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DIGITALIZATION OF RENEWABLE ENERGY

Monography



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This monography looks to understand and research the issues associated with the implementation of digital twin (DT) models in power engineering and renewable energy. Analyzed usage DT results and benefits for power engineering and renewable energy. This monography deals with digital twin (DT) technology in power systems. Definition DT are presented. In the monography are classified DT models and explained DT substations. Presented role DT in UE electricity grid and shown futurities used DT in power system. Analyzed policies on decarbonization and digitalization, and how DT can accelerate a green deal. Described the energy action plan and placed DT in it. Proposed DT on classification on technology and mathematical methods realize DT in power system (ANN, clustering, Kernel method). Elements DT, backers implementation DT and examples were presented. Analyzed financial investment in developing and implementing DT and showed program financial support for developing DT. The paper presents an analysis of the instability of electricity generation renewable energy sources (RES). The second chapter of monography deals with analyzing RES electricity generation in the World and Ukraine. The following chapter describes on features of functioning power grids in modern conditions in Ukraine and ways of ensuring the balance reliability in the power system for conditions of high-grade RES integration. Also, presented models DT RES allows install and operate with high efficiency, because help predict all influences start from sheading up to optimize battery system. This research was funded by projects 24-PKVV-UM-007, 24-PKVV-UM-006 and MSCA4Ukraine ID number 1233365.

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LIST OF SYMBOLS AND SHORTCUTS

CPS	Cyber-Physical Systems (CPS)
DoEAP	Digitalization of Energy Action Plan
DSO	Distribution system operators
DT	Digital Twin
PS	Power System
RES	Renewable energy sources
TEN-E	Trans-European Networks for Energy
TSO	Transmission System Operator

INTRODUCTION

Implementation of DT models in renewable energy. Analyze usage DT results and promises great benefits for power engineering. This monography deals with digital twin (DT) technology.

Digitalization and decarbonization of the energy sector, exactly the power system, can contribute to boosting European competitiveness and innovation, opening new global markets for products and services, and drive innovative solutions by encouraging the development of trustworthy technologies. But, in this moment are new challenges, for instance, related to cybersecurity, data access governance, data protection and privacy, and the growing energy consumption of the IT sector.

The topics of research which will finance Horizon Europe will develop new or improving existing technologies to make them practically and economically viable in the industrial world and will encompass modern manufacturing technologies such as digital twins.

By implementing a Digital Twin, power systems have the capability to balance and optimize trade-offs between important factors over which they prior had minimal visibility or control. The dispatcher sees a much bigger picture, giving them the confidence to make calculated commitments to dispatching energy without unforeseen maintenance or wasted fuel power plants, additional power losses and optimization of power systems TSO and DSO. The Digital Twin will allow “what-if” scenarios to be tested against business objectives creating the most informed decisions possible.

In papers it is possible to find a lot of definitions DT, but the DT of power system have some specific, how it is shown in paragraph 1.

The monograph presents an analysis of the instability of electricity generation renewable energy sources (RES). The first paragraph deals with analyzing RES electricity generation in the World and Ukraine. The following

chapter describes on features of functioning power grids in modern conditions in Ukraine and ways of ensuring the balance reliability in the power system for conditions of high-grade RES integration. The fast increase in electricity generation RES causes control problems of distributed power supply and the power grid. A mathematical model of the control of the parameters normal mode electric power system for conditions with high integration of RESs is proposed in the second paragraph. Investigated components of the optimality criterion at the control of normal mode parameters of the electric power system with RESs. Digital transformation helps decarbonize energy supply, decrease dependency on fossil fuels and integrate renewables in power system. Proposed model Digital Twin (DT) photovoltaic system models, exactly 3D visualization, analyses accumulator system depend on load and generation are presented. The Digital Twin problematics is very widely discussed, but many papers and studies are very general without any practical implementations. The main part focuses of research deals with daily electricity generation during different kinds of RES, namely, mini-hydropower station, photovoltaic power station, and wind power station. Measured data of electricity generation photovoltaic power plants, wind power plants, and mini hydropower plants, obtained meteorological factors have been allowed calculation Spearmen's, Kendel's, Pearson's correlation rank coefficients. The main contribution of this research is to determine of main metrological factors for each kind of studied RESs. In the future, it will help to decide the task of forecasting power generation more presciently. Also, presented models DT RES allows install and operate with high efficiency, because help predict all influences start from sheading up to optimize battery system.

Keywords: Digital Twin; renewable energy sources; photovoltaic power plant; wind power plant, small hydropower plant, instability, criteria correlation Spearman.

CHAPTER 1.
DEFINITION DT FOR POWER SYSTEM

On the IBM version, a digital twin is a virtual model designed to accurately reflect a physical object, and this object can be a wind turbine — is outfitted with various sensors, which collect and send obtained data (data about different aspects of the physical object's performance, such as energy output, temperature, weather conditions and more), and this data is then relayed to a processing system and applied to the digital copy. DT is a real-time digital replica with Hardware-In-the-Loop capability (Fig. 1.1.) [1]. DT can be understood as a digital representation of a physical asset, e.g. a substation [2].

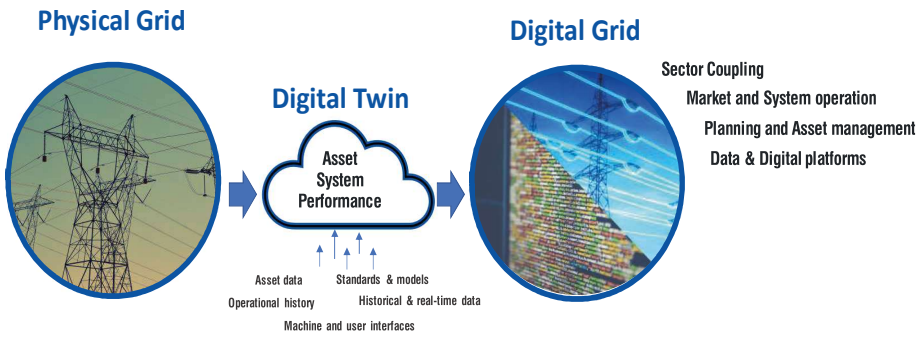


Fig. 1.1. DT in ENTSOE definition [3]

A Digital Twin is the digital representation of a unique asset (product, machine, service, etc.), that compromises its properties, condition, and behavior by means of models, information, and data [4].

According to [5] a digital twin is a virtual model designed to accurately represent a physical object or system using big data, simulation and machine learning to support decision-making. In the context of electricity grids, a digital twin of the grid is a virtual representation of the grid that should support TSOs

and/or DSOs in performing a well-informed and future-proof decision-making, for example in grid planning, secure operation or enabling flexibility (Fig.1.2).

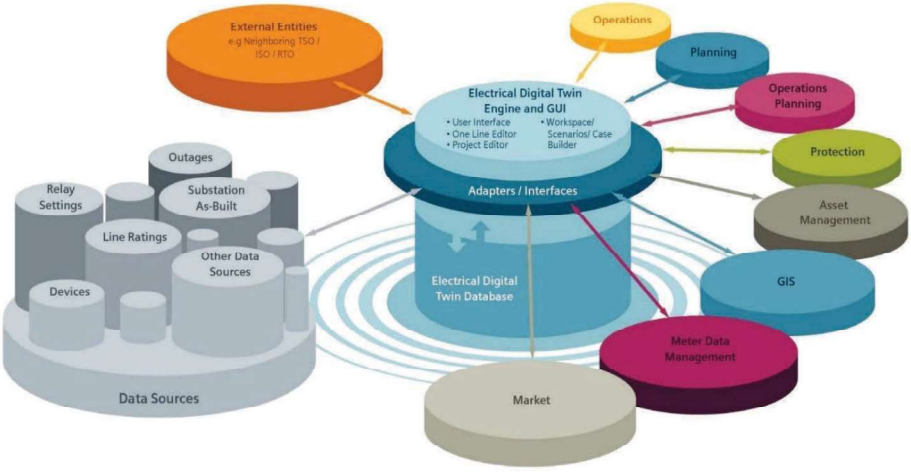


Fig.1.2. Electrical Digital twin (Siemens version) [6]

Digital Twins are software-based abstractions of complex physical systems or objects which are connected via a communication link to the real object through a continuous data flow from the real world. DT is used like mirror for real object and represent them in o digital. About recent developments of control center technology for power system s based on a dynamic simulation engine (dynamic digital mirror) is written in [7].

The Electrical Digital Twin enables utilities to simplify the data maintenance and exchange process. DT PS (Siemens definition) must have key features: an accurate single source of truth for data; automated data and model synchronization across multiple domains; spans transmission and distribution for integrated analysis; scalable data maintenance and exchange across the IT landscape; vendor-neutral and standards-based [6]. All sources of data and participants' creation digital twin process are shown in Fig. 1.2.

CHAPTER 2.
DT MODELS

On other words, a DT twin is a virtual representation of a physical product, process or facility used to understand and predict the physical counterpart's performance [11]. DT models divided five main groups, like shown on Fig. 2.1. In [8] proposed simplify classification DT, because author more concentrated on DT platform SUMITOMO SHI FW (Fig. 2.2).

Starting to build the Digital Twin of the European Electricity Grid based on existing national initiatives, also promoting the uptake of specific digital technologies (AI, HPC). These initiatives could be supported through the upcoming Horizon Europe Work Programme [5].

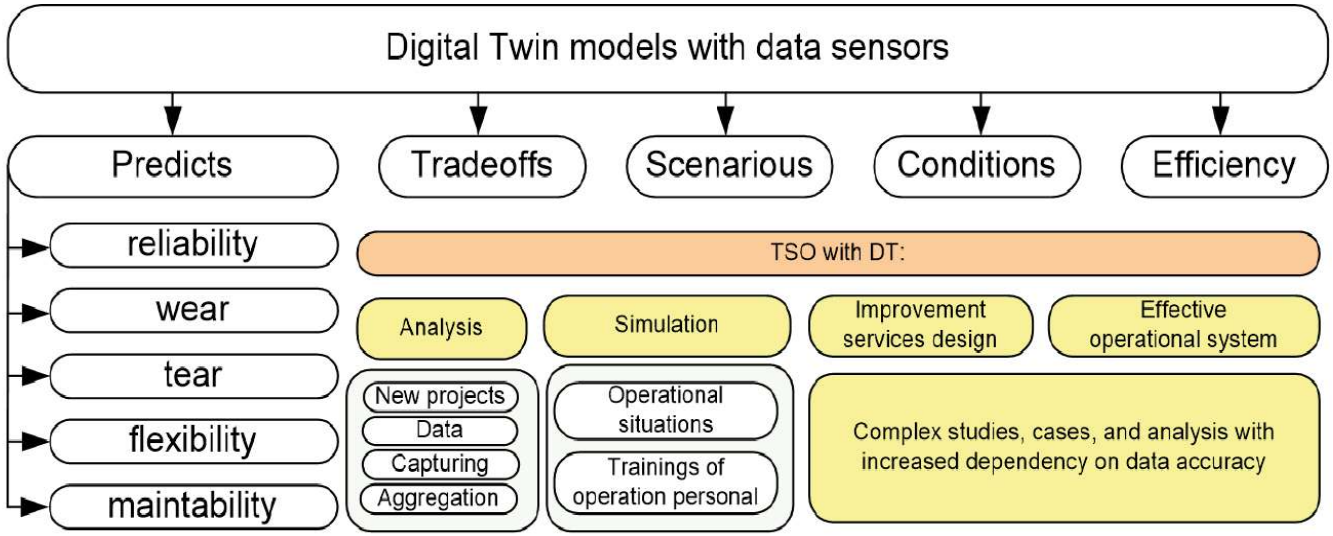


Fig. 2.1. DT models

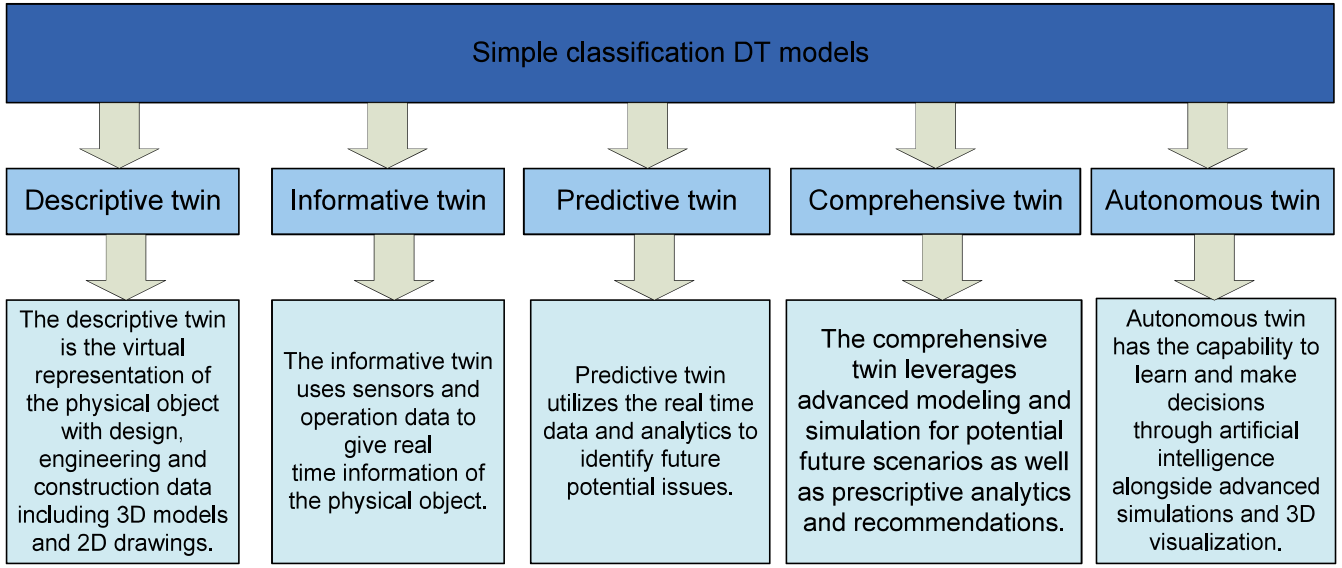


Fig. 2.2. Classification DT

CHAPTER 3.
DT SUBSTATION

Digital Substation (DS) represents complex of hardware and software solutions, which are utilizing effects from continuous progress of the power system digitalization [9]. With the implementation DT in operate electrical substations to benefit from digitization, various aspects of the systems and networks need to be revisited, including cybersecurity [10]. This approach is fully corresponding with the innovative concept of the cyber-physical grid. Consequently, as a key component of the transmission system, a Substation has to evolve from the classical power hub to a power and data hub, the Digital Substation. More generally, each component of the network, even the most passive one, will have to evolve to a data emitter.

The capabilities of DT will improve utilization of data obtained from market participants, generation providers, and power plants and grid elements in the system for further analysis to get actionable insight for informed decision-making. In the DS environment, the TSO experts can simulate reactions of the power system in different scenarios, investigate and improve operational measures, and control the system with deep knowledge of its comprehensive parameters. In presentation [11], author shows main benefits DT for PS and structure and show Energy system model like Dynamic Digital Mirror.

Classification of mathematical methods is used in DT presented in [11], but still not developed a unique methodology, that can work with DT and take into account specific condition power system objects. So, still, need to improve the existing models and create a new mathematical approach that can to work with DT PS. In this case, may be relevant will be to combine ANN analyses time row (wavelet), theory similarity and sensitivity.

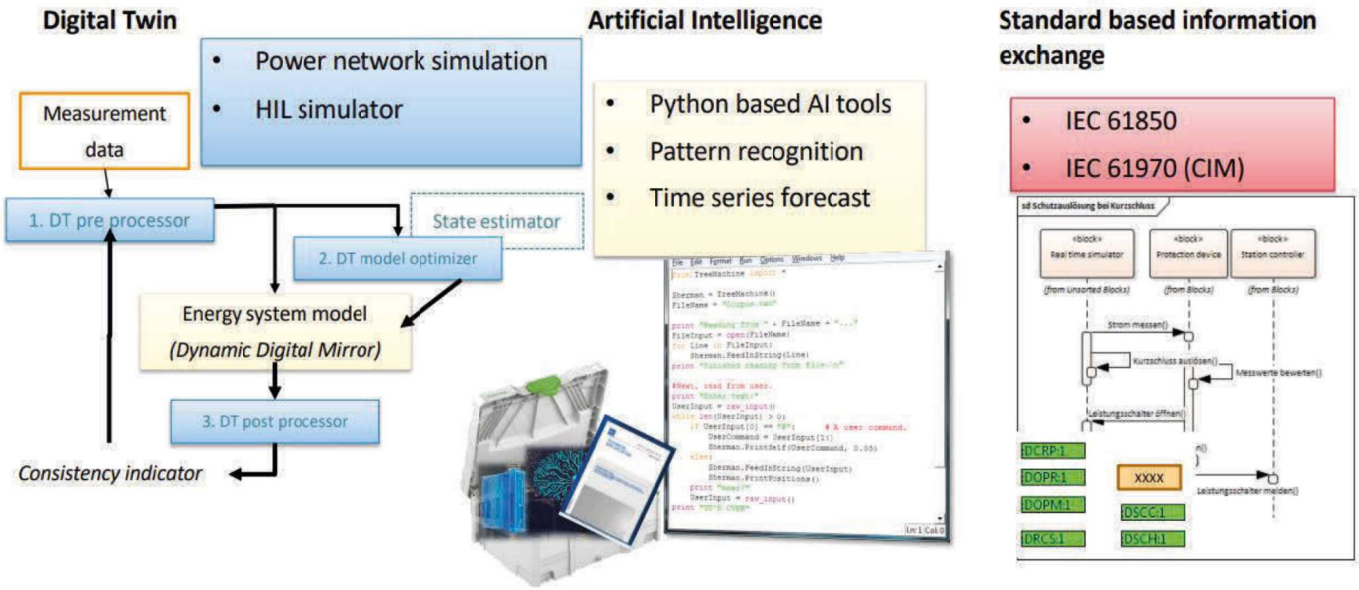
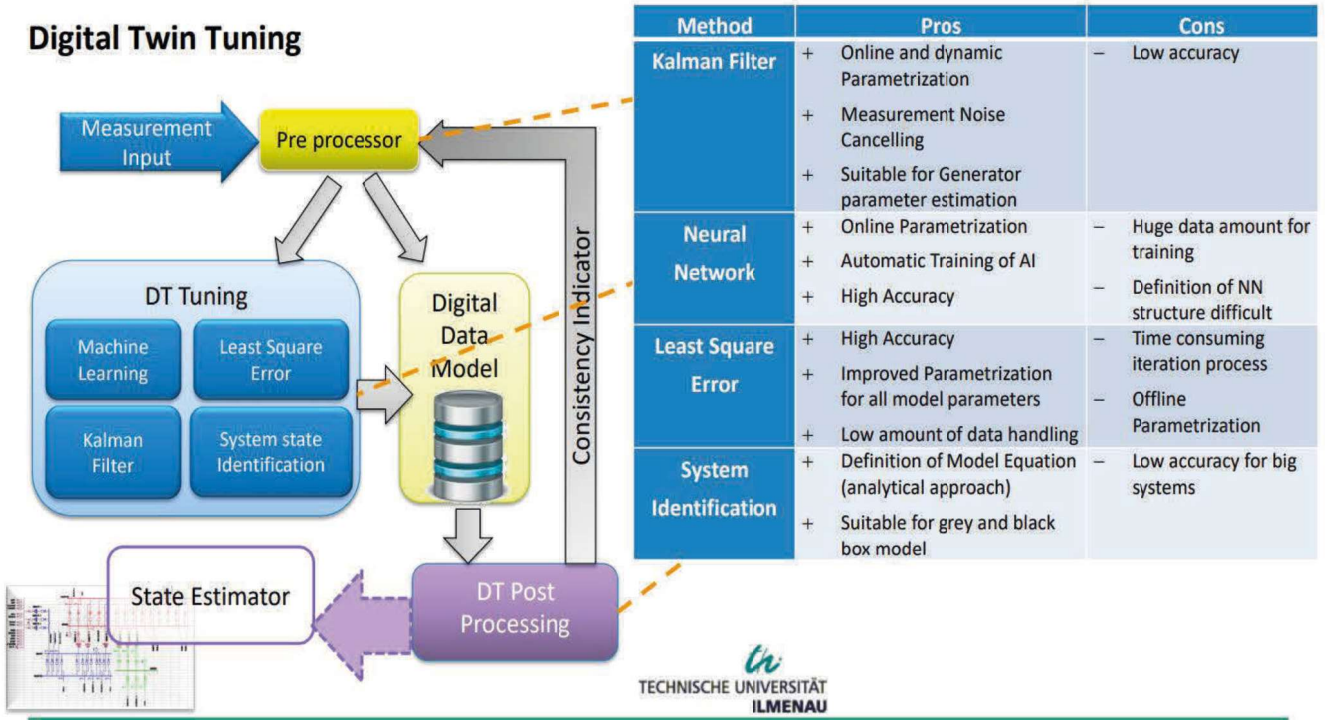


Fig. 3.1. Place DT substation [11]



Method	Pros	Cons
Kalman Filter	+ Online and dynamic Parametrization + Measurement Noise Cancelling + Suitable for Generator parameter estimation	– Low accuracy
Neural Network	+ Online Parametrization + Automatic Training of AI + High Accuracy	– Huge data amount for training – Definition of NN structure difficult
Least Square Error	+ High Accuracy + Improved Parametrization for all model parameters + Low amount of data handling	– Time consuming iteration process – Offline Parametrization
System Identification	+ Definition of Model Equation (analytical approach) + Suitable for grey and black box model	– Low accuracy for big systems

Fig. 3.2. DT tuning [11]

It applies systems thinking techniques to analyze and refine these problems. The art analysis dedicates that DT technology is presented as a complicated system, during diagnostic and prognostic functions. The ideal DT model must be continuously adapting to different circumstances system that improves. In [2] indicated that DT should respond to attributes of conception are communication, emergence, transformation, function, boundary, harmony, and relationships. The difficult task is to create DT models that follow physical parameters search objects precisely. Problems for implementation of a digital twin are challenging because of its complexity, novelty, cost, and involve the installation of new components and systems. Effective implementation of a digital twin needs careful assessment of adequately and sensitivity of DT models with taking into account set all conditions.

CHAPTER 4.
DT OF THE EU ELECTRICITY GRID

In [12, 13] noted that declining costs for renewable energy technologies, market developments, rapid innovation regarding storage systems, electric vehicles, as well as digitalization are all factors leading naturally toward greater energy system integration in Europe. Digital Twin power system EU is system-wide Digitalization of Energy Action Plan that could accelerate the implementation of digital solutions and the integration of energy systems. Commission will propose an action plan for an accelerated digital transformation of the sector, which is needed to ensure the shift towards renewables, connected mobility, smart buildings, and a more integrated energy system with consumers at its core [12].

For develop DT in power system is to start with interested TSOs and DSOs across different member states [12].

According [3] implementation of DT can ensures the advancement of standards, models, data handling, interfaces, and interoperable architectures for digital twin and digital grid. Further development of Digital twins as a tool for data-driven performance in future digital power grids, especially in Power System Operation, Grid planning and maintenance, Power System Economics, and Flexibility Markets can support the Green Deal and Strategy and Digital Transformation of the power system.

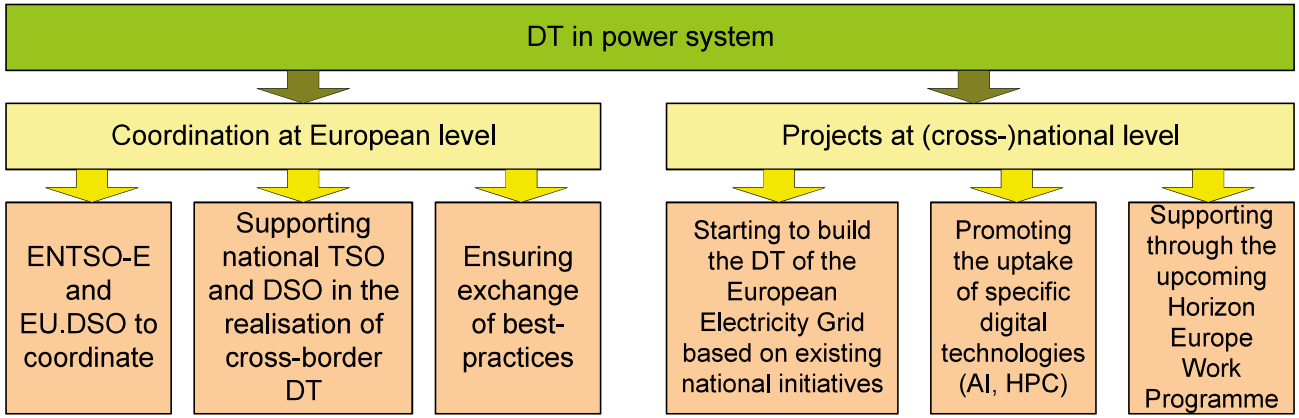


Fig. 4.1. DT in power system

CHAPTER 5.
DT FOR GREEN DEAL

The European Commission presented its proposal on a revised TEN-E on 15 December 2020. The revision of the TEN-E Regulation identifies 11 priority corridors and 3 priority thematic areas to develop and interconnect. It updates the infrastructure categories eligible for support with an emphasis on decarbonization and adds a new focus on offshore electricity grids, hydrogen infrastructure, and smart grids [14]. In [15] is declared, the importance of smart electricity grids, which do not always include the crossing of a physical border, in achieving the Union's energy and climate policy objectives was acknowledged in the Commission communication of 8 July 2020 entitled 'Powering a climate-neutral economy: An EU Strategy for Energy System Integration' (the 'EU Strategy for Energy System Integration').

The criteria for that category should be simplified, should include technological developments regarding innovation and digital aspects, and should enable energy system integration. So, in this case, usage DT can decide this task. Promoting Investments to support the smartness of the electricity grid, to accelerate the energy system transformation: by monitoring the digital transformation of the energy system in the EU; by supporting the implementation of a Digital Twin of the Electricity Grid [5].

In [16] noted, that in its Vision 2030 on Market Design and System Operation, ENTSO-E identified four key elements as major drivers for the power system of the next 10 years: the rise of renewables, the drive for electrification, the increase of decentralized resources, and digitalization.

COMPLEX APPROACH FOR COMPENSATION INSTABILITY POWER GENERATION

An integrated approach seems to be optimal when several methods are used to compensate for the instability of RES generation. In this case, the total cost of C_{Σ} to compensate for the instability of RES generation by power reservation is minimized. The task of optimizing power reservation is set as:

$$C_{\Sigma} = C_{ch}(P_{ch}) + C_h(P_h) + C_b(P_b) + C_{ps}(P_{ps}) + C_{tl}(P_{tl}) \to \min \qquad (6.1)$$

where $C_{ch}(P_{ch})$ is the cost of the reserve by chemical type (battery energy storage system); $C_h(P_h)$ is costs of hydrogen technologies; $C_b(P_b)$ is costs associated with the use of biogas technology as a reserve; $C_{ps}(P_{ps})$ is the cost of using the system reserve, it is actually compensation for the maintenance of the reserve for loading for TPP units operating on price bids and is determined by the equation:

$$C_{ps} = \begin{cases} P_{ps} \cdot (c_c^{ps} - dc_f), c_c^{ps} \rangle c_f \\ 0, c_c^{ps} \langle dc_f \end{cases} \qquad (6.2)$$

Where c_c^{ps} is the marginal price of the system, which is formed for the settlement hour on the wholesale electricity market; dc_f is the increased price of fuel, which is determined on the basis of the derivative function of fuel consumption for electricity production by the level of load of the power plant unit and the cost of the required fuel; $C_{tl}(P_{tl})$ is costs for reserves of transmission lines power capacity; P_{ch}, P_h, P_b, P_{ps}, P_{tl} accordingly, the optimal power values, which are determined from each of the power reservation methods.

MATHEMATICAL CRITERION MODEL OF COSTS FOR 1 kW OF RESERVATIONS UNDER THE SCENARIO WHICH ELECTRIC CHEMICAL STORAGE IS USED

The modified mathematical model of specific costs per 1 kW of redundancy according to the scenario in which chemical accumulators are used and the system reserve is presented:

$$C = \frac{C_1}{P_{ch}} + C_2 P_{ps} + C_3 P_{tl} + C_4 \frac{P_{ch}^2}{P_{ps}^2 \cdot P_{tl}} \rightarrow min \qquad (7.1)$$

where C_1, C_2, C_3, C_4 are generalized constants containing the original data of the problem; P_{ch}, P_{ps}, P_{tl} are respectively, storage capacity, system reserve and bandwidth as variables that are optimized.

The **first component** of the equation takes into account the specific costs of the implementation of redundancy using a system of chemical storage of electricity. **The second**, **third** and **fourth** components take into account the system costs of electrical networks.

The orthonormal system of equations with respect to the similarity criteria for (4) is written:

$$\begin{cases} -\pi_1 + 2\pi_4 = 0 \\ \pi_2 - 2\pi_4 = 0 \\ \pi_3 - \pi_4 = 0 \\ \pi_1 + \pi_2 + \pi_3 + \pi_4 = 1 \end{cases} \Rightarrow \begin{bmatrix} -1 & 0 & 0 & 2 \\ 0 & 1 & 0 & -2 \\ 0 & 0 & 1 & -1 \\ 1 & 1 & 1 & 1 \end{bmatrix} \times \begin{bmatrix} \pi_1 \\ \pi_2 \\ \pi_3 \\ \pi_4 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} \quad (7.2)$$

Solution of this system of equations: $\pi_1 = \pi_2 = 2/6$

$\pi_3 = \pi_4 = 1/6$

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MATHEMATICAL CRITERION MODEL OF COSTS FOR 1 kW OF RESERVATIONS UNDER THE SCENARIO WHICH ELECTRIC CHEMICAL STORAGE IS USED

Economically feasible values of the optimized parameters are determined from the system of equations:

$$\begin{cases} \pi_1 = \frac{2}{6} = \frac{C_1}{P_{ch}} & \pi_2 = \frac{2}{6} = C_2 \cdot P_{ps} \\ \pi_3 = \frac{1}{6} = C_3 \cdot P_{ps} & \pi_4 = \frac{1}{6} = \frac{C_4 \cdot P_{ch}^2}{P_{ps}^{-2} \cdot P_{tl}} \end{cases} \quad (8.1)$$

Solution of this system of equations:

$$P_{ch} = \left(\frac{C_1^4}{4C_2^2 \cdot C_3 \cdot C_4} \right)^{\frac{1}{6}} \quad (8.2) \qquad P_{ps} = \left(\frac{4C_1^2 \cdot C_3 \cdot C_4}{C_2^4} \right)^{\frac{1}{6}} \quad (8.3)$$

In the criterion form, the cost expression (4) is written as:

$$C_* = \frac{\pi_1}{P_{ch*}} + \pi_2 P_{ps*} + \pi_3 P_{tl*} + \pi_4 \frac{P_{ch*}^2}{P_{ps*}^2 \cdot P_{tl*}} \quad (8.4)$$

Taking into account the values of the similarity criteria (6):

$$C_* = \frac{2}{6P_{ch*}} + \frac{2P_{ps*}}{6} + \frac{P_{tl*}}{6} + \frac{P_{ch*}^2}{6P_{ps*}^2 \cdot P_{tl*}} \quad (8.5)$$

Separate the component of the cost of redundancy with chemical storage (first term) and the components that characterize the cost of using the system reserve and the cost of increasing the capacity of transmission lines (second term) and substitute the numerical values of the similarity criteria:

$$C_* = 0{,}333 \cdot P_{ch*}^{-1} + 0{,}667 \cdot \left(0{,}5 \cdot P_{ch*} + 0{,}25 \cdot P_{tl*} + 0{,}25 \cdot P_{ch*}^2 \cdot P_{ps*}^{-2} \cdot P_{tl*} \right) \quad (8.6)$$

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The analysis of the sensitivity of unit costs in relative units to changes in one of the influencing factors with constant others

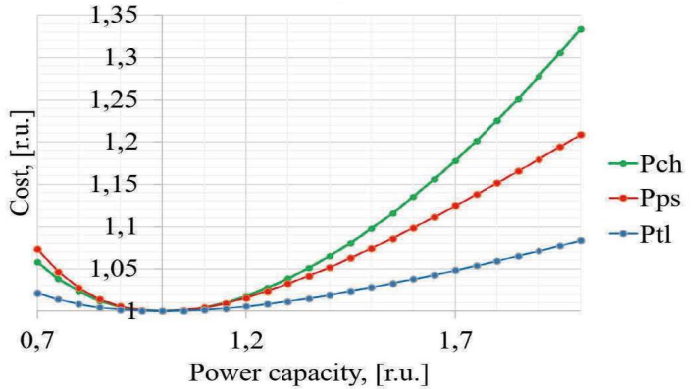


Fig. 9.1. Cost sensitivity: to changes in the capacity of chemical unit (green curve); to change the power of the system reserve (red curve) and to change the power of the capacity of power lines (blue curve).

Cost sensitivity depending on the simultaneous change in the power capacity of chemical storage and to the change in the capacity of the system reserve

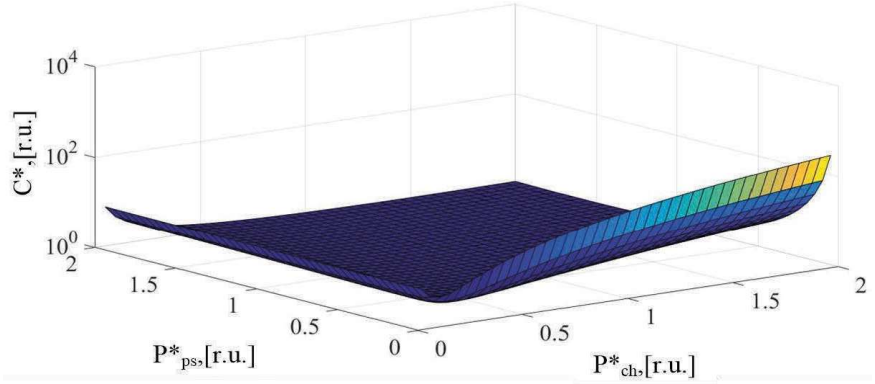


Fig. 10.1. Cost sensitivity to simultaneous changes in the capacity of chemical type (battery energy storage system) and the power capacity of the system reserve.

COST SENSITIVITY

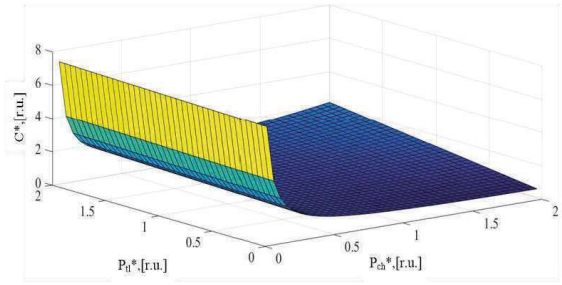


Fig. 11.1. Cost sensitivity to simultaneous changes in the capacity of chemical type (battery energy storage system) and to changes in the capacity of transmission lines.

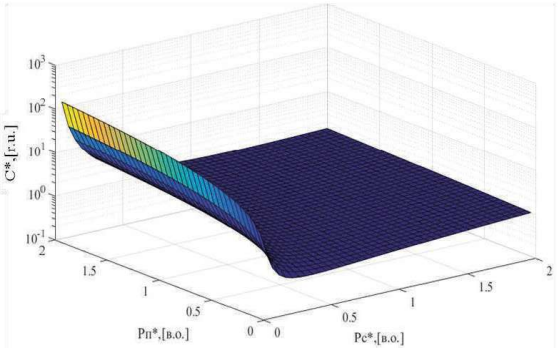


Fig. 11.2. Cost sensitivity to simultaneous changes in transmission line power capacity and system reserve power capacity

Need take into account

- model of location
- model of climate
- model of PV modul
- model of PV inverter
- model of battery
- Models of components
- model of load chart
- model of financing









Наукове видання

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КУДРЯ Степан
РУБАНЕНКО Олена

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