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Designing a Digital Twin of a Wind Farm †

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Abstract: The article is devoted to the development of a prototype digital twin of a wind farm. An overview of existing works and solutions in the field of digital twins in wind energy is given. The approach to building a digital twin based on ontological engineering, which is widely used in the works of the authors, is considered in detail. An ontological approach is described, which the authors develop and use in the design and development of digital twins (the development is carried out on digital twins of wind farms and photovoltaic systems). The adapted stages of ontological engineering, examples of fragments of the ontological knowledge space in the field of wind energy and the ontology of tasks of the digital twin of a wind farm are given. The architecture of the digital twin prototype under development has been developed and proposed for consideration. The key parts in the structure of the developed digital twin are described. A mathematical model for determining the operation parameters of a wind farm is considered. Special attention is paid to the stages of implementation of the prototype of the digital twin of the wind farm.

Keywords: digital twin; wind farm; ontological engineering

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1. Introduction

Currently, more and more questions are being raised about the need to build renewable energy facilities, in particular, wind farms. They are used to generate carbon-neutral energy. It should be noted that many European countries are already actively using wind power plants (WPP) [1]. Research [2] shows that in most cases the use of renewable energy sources is economically feasible.

Wind farms do not constantly produce electricity; because of this, it is desirable to consider electric energy storage devices. The tasks of power consumption management and activation of the role of consumers in this process are also relevant. It is advisable to use the technology of digital twins to consider all the proposed items together and their interactions with each other. A detailed description of the technology of digital twins is provided below.

The relevance of using renewable energy sources (RES) in the Russian Federation is due to the fact that a significant part of the territory of Russia is not covered by a centralized power supply. Areas of decentralized energy supply occupy about 60% of the area of the Russian Federation and are located mainly in the northern regions of the country [3]. There are many small isolated settlements in these areas. Their power supply is provided mainly on the basis of diesel power plants using expensive imported fuel.

At the same time, one main problem arising when using renewable energy sources is the volatility of electricity generation, in particular, solar and wind power plants are highly dependent on external factors, primarily on weather conditions. Accordingly, it is necessary to develop not only systems for managing RES, but also systems for predicting the behavior of these objects in changing conditions for the effective use of RES.

One of the technologies used in the digitalization of energy sector is the technology of digital twins (DT) [4]. A digital twin is a virtual prototype of a real object, with which one can conduct experiments and test hypotheses, predict the behavior of an object and solve the problem of managing its life cycle [5]. The digital twin saves equipment and system design costs as a whole, as well as reduces operating costs by improving object observability and the ability to simulate its life cycle, which contributes to timely diagnosis and troubleshooting. Consequently, the use of digital twins in the design of WPP has a positive impact at all stages of the life cycle of the object from the design stage to its operation.

The article considers the existing works in the field of building a DT WPP, the use of ontological engineering for designing a DT WPP, as well as the proposed information model and architecture of the DT WPP. Conclusion describes directions for further development of this work.

2. Analysis of Existing Solutions for the Development and Application of Digital Twins in Wind Energy

The problem of transition to high-tech and efficient production in recent decades has become particularly relevant in the conditions of general competition. It became possible to collect, store, transmit and analyze large amounts of data collected from real objects due to the rapid development of information technology. This revealed the need to revise the standard approaches to managing production processes in enterprises. These factors have prompted the development and adoption of strategic industrial development programs in a number of countries, such as Industry 4.0 Platform (Germany), Made in China 2025 (China), National Technology Initiative (Russia), etc. All proposed programs are aimed at increasing labor productivity, increasing the economic efficiency of production and introducing modern science-intensive technologies [6]. The implementation of these strategies is reflected in an increase in the level of automation of enterprises and in a wider digitalization of production processes. Such changes are due to the need for enterprises to quickly and accurately model the product and its production technology in order to increase profitability and save resources in a competitive environment.

A digital twin can help to solve this problem. DT combines both the virtual environment of the enterprise (data from sensors, mathematical and geometric models, etc.) and the physical environment (actuators, machines, circuits, etc.), and also describes the process of interaction between these environments and complements this with automation technologies. In 2018, Gartner, the world's leading research and consulting company, included digital twins in the list of 10 strategically important technologies. The company noted that "digital twins in the context of IoT projects are especially promising over the next three to five years" [7].

Currently, digital twin technology remains one of the most promising technologies that is widely researched and integrated into various areas of human activity [8–14]. The analyzed articles consider both the troubles in the development of digital twin for renewable energy facilities and the process of developing digital twin for energy facilities in general and for some equipment, for example, wind turbine blades.

The spread of the digital twins' concept began, in particular, with the automotive industry. Glaessgen and Stargel in one of their papers [15] explain the principle of using digital twins for vehicle certification and fleet management: "A digital twin is an integrated multiphysics, multiscale, probabilistic model of an assembled vehicle or system that uses the best available physical models, sensor data, and fleet history to simulate the condition of the original operating in real field conditions".

It can be noted that research and development in the field of digital twins in wind energy is aimed at the tasks of functioning at present [9–11,13,16–19], like our work. Relevance of the research is noted that in our time is widely conducted development of digital twins for objects wind energy [20,21].

Development and research in the field of digital twins of wind power plants are divided into two areas: the development of a digital twin of a separate part of a wind power plant, in particular, the development of a digital twin of the rotor blade of a wind power plant [11], and the development of a digital twin of a wind power plant as a whole [9,10].

The main difference of the presented work lies in the fact that it is proposed to use the information obtained at the stage of solving the problems of the functioning of objects to further solve the problems of developing wind turbines, integrating them into a common isolated power system based on digital twins, and subsequent integration in a single digital space. In addition to this work, the authors simultaneously solve the problems of designing a digital twin of a photovoltaic system [22].

3. Ontological Engineering in the Construction of DT WPPs

The use of ontologies in the structure of a digital database (DB) is given in [21]. Ontological engineering for the construction of the DT was also applied in the construction of the DT of the photovoltaic system [22]. The classical stages of ontological engineering regarding the development of DT WPP were used within the framework of this work.

Below are the results of these steps:

1. In the first stage the goal of building an ontology system was formulated. The goal is to extend the existing ontology of the fuel and energy complex to include the wind farm ontology system. In addition, at this stage it is necessary to formalize the knowledge of experts in the field of wind power for building a digital twin. Next, it is necessary to select the type of ontology and designate its scope. The developed ontology belongs to the type of light (heuristic) ontologies and will be used to build a digital shadow and a digital twin.
2. The second stage is aimed at highlighting and verbalizing the key knowledge of the subject area. After the above step, the objects related to the listed areas were selected: generation system; renewable energy sources; WPP; wind farm equipment.
3. The third step was to designate all the main levels of abstraction and the identification of a structured hierarchy. Based on the results from the previous step, the hierarchy was constructed as shown below:
    - Electric power systems;
        - Generation systems;
            - Renewable energy sources;
                - Wind power plants;
                - Wind farm equipment
4. The ontology system built on the basis of the previous steps has been modified by eliminating contradictions, duplications and synonymy. This step is necessary to improve the visual component of the constructed ontology by additional elaboration of concepts and relations between them.

Figures 1 and 2 present the wind farm ontology system built using the above algorithm.

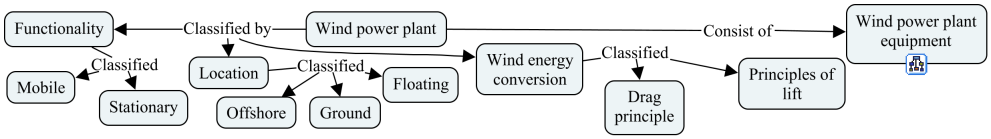


Figure 1. Ontology of wind farms.

Ontologies are used, on the one hand, for structuring the knowledge of the subject area, on the other hand, as the basis for developing a data model when designing DB. Figures 1 and 2 illustrate the main entities of the data model: wind farm equipment, functionality, location, wind power conversion.

The developing of the digital twin involves an ontology of the tasks of designing, functioning and developing a digital twin presented in Figure 3. It includes a description of the main tasks, methods and ways to solving these problems, and rather refers to the structuring of knowledge in the development of a digital database. Ontologies were built in the freely distributed tool CMapTools.

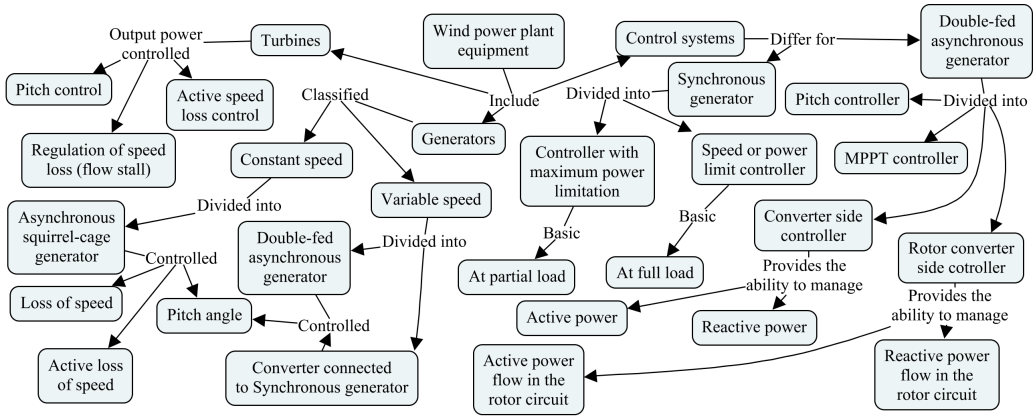


Figure 2. WPP equipment ontology.

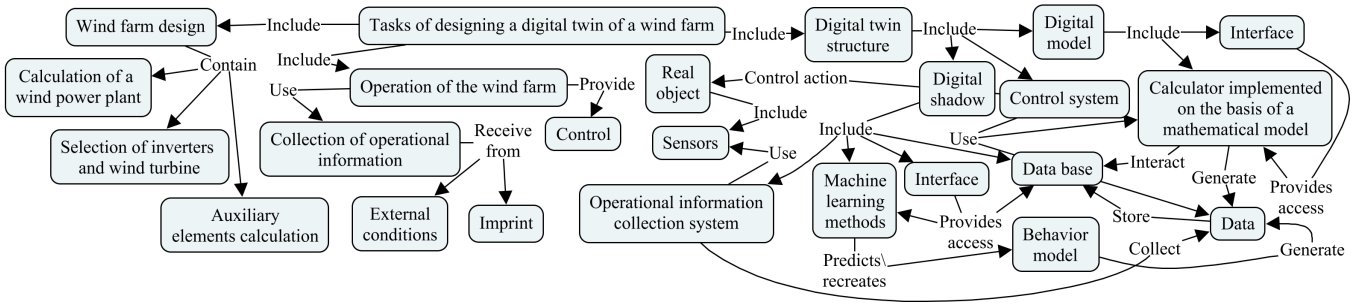


Figure 3. Ontology of tasks of the DT WPP.

4. Description of the Mathematical Model

In this paper, the approach proposed by E.V. Oganesyan, E.A. Bekirov, et al. [23] was used to build a mathematical model of DT. DT WPP based on mathematical model, description of which are given below for determining the parameters of the operation of a WPP. The calculation of the generated power of a WPP requires to use such parameters as: wind speed, wind energy utilization factor, rapidity wind turbine (rapidity), efficiency and swept surface area. The power characteristic of the wind turbine is calculated depending on the wind speed in Formula (1).

$$P_{WT}(V_i) = \rho C_P S_0 \eta \frac{V_i^3}{2} 10^{-3} \quad (1)$$

where ρ—air density (taken equal to 1.226 $\frac{\text{kg}}{\text{m}^3}$); C_P is the wind energy utilization factor; S_0 is the area of the swept surface of the wind turbine; η—total efficiency factor of WPP; V_i^3—wind speed.

Next, it is necessary to calculate the characteristic of the wind energy utilization factor C_P from the rapidity $Z(Z_{opt} < Z < Z_{max})$ (2).

$$C_P = C_{Pmax} - \frac{C_{Pmax}}{(Z_{max} - Z_{opt})^2}(Z - Z_{opt})^2, \quad (2)$$

where C_{Pmax} is the maximum wind power utilization factor; Z_{max}—maximum rapidity, selected based on the passport data of the blade; Z_{opt}—optimal rapidity, selected based on the passport data of the blade.

For $Z \leq Z_{opt}$:

$$C_P = C_{Pmax} - (\frac{Z}{Z_{opt}})^2(3 - 2\frac{Z}{Z_{opt}}), \quad (3)$$

The following expression is used to find the rapidity.

$$Z = \frac{\omega R}{V_0}, \quad (4)$$

where ω is the angular velocity; R is the radius of the wind wheel; V_0 is the speed of the incoming air flow. The effective output specific power ΔP per 1 m^2 swept surface of the wind turbine is calculated by the formula:

$$\Delta P = \Delta P_{WF} C_P \eta, \quad (5)$$

where $\Delta P_{WF} = \rho 10^{-3} \frac{V_{NOM}^3}{2}$—specific power of the wind flow at wind speed V_{NOM}; ρ—air density (winter—1.25, summer 0.72 $\frac{kg}{m^3}$); C_P is the average wind power utilization factor (assumed to be 0.31); $\eta = \eta_A \eta_{GE} \eta_{EG}$—total efficiency factor of WPP; η_A is the aerodynamic efficiency of the wind turbine (WT) (accepted within 0.91–0.916); η_{GE}—gear efficiency (accepted within 0.95–0.96); η_{EG}—the efficiency of the electric generator, depending on its power. After calculating the value of ΔP, the area of the swept surface of the WT is determined:

$$S_0 = \frac{P_{WTNOM}}{\Delta P}. \quad (6)$$

where P_{WTNOM} is the nameplate power of the wind turbine; ΔP—effective output specific power per 1 m^2 swept surface of the wind turbine.

Using data from the mathematical model allows the digital twin to predict the behavior of the object and solve the problem of managing its life cycle.

5. Design of DT WPP

It is necessary to use a large amount of data that needs to be organized and stored when designing and operating the digital twin of a wind farm. For example, it can be weather conditions, equipment characteristics, etc. The study uses the PostgreSQL relational database, which has the following advantages: functionality, convenience, and resource consumption.

The database design was based on ontologies (Figures 1–3) described in Section 3 "Ontological Engineering". The following entities were identified as a result of the design: weather characteristics; characteristics of the wind generator; characteristics of the network inverter; isolated system; network inverter; grid inverter calculation results; wind generator; wind generator calculation results; isolated weather system. Figure 4 shows relationships between entities.

Depending on the nature of the data flows between physical and digital objects, the authors distinguish three main stages in the construction of a DT: a digital model, a digital shadow, and a digital twin. A digital model is understood as an exhaustive description of a part or all of the physical object for which a DT is being developed. A digital model can be represented by both mathematical and other models, as well as the integration of several models. As a rule, a digital model cannot automatically exchange data with its real object. A digital shadow is a digital object to which there is a one-way data flow from the real object. In our case, the digital shadow is defined as a system of relationships and dependencies derived from a real object under normal operating conditions and contained in the Big Data that uses Industrial Internet technologies. In our case, the digital shadow is defined as a system of relationships and dependencies obtained from a real object under normal operating conditions and having Big Data, which use Industrial Internet technologies. DT construction is the development of a digital shadow, which is able to predict the behavior of a real object only in the conditions in which the data were collected, but does not allow

the simulation of other situations [24]. The last stage of DT design involves organizing bi-directional automatic data communication between the physical object and the digital object, whereby the digital object can generate feedback to control the physical object. In this case, we can already talk about creating a digital duplicate of the real object.

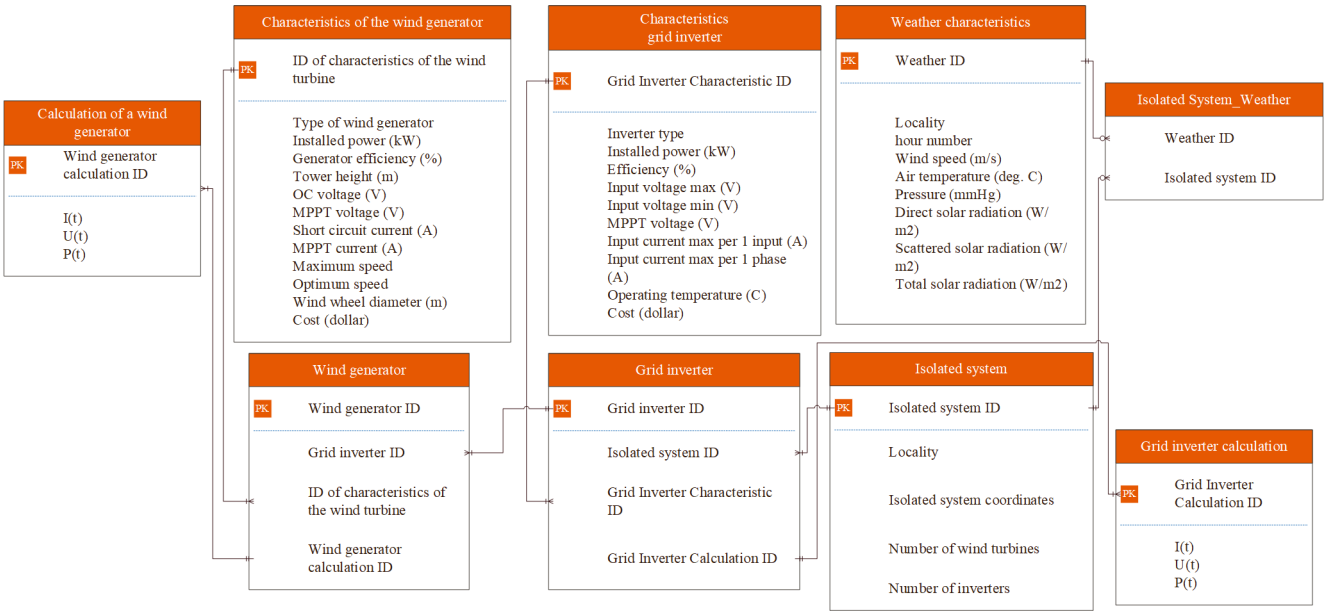


Figure 4. Database entities and relationships between them.

The digital shadow in the developed architecture of the DT includes a data model, methods for collecting information from a physical object and machine learning methods based on time series of weather characteristics and electricity consumption to predict the data needed by the digital twin for the operational management of a wind or solar power plant. The digital model, in turn, includes mathematical models of the behavior of a wind and solar power plant, on the example of which the development of DT is carried out. Research is aimed at developing a generalized methodology for creating a DT, which includes the following steps:

- Ontological engineering of the field in which the DT is developed.
- Construction of a data models based on the carried out ontological engineering.
- Study of the need to use machine learning methods in DT development.
- Implementation of the digital shadow of a physical object.
- Selection and/or development of mathematical and other models necessary to describe a physical object.
- Implementation of a digital model of a physical object.
- Determination of data emulation methods for testing the DT.
- Integration of a digital shadow and a digital model as parts of a DT, using data series obtained as a result of emulation.
- Development of a communication system with a physical object and testing a digital twin on real data.

Figure 5 shows the generalized architecture of the developed DT (solar and wind power plants). It was decided to implement calculations using mathematical models on the server side of the digital twin application given their complexity. It was also decided to store the database on the server side of the application.

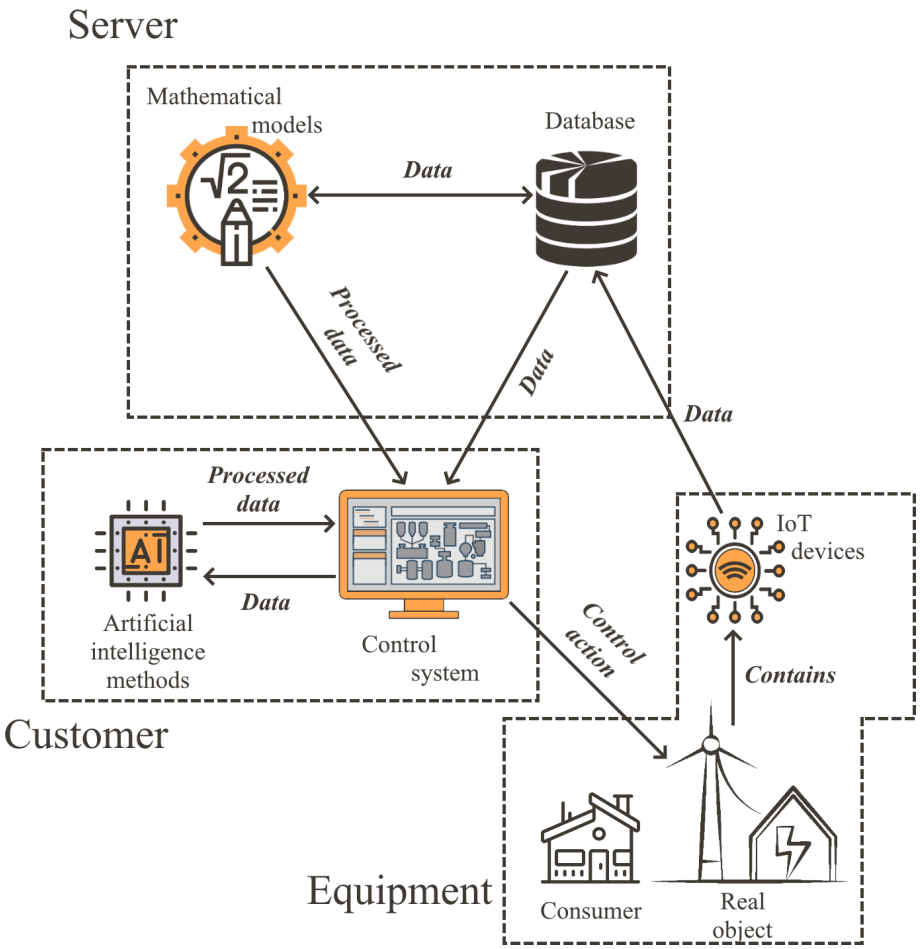


Figure 5. Generalized architecture of developed digital twins (solar and wind power plants).

6. Conclusions

The article considers the current state in the field of DT development, identifies the main shortcomings of these studies, primarily related to the difficulties of their integration with the DT of other systems. The ontological approach developed by the authors to the construction of the DT is considered and the results of its application in the development of the DT of a wind power plant are presented. It is worth noting that ontological engineering is a valuable step in the development of a DT. The structure of the database was developed on the basis of the ontological model and describes the main components and links between them. Integration and formal description of all components (models, databases, knowledge bases) is a key goal of ontologies in the development of a DT. The generation of data series made it possible to use machine learning methods in the implementation of the DT, which will be discussed in the following articles.

In the future, the digital twin will work extensively with the real object. The real object generates large amounts of data, which it needs to analyze. It follows that the digital twin must have the means and methods to perform this function. Big Data technology is used to solve this problem. Because of this, the data is processed within a reasonable timeframe.

As a result of the implementation of all these stages it will be possible to verify the DT prototype according to the data obtained from the real object, and, if necessary, its further adjustment.

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