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TOOLS FOR IMPLEMENTING A DIGITAL TWIN OF A DISTRIBUTED COMPUTER SYSTEM WITH ENERGY FACILITIES

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Abstract. *The paper discusses approaches to the design and implementation of a digital twin of a distributed computer system containing various types of energy facilities. Considering current challenges in Ukraine's energy sector—such as geographical dispersion, system complexity, and external risks—the relevance of digital twins for real-time modeling, monitoring, and forecasting of energy systems is substantiated. The architecture components of the digital twin of an energy network as a distributed computer system are presented. Key physical and logical components are defined, along with the software implementation tools, including platforms for electrical modeling, visualization, data storage, and analysis. Examples of digital twin implementations in global practice are provided, and a concept for adapting such solutions to the needs of Ukraine's energy sector is proposed.*

Keywords: *digital twin, energy system, distributed computer system, modeling, anomaly detection, forecasting, IoT, SCADA, PowerFactory, energy security.*

Problem Statement and Relevance. Ukraine's energy infrastructure includes a wide variety of facilities—from power plants, substations, and transformers to energy storage systems and solar panels of end users. Given the geographic dispersion, technical complexity, and external risks (e.g., cyberattacks or physical intrusions), the system must be viewed as a distributed network. This allows the detection of abnormal events and potential threats through comprehensive real-time data analysis. Since testing on a real energy network is unacceptable, the implementation of a digital twin is necessary for its protection. The topic's relevance is due to the growing need for digitalization in the energy sector and a shift toward adaptive management with crisis prevention capabilities. Creating a digital twin to simulate the dynamics of an energy system enables the simulation of failures, monitoring of component behavior under changing conditions, and timely threat detection. This is a complex task encompassing physical process modeling, IoT infrastructure development, mathematical modeling, and network visualization.

Review of Recent Research and Publications. According to studies [1, 2], digital twins are actively used in aviation, mechanical engineering, logistics, and medicine. In the energy sector, applications include equipment failure prediction, maintenance optimization, and load management. Work [3] explores a digital twin for a wind power plant, improving energy production forecast accuracy up to 95% by combining climate models with AI. Study [4] analyzes the digital twin architecture for microgrids, involving IoT modules, a SCADA system, and a cloud data platform. Despite success in specific areas, building an effective digital twin for a distributed system with numerous energy objects remains a challenge due to the need to process large heterogeneous datasets, ensure scalability, high availability, and integration with existing management systems.

In practice, the concept of digital twins has already been successfully applied in the energy sectors of different countries, demonstrating effectiveness in management, optimization, and modernization tasks. Table 1 presents examples of digital twin implementations in energy.

Table 1

Examples of Digital Twin Implementations in Energy

Digital Twin	Description	Functionality
GE Digital Grid [5]	Digital twin for power grids with failure prediction and load balancing	1. Grid behavior simulation for failure prediction. 2. Network optimization to increase efficiency.
Siemens Energy Digital Twin [6]	Digital twin for generation optimization and maintenance cost reduction	1. Optimization of production processes and energy management systems. 2. Reduced energy consumption and improved efficiency.
National Grid ESO (UK) [7]	Digital twin of the UK's national energy system	1. Digital copy for improved modeling and forecasting. 2. Support for carbon neutrality transition by system optimization.

The digital twin for a distributed computer system with energy facilities ensures: 1) real-time technical state modeling of components; 2) detection of deviations and failure prediction; 3) integration with control systems and decision support.

Objective – to define the concept and software toolkit for a digital twin of the energy network.

Main Part. Components of a digital twin include both physical objects and logical nodes. Physical components: 1) generation facilities (solar, wind, hydro and thermal power plants); 2) transformers, substations, relay protection systems; 3) energy storage systems (batteries, hybrid accumulators); 4) smart meters, consumer devices; 5) communication equipment (routers, controllers, IoT sensors). Logical components: 1) energy consumption and generation models; 2) data aggregation nodes (Data Concentrator Units); 3) Forecasting algorithms for consumption/production; 4) anomaly detection modules; 5) data transmission channels (communication protocols, encryption). These components should be virtualized and connected as network nodes, enabling a full graph model of the energy system for anomaly detection in specific segments. This approach supports not only real-time system visualization but also complex behavioral analysis, failure prediction, adaptive response, and scenario simulation.

Modeling Software and Tools. Developing a digital twin of an energy system is a complex multi-level task requiring various tools for modeling, simulation, data processing, and visualization. Depending on goals—electrical modeling, stability analysis, anomaly detection, forecasting, or 3D visualization—different specialized platforms are used. One of the key tools is DIgSILENT PowerFactory [8], which is widely used for detailed electrical modeling of generation, transmission, and distribution processes. It enables both static and dynamic analysis of power systems, as well as modeling of load modes, emergency situations, and operational network control. Its use is appropriate when building a digital twin at the level of a unified power system or regional networks.

Specialized modeling environments are used to create mathematical models of system components, simulate control and automation processes, and perform optimization—offering flexibility in design and integration through APIs and data exchange protocols. These tools play a key role in implementing both the physical behavior and logical structure of a digital twin.

Thus, effective design and implementation of a digital twin requires the comprehensive use of various tools, each performing a specific function within a unified architecture. Their coordinated integration allows for the creation of a flexible, scalable, and fault-tolerant system of digital representation of the real energy environment.

Conclusions: a concept of a digital twin for the energy network has been proposed, which enables:

1. Real-time detection of anomalies and external intrusions.
2. Optimization of system operation modes based on forecasts.
3. Reduction of technical and operational risks.
4. Implementation of "What-If" scenarios for emergency planning.

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ЗАСОБИ РЕАЛІЗАЦІЇ ЦИФРОВОГО ДВІЙНИКУ РОЗПОДІЛЕНОЇ КОМП'ЮТЕРНОЇ СИСТЕМИ З ЕНЕРГЕТИЧНИМИ ОБ'ЄКТАМИ

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Анотація. *У роботі розглянуто підходи до проєктування та реалізації цифрового двійника розподіленої комп'ютерної системи, що містить енергетичні об'єкти різного типу. З урахуванням сучасних викликів в енергетичному секторі України, таких як географічна розгалуженість, технічна складність систем та ризики зовнішнього втручання, обґрунтовано доцільність застосування цифрових двійників для моделювання, моніторингу та прогнозування роботи енергосистем у реальному часі. Представлено компоненти архітектури цифрового двійника енергетичної мережі як розподіленої комп'ютерної системи, визначено ключові фізичні та логічні компоненти, а також інструменти програмної реалізації, включно з платформами для електротехнічного моделювання, візуалізації, зберігання та аналізу даних. Представлено приклади реалізації цифрових двійників у світовій практиці та запропоновано концепцію адаптації подібних рішень до потреб української енергетики.*

Ключові слова: *цифровий двійник, енергетична система, розподілена комп'ютерна система, моделювання, виявлення аномалій, прогнозування, IoT, SCADA, PowerFactory, енергетична безпека.*

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