and researchers to conduct hardware experiments remotely, taking into account the real complexities of robotics. In [18], the authors compared the performance of four software environments: C, Python, MATLAB, and LabVIEW during the development of a fully automated ultrasonic computed tomography (UCT) system. Two experiments were conducted for each language – without data processing and with data processing – to evaluate performance indicators such as start-up time, CPU, memory and I/O usage, as well as graphics rendering and real-time control efficiency. The authors emphasised that the choice of programming language depends on the specific application, ease of development, and licence cost: MATLAB and LabVIEW are commercial products, while C and Python are free and open source.

The third group of studies directly concerns control systems for pneumatic installations and compressors [19, 20]. In [21], compressor control systems and issues related to improving reliability against component failures are described. The above works consider mathematical models of compressors, pressure and performance control algorithms, in particular PID control. However, most of them focus on industrial applications or simulation modelling and do not address aspects of their integration into the educational process in the format of a remote laboratory.

In addition, modern research focuses considerable attention on improving the energy efficiency and control accuracy of electromechanical systems, which is important for their application in both industrial and educational laboratory complexes [22, 23].

Despite a significant number of publications, the analysis of existing solutions has revealed a number of systemic limitations:

1. Many of the systems presented are based on expensive commercial software (LabVIEW, MATLAB) or require significant effort to develop and maintain their own web servers, which complicates their dissemination to other educational institutions due to high cost and complexity of replication.
2. Solutions that require the installation of specialised software on the client side are not truly universal and convenient for students who use different operating systems and devices.
3. Some academic solutions, especially those based on microcontrollers, demonstrate the principle of operation but do not give students experience of interacting with industrial-grade systems, which are standard in real production.
4. Only a small portion of the works consider the use of modern cloud IIoT platforms and web-oriented SCADA, which are the basis of Industry 4.0 and provide maximum flexibility, scalability, and availability.
5. Existing solutions rarely have user-friendly learning interfaces or scenarios for students. There are no ready-made educational modules with instructions and user interfaces focused on distance learning of practical skills for working with compressors or related systems.

Unsolved aspects of the problem. The conducted analysis shows that although there are many solutions for creating remote laboratories, there is still a gap between academic developments and the requirements of modern industry in the context of total digitalisation and the need for distance learning. The problem of creating a cost-effective, easily scalable, and platform-independent laboratory testbench that would simulate a real industrial process and use modern, web-oriented control tools that fit the Industry 4.0 paradigm remains unresolved. Most existing systems are either too complex and expensive, or do not provide students with experience working with tools similar to industrial SCADA systems. The use of specialised cloud platforms, such as WebHMI, to solve this problem has not been sufficiently covered in academic literature.

Therefore, there are still gaps in the overall problem of remote monitoring and control of compressors. First, there are no open and accessible platforms that would combine a real laboratory compressor stand with an internet interface for students. Secondly, little attention has been paid to integrating such systems into a distance learning environment and adapting them to the requirements of COVID-19 and wartime. The issue of visualisation and intuitive control, which greatly facilitates practical training, has also not been fully resolved. Thus, there is a need to develop a specialised approach or environment that will allow students to work safely and effectively with compressor equipment in a remote format.

Purpose. The main aim of this article is to develop and experimentally test a laboratory testbench for remote control of a diaphragm compressor with PID control capability, integrated into the architecture of a WebHMI-based SCADA system, suitable for educational purposes and scientific research in the field of automated electric drives and control engineering. The object of the research involves processes of acquiring, transmitting and converting information in a web system for remote control of a laboratory compressor unit. The subject of the research is software and hardware of a web system for remote control of a laboratory compressor unit.

Methods. To achieve the aim of the study, a set of methods was used, including: critical analysis and logical generalisation of the results of previous scientific works in the field of remote control of electromechanical systems; provisions of control engineering; computer modelling methods; synthesis and analysis of structural and algorithmic solutions for web-oriented control systems; functional programming tools; and a combination of computer modelling and physical experimentation.

The methodological basis of the study is the development and experimental testing of a laboratory testbench for remote control of a membrane compressor with an implemented PID control mechanism. The main difference of the proposed approach is the use of the web-oriented WebHMI platform as a SCADA system to provide full remote access to equipment in real time. In contrast to traditional solutions based on commercial software (LabVIEW, MATLAB/Simulink), the chosen architecture involves the use of an embedded web server and open communication standards. This significantly reduces implementation costs, ensures platform independence, and facilitates system scaling.

Fig. 1 shows a generalised block diagram demonstrating the step-by-step development process – from the formulation of functional requirements and task setting to the creation of hardware and software components, testing, debugging and integration into the educational process.

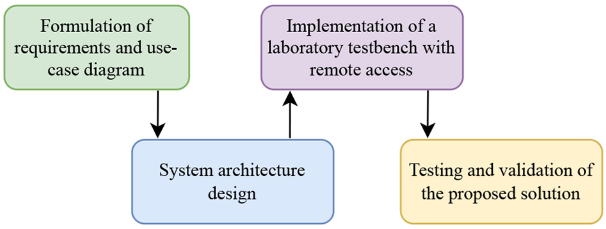

Fig. 1. Generalised block diagram of the development sequence for a laboratory testbench for a compressor installation

The requirements were formulated based on the analysis of educational and research needs, as well as taking into account the capabilities of modern SCADA systems and Industry 4.0 standards. Fig. 2 shows a use-case diagram, which also reflects the list of basic functional requirements for the system

Therefore, summarising the results of the research in the field of creating web-oriented systems for remote control of laboratory electromechanical equipment has allowed the formulation of a set of requirements for the system developed in this work. In particular, the functional requirements include: automatic pressure control in the air tank using a built-in PID algorithm integrated into the variable frequency drive (VFD); real-time monitoring of parameters with the ability to display current pressure values, setpoints, the status of actuators, and control dynamics in the form of trends; remote control of the installation, where the user must be able to start and stop the compressor, change the setpoint, edit the PID controller coefficients and control the execution of commands; use of a web interface without installing additional software on the client side, which provides universal access from any device with Internet access; system modularity, which provides for the integration of additional sensors, actuators or alternative control algorithms; authorisation and restriction of user actions in accordance with their assigned role; automatic disconnection of users when the active session limit is exceeded; the ability to restrict parameters when working with the user interface.

Non-functional requirements include: continuous operation of the system with the possibility of round-the-clock connection; maintaining operability during network failures and the ability to automatically resume operation; protecting access through user authentication and authorisation, as well as the use of secure communication channels; ease of expanding functionality by connecting new hardware and software modules; availability of an intuitive interface for users of different skill levels; compliance with industrial communication standards (Modbus RTU, Modbus TCP, Ethernet), allowing integration with related systems.

Therefore, these requirements determine not only the functional capabilities but also the qualitative characteristics of the system, which ensure its suitability for educational and research applications.

Fig. 3 shows a generalised structural diagram of the architecture of the system under development. It is based on four key components:

- hardware level: membrane compressor, induction motor, pressure sensor, valve system and air tank;

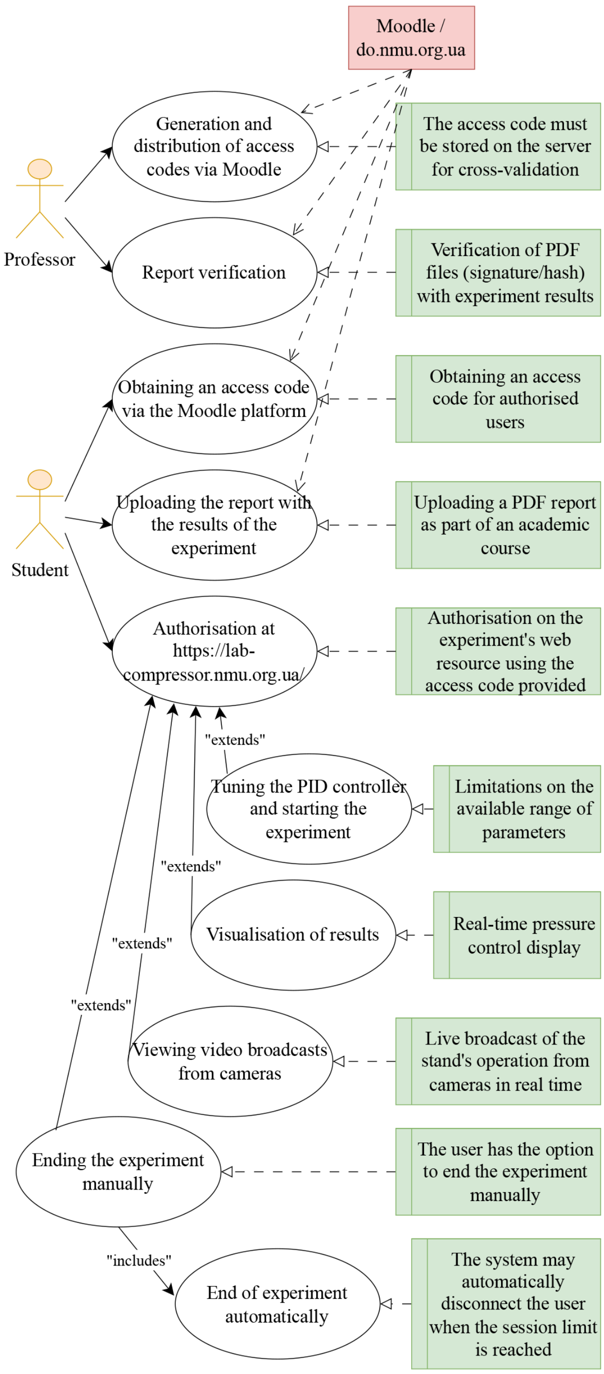

Fig. 2. Use-case diagram and functional requirements

- control level: variable frequency drive (VFD) with built-in PID controller that generates a control signal for the induction motor;

- SCADA level: a web server responsible for acquiring, processing and displaying data, as well as implementing remote control;

- user level: a web interface accessible via a browser from anywhere in the world, providing interactive communication between the student or researcher and the system.

The system developed in Fig. 3 operates on the basis of a closed-loop automatic control circuit, in which the value of the controlled parameter (pressure) is continuously measured, compared with the setpoint, and used to generate a corrective action. Data transmission from the pressure sensor to the controller as feedback is carried out in the form of an analogue signal, after which the VFD executes the control algorithm and changes the speed of the electric motor. At the conceptual level, the system's operation can be summed up as the coordinated interaction of the four levels mentioned above. At the hardware level, the status of the object is registered and data is transmitted to the control circuit. At the control level, mathematical processing of information is performed, implementing the PID control algorithm and generating a control signal. According to this signal, the operating mode of the object changes, ensuring stabilisation of the parameter within the specified range. At the same time, data on the current state of the system is sent to the SCADA level, where it is displayed in the form of visualised parameters, graphical trends and interactive indicators. Due to integration with SCADA, the user can not only observe the dynamics of the process but also change the setpoint or controller parameters remotely. Therefore, the system's operation ensures the implementation of a closed control loop with interactive user interaction via a web interface.

The last two stages of development (Fig. 1) included the following: selection of hardware components, development of pneumatic and electrical diagrams, integration of sensors and actuators; selection of initial parameters (coefficients *P*, *I*, *D*), verification of control adequacy under variable load conditions; creation of a web interface in WebHMI, configuration of data collection and display channels, formation of trends and control panels; verification of data exchange correctness, interface compliance with functional requirements; verification of system stability when changing settings; analysis of remote operation from different types of devices.

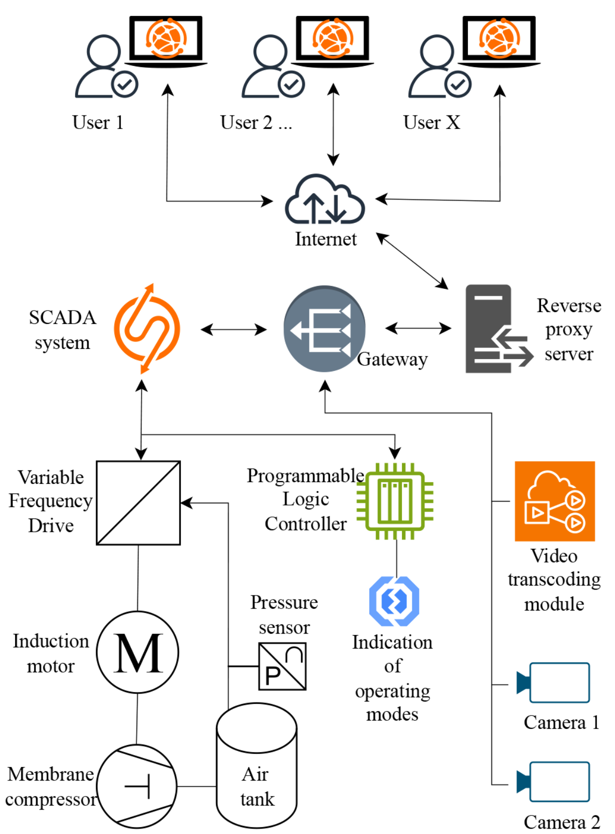

Fig. 3. Generalised structural diagram of the architecture of the system under development

The software used in the implementation of the developed system (Fig. 3) ensures the integration of the control level and the SCADA level and the organisation of communication links between individual components of the architecture. The PLC was programmed and the parameters for interaction with the WebHMI system were configured using the SoMachine Software v4.1.0.1 Final environment, which made it possible to implement the necessary algorithms and set up the correct data exchange channels. The VFD parameters are configured in the SoMove v2.9 environment, which allows for optimisation of the control section operating modes. To ensure compatibility and stability of information exchange with the VFD, the Schneider Electric Altivar Process ATV32 DTM Library v1.7.2 was additionally integrated. The development and configuration of WebHMI functionality was carried out using the LUA programming language in combination with a built-in web server (Kernel version 4.1.23), which provides the ability to remotely monitor and control the object.

Results. The implemented architecture of the developed system (Fig. 4) is presented as an integral architecture that combines hardware and software components for the implementation of a functionally complete complex for remote control of a laboratory compressor testbench. Conceptually, the architecture complies with the principles of modularity and separation of concerns: each logical level performs clearly defined functions, which allows isolating the tasks of measurement, control signal calculation, and user interface organisation. The structural diagram details the logic of data routing, synchronization mechanisms between system elements, and control command transmission paths, ensuring clear correspondence between subject area requirements and the implemented infrastructure.

The architecture includes a reverse proxy server that provides domain name assignment and implements traffic encryption mechanisms using the HTTPS protocol, creating a secure environment for user interaction with the system. At the communication level, a router is used, to which key hardware nodes are connected via TCP/IP: WebHMI, Raspberry Pi 4 microcomputer, and IP camera. WebHMI acts as the central node and master device with which users interact; data exchange between WebHMI, the Modicon M232 PLC and the ATV32 VFD is organised using the Modbus protocol, which ensures compatibility and determinism of information exchange. The PLC is responsible for indicating the system status. The VFD changes the power supply frequency of the induction motor, allowing adjustment of its rotation speed and maintaining the required pressure level in the compressor installation. The current pressure level is measured using the XMLF010-D2115 sensor. An IP camera and a Raspberry Pi Camera module are used for visual monitoring of the testbench operation. Video streams from these devices are captured and processed on a Raspberry Pi 4 microcomputer, then transcoded and transmitted to the WebHMI environment via a secure HTTPS channel.

Thus, the presented architectural solution (Fig. 4) allows integrating heterogeneous hardware into a single system, providing remote monitoring and control of the compressor installation using a secure web interface. This organisation of functional connections creates conditions for the implementation of educational and research tasks, combining technical reliability and user-friendly interaction.

The information and communication model developed during the design process reproduces the data exchange layers and interaction protocols between system elements (Fig. 5). The architecture provides for the separation of the local control area and the remote access level, using standard industrial and web protocols to ensure compatibility and portability of the solution. The model highlights channels for real-time operational data transmission, channels for controller parameter configuration, and channels for experimental data archiving. This organisation of infocommunication ensures the determinism of the data route in the local network while maintaining the possibility of access from the global network, which is essential for balancing the requirements of system performance and availability.

The developed WebHMI graphical interface implements a set of functional panels that provide interactive

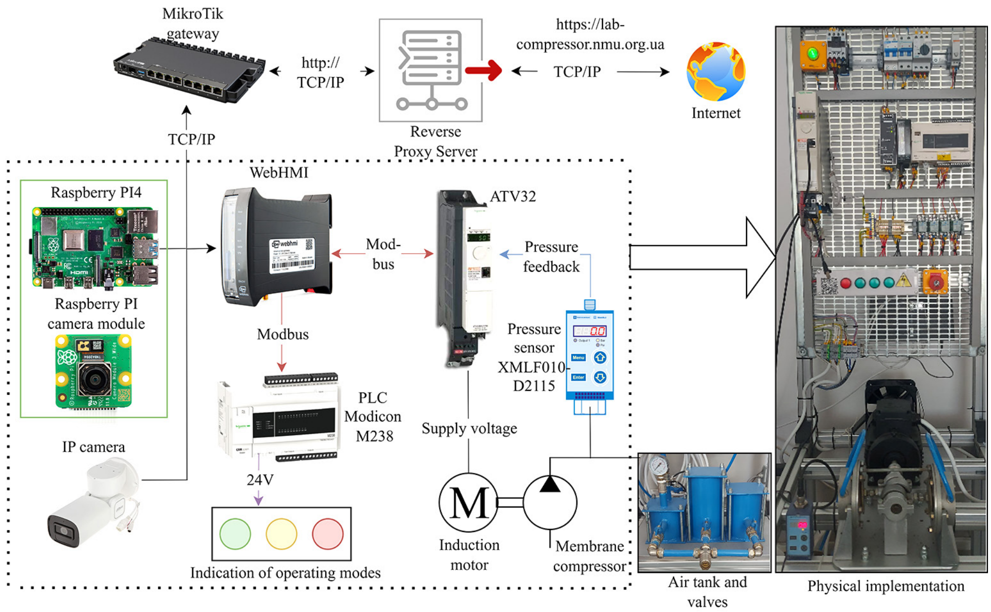

Fig. 4. Detailed structural diagram of the architecture of the system under development

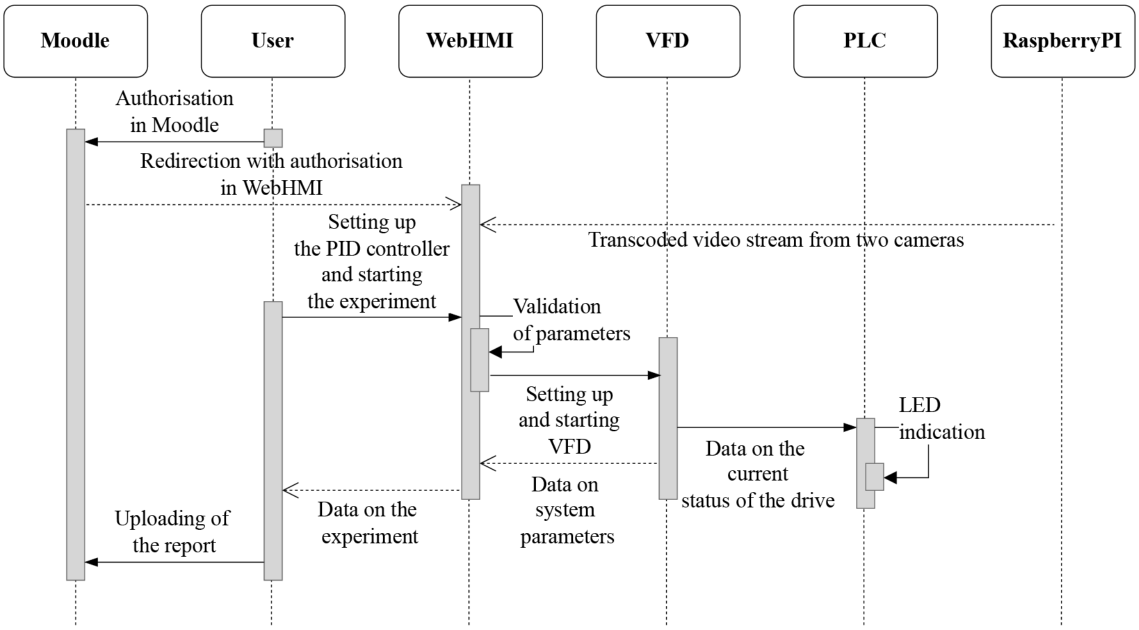

Fig. 5. Basic infocommunication scheme at different architectural levels of the developed system

monitoring and control of the system (Fig. 6). The interface includes a display of current values of controlled parameters, trend graphs for analysing pressure change dynamics, panels for setting regulator setpoints and coefficients, as well as tools for initiating typical operating scenarios (start/stop, emergency stops, error reset). The interface design takes into account the principles of minimising cognitive load on the user and ensuring clarity of system status (panels: Drive status and Indication), which is important for educational use in remote access environments.

From the point of view of implementing the algorithmic part of the system, the synthesis and integration of a closed PID controller was carried out within the scope of the work performed. The integration of the regulator ensures the formation of a corrective influence on the control object based on regular measurements of the controlled parameter and the selected setpoint. Architectural solutions provide for the possibility of remote modification of controller parameters in real time, with the mechanism for changing settings and coefficients accompanied by logging for subsequent reproduction of experimental conditions and analysis of results.

The implemented mechanisms for controlling the consistency of control parameters prevent incorrect configurations and ensure the integrity of experimental data and hardware components.

Functional verification of the implemented system was performed in terms of checking the correctness of data exchange, stability of regulation, and suitability of the interface for educational and research use. The correctness of data exchange was verified by sequential validation of operational telemetry transmission channels, control commands, and system status messages. No unjustified message losses were recorded within the verified operating scenarios, and data consistency between the control and visualisation levels was confirmed. The

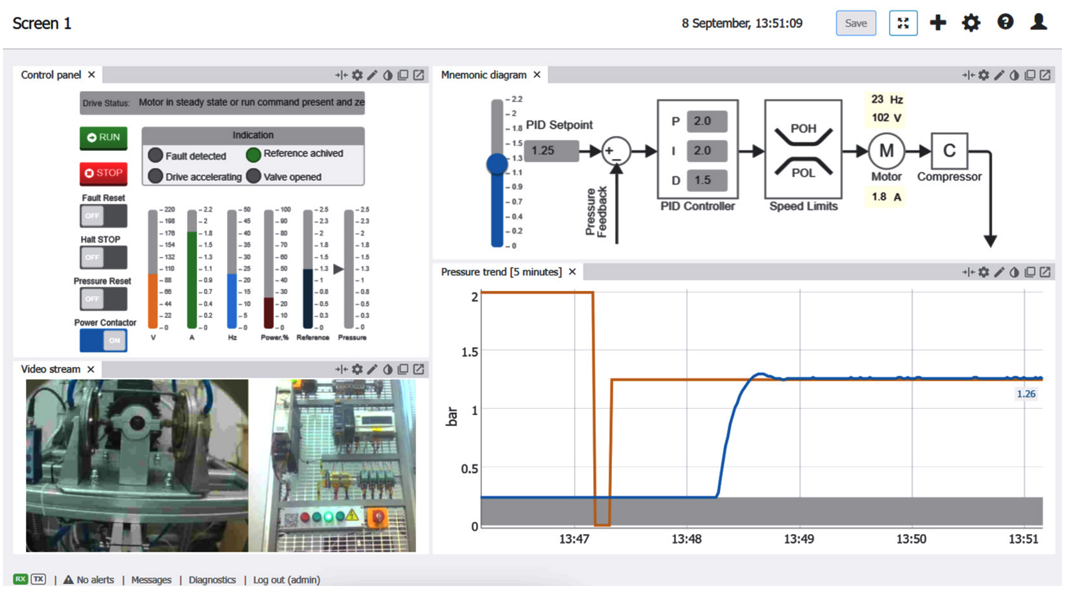

Fig. 6. Graphical interface of the developed remote control system based on WebHMI

stability of PID control was tested in a series of controlled scenarios with varying setpoints and input disturbances; analysis of transient processes showed that control actions were formed correctly and the controlled parameter returned to the setpoint within acceptable dynamic characteristics for laboratory conditions (graph in Fig. 6). At the same time, a typical set of system responses to changes in regulator parameters was identified, which allows the testbench to be used for educational demonstrations of the influence of *P*, *I*, and *D* coefficients on the quality of pressure level control.

The assessment of the system's operational properties included research into aspects of accessibility, scalability, and system behaviour when accessed from different categories of client devices. The test scenarios confirmed the web interface's performance both on the local network and when accessed remotely via public communication channels. The interface adapts correctly to different screen sizes and provides monitoring and control functionality from mobile devices. Architectural solutions for load distribution and data archiving logic ensure that the history of experimental launches is stored in a structured form, which is a prerequisite for further systematic analysis and pedagogical use.

Discussions, limitations and prospect research directions. The scientific results obtained have several levels of interpretation. First, the practical applicability of the approach combining web-oriented SCADA tools with embedded control logic for the implementation of remote laboratory complexes in the field of automation and control engineering has been confirmed. Secondly, experimental tests demonstrate that the applied architecture meets the defined functional and non-functional requirements: remote monitoring and control in real time are provided, a reliable archiving mechanism and the ability to quickly reconfigure the controller from a remote interface are implemented. Thirdly, the proposed structural and algorithmic solutions for data routing and separation of concern allow for effective scaling of the testbench to integrate additional objects or control algorithms without significant reworking of the basic architecture.

Along with positive results, a number of limitations and areas for further research were identified during implementation. Among the identified limitations, it is worth noting the impact of network conditions on the Internet on the determinism of command transmission in scenarios with minimum acceptable bandwidth, which necessitates further research on bandwidth measurement and optimisation, as well as the implementation of mechanisms for prioritising critical messages. It is also advisable to conduct further formalised research into the impact of different data archiving and aggregation strategies on system performance when the number of concurrent users and connected objects increases. In addition, it is recommended to conduct more formalised studies to assess the educational effectiveness of the testbench, which will include quantitative metrics of learning progress and UX assessments for different categories of students.

The use of the developed testbench has a dual effect. The educational effect is that students gain practical skills in working with real equipment, master the principles of PID control, learn to analyse dynamic processes and generate reports based on archived data. Remote access makes laboratory work accessible in distance learning conditions. The scientific effect lies in the fact that the testbench has the potential to test new control algorithms, integrate alternative control systems and verify mathematical models of compressor processes.

In summary, the implemented system reproduces the coordinated architecture of a web-oriented remote control system and demonstrates its suitability for use in educational and research purposes. Detailed structural diagrams, a multi-level information and communication model, and an implemented graphical interface (Figs. 4–6) form a comprehensive technical and methodological basis for further scaling of the system and for conducting quantitative experiments aimed at optimising control quality and improving operational reliability.

Conclusions. As a result of the research, the architecture of a laboratory testbench for remote control of a membrane compressor with an implemented PID control mechanism based on the WebHMI platform was developed and tested. The formulated functional and non-functional requirements made it possible to identify key criteria for building the system, which include remote monitoring, real-time control, data archiving, and compliance with modern industrial automation standards. The structural architecture created ensured the integration of heterogeneous technical means into a single information environment, where the interaction of the hardware level (compressor installation, PLC, VFD) and the software level (WebHMI, user interfaces, communication protocols) is implemented in a closed-loop control format with remote access. The developed WebHMI interface provides interactive control and visualisation of the process, confirming the suitability of the system for educational use in distance learning environments. Experimental testing confirmed the functional performance of the system, the correctness of data exchange between all levels of the architecture, the stability of the controller to changes in settings and input disturbances, as well as the adequacy of the web interface in remote access conditions. Verification proved that the system meets the specified requirements for accessibility, scalability, and security.

Further development of the research should focus on expanding the functionality of the system by integrating alternative control algorithms, optimising experimental data processing mechanisms, and increasing the level of cyber security to ensure stable operation in a scalable multi-user environment.

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Результати розробки лабораторного стенду віддаленого керування компресорною установкою на базі WebHMI

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Мета. Розробити й виконати експериментальну апробацію лабораторного стенду для віддаленого керування мембранним компресором із можливістю ПІД-регулювання, що інтегровано в архітектуру SCADA-системи на базі WebHMI, придатної для навчального процесу й наукових досліджень у галузі автоматизованого електропривода та інженерії керування.

Методика. Використані методи критичного аналізу й логічного узагальнення результатів досліджень у сфері віддаленого керування, теорію автоматичного регулювання, комп'ютерне моделювання, а також експериментальну перевірку функціональних характеристик системи. Розроблена методика включала проєктування архітектури, інтеграцію апаратних і програмних компонентів, налаштування параметрів ПІД-регулятора й верифікацію працездатності системи в умовах віддаленого доступу.

Результати. Імплементована структурна архітектура стенду, що об'єднує програмований логічний контролер, частотний перетворювач, Raspberry PI, відеокамери та WebHMI у єдине інформаційне середовище. Забезпечена можливість моніторингу й керування у режимі реального часу, архівацію даних і відтворення експериментальних сценаріїв. Верифікаційні випробування підтвердили коректність обміну даними, стійкість ПІД-регулювання до зміни уставок і зовнішніх збурень, а також працездатність веб-інтерфейсу в умовах глобального доступу.

Наукова новизна. Запропоноване архітектурне рішення, що інтегрує веб-орієнтовану SCADA-платформу з алгоритмами регулювання промислового рівня, яке дозволяє реалізувати віддалений лабораторний комплекс для компресорних установок та інших подібних систем із можливістю керування й візуалізації процесу в умовах багатокористувацького доступу.

Практична значимість. Розроблений стенд може застосовуватися у навчальному процесі для формування практичних навичок у галузі автоматизованого електропривода, інженерії керування, а також у наукових дослідженнях для перевірки алгоритмів регулювання й аналізу характеристик компресорних систем. Отримані результати створюють передумови для подальшого масштабування системи й розширення її функціональності.

Ключові слова: *мембранний компресор, SCADA, WebHMI, ПІД-регулятор, віддалений доступ, Індустрія 4.0, кіберфізична система*

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