The Application of Digital Twin on Power Industry

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Abstract: Digital Twin (DT), integrating some current popular technologies, such as smart sensors, 5G communications, cloud platforms and big data analysis, is an integrated multi-discipline, multi-physical, multi-scale and multi-probability simulation process. To promote the accelerated development of China's manufacturing industry, it is needed to develop a smarter new generation of Smart Power System (SPS), and it is time for DT’s emergence. This system can comprehensively improve the intelligence of grid operation by using DT, which is driven by the data stream generated by the smart grid. Besides, it uses real-time situational awareness and uses real-time virtual deduction as cognitive means, and real-time feedback from virtual space to real space as an iterative method. Based on the applications of DT in the power industry, this article analyzes some applications in power system control, equipment fault prediction and diagnosis, and power online analysis from the demand for the core technologies of DT and DT of power system intelligence. Thus, the design framework, core technologies and implementation approaches of the Power System Digital Twin (PSDT) are presented. Finally, the challenges faced by the applications of DT in the power industry are analyzed, and the future trend of the power of DT is summarized.

1. Introduction
On April 7, 2020, the National Development and Reform Commission (NDRC) and the Office of the Central Cyberspace Affairs Commission (OCCAC) issued the Implementation Plan on Promoting the Action of "Enabling Intelligence by Using Numbers in Cloud" to Cultivate New Economic Development, which first proposed seven new-generation digital technologies, and DT was one of them. This document clearly stated that China should promote the "Digital Twin Innovation Initiative". The relevant policy documents of the Ministry of Industry and Information Technology of the People's Republic of China (MIITPRC) also frequently mention DT and require to increase researches and applications of DT.

The power industry is an important national basic energy industry and public utility industry related to the national economy and people's lives. The safety, stability and adequate supply of electric power is an important guarantee for the comprehensive, coordinated and sustainable development of the national economy. Nowadays, the applications of DT in the aerospace, workshop, and oil and gas industries are relatively mature. However, the researches and applications on power industry are still in their infancy, which means that there is a great potential for development and broad innovation space for DT. Therefore, the research on the applications of DT can bring more inspiration for the further application of DT in the power industry.

In the Internet era, digitization and intelligence of power system, power grid, and power equipment are important guarantees for the healthy development of the national economy and people’s normal
lives. The application of digital twin technology on the power industry mainly includes dynamic monitoring and maintenance of power generation equipment and power control centers, and real-time operational control of the power grid. Specifically, it includes the following aspects.

1) To overcome the safe and stable operation mechanism and characteristic analysis technology of the power systems.
2) To build new generation of the simulation platforms.
3) To improve calculation efficiency and accuracy.
4) To break through fault diagnosis, recovery and automatic reconstruction and other technologies.
5) To comprehensively improve the power system's defense capabilities under cascading failures, extreme disaster weather or external damage conditions, etc.

The main contents of this article are as follows. The first part briefly introduces the application status of digital twin technology on power industry. The second part gives a preliminary introduction to the concept of DT. The third part analyzes the application of DT on power industry in detail, summarizes and analyzes the design framework, core technology and implementation path of the PSDT through the application in specific scenarios. Finally, the challenges faced by the applications of DT are analyzed on power industry, and the future trend of the power of DT is described.

2. DT and its significance
DT, integrating some current popular technologies, such as smart sensors, 5G communications, cloud platforms, big data analysis and artificial intelligence, is an integrated multi-discipline, multi-physical, multi-scale and multi-probability simulation process with the aim of designing a virtual model in digital space and establishing a mapping relationship between a digital virtual and a physical entity by fully exploiting and utilizing the benefits of a large amount of data resources to "mirror" entities [1-2]. DT is widely used in aerospace, medical, oil and gas, electric power and other industries now. However, to a large extent, it was just a concept when it emerged in 2002. Later, DT was first applied to the health maintenance and protection of aircraft in the National Aeronautics and Space Administration (NASA).

In recent years, the topic of DT in industrial manufacturing is getting a growing popularity. China Academy of Industry 4.0 has joined hands with the digital twin research team of Beihang University (BUAA) and lots of enterprises to devote themselves to the research and development of DT in various industries to meet the Fourth Revolution of Science and Technology. As an important guarantee for the people's livelihood and national economy, the power industry needs the in-depth application of DT to promote its further development. Nowadays, DT provides advanced analysis for its mirrored system by connecting the physical world and the digital world, making it possible to reflect physical conditions in real-time.

3. DT’s applications and analysis framework on the power industry

3.1. DT applications

3.1.1. Power Monitoring System (PMS)
Distributed motor has a high energy efficiency, while to a certain extent, its wide application partly increases the probability of fault or accident in the power system. Therefore, the demand for a power monitoring system to reduce the response time to critical faults is increasing rapidly. Solving of this problem depends on the further development of monitoring technology in the Power System Control Center (PSCC).

DT is applied to PMS because of its data-driven, real-time situational awareness and closed-loop feedback. The fault prediction and detection method based on DT enables operators to predict the possible future state and provide solutions in time before the power system’s failure or emergency occurs, which will lead to the future development of PSCC technology. In [3], Brosinsky et al. proposed a digital twin concept for the PSCC in 2018, as illustrated in Fig. 1. The design idea is
derived from Dynamic Digital Mirroring (DDM). As a part of PMS, DDM is a dynamic model that reflects the system status in real-time. The data of Remote Terminal Unit (RTU) and Phasor Measurement Unit (PMU) sensor are input into the DT database, and then used for real-time simulation, fast system analysis and control feedback in DDM modeling instance. In the modeling process, cross-checking is used to ensure the correct allocation of relevant assets and sensor data. Based on self-learning and machine learning algorithms, combined with the real-time operational data flowing into DT from the power system, the digital twin data are enriched continuously, thereby the description of the system state can be more accurate, and the accuracy of prediction or monitoring can be improved too. Although there are not many examples of DT applications on Power System Monitoring Center (PSMC), the possibility and advantages of DT in the future are self-evident.

![Fig. 1. PMA based on DT](image)

3.1.2. Pitch angle control of Variable Speed Wind Turbine (VSWT)

VSWT has higher power generation efficiency and better power generation quality, so there is a great significance of research on it. Generally, VSWT has two control zones, which are the ones below the rated speed and above the rated speed, and the control of the maximum Power at high wind speed has always been challenging [4-5]. [5] proposed a simple power control strategy suitable for VSWT, which covers the entire wind speed range. [6-9] proposed the Proportional Integral (PI), Fuzzy Inference System (FIS), Neural Network (NN), Backstepping Sliding Mode Control (BSMC) and the modified Newton Rapshon (MNR) algorithm to enhance the system's robustness as facing the changes of the parameters and optimize the control performance to the dynamic and static speed. [10] designed a new robust adaptive controller with full state feedback.

![Fig. 2. A design strategy of adaptive controller system for VSWT based on DT](image)
and Model-Free Control (MFC) (DDPG-NIB-MFC) to reduce the difference between the reference input and output in HIL, and use the pitch angle output of HIL as the reference input in SIL. The simulation and implementation results have proved that the new controller is more effective, robust and more adaptive than the PI controller optimized by PSO under the condition of uncertainty.

3.1.3. New five-dimension DT model and Prognostics and Health Management (PHM)

The DT research team led by Professor Fei Tao of BUAA explained the new five-dimension DT model and introduced it into PHM. Based on this, a PHM method based on DT was proposed [13-15]. As shown in Fig. 3, this new dynamic multi-dimension and multi-space-time model not only constructs the traditional geometric and physical dimensional model of a physical entity, but reflects the multi-dimension dynamics of its geometry, physics, behavior, rule and constraint so that the simulated result, predictive result, Assessed and optimized result can be made more accurate.

Fig.3. A new five-dimension DT model

3.1.3.1. Power plant control system based on five-dimension DT

Beijing BKC Technology Co., Ltd. developed an intelligent power plant management and control system based on five-dimension DT. As shown in Fig. 4, it has realized application services such as visualized intelligent real-time monitoring of shaft system of steam turbine generator set, visualized online precision diagnosis of a large-scale rotator, visual management of underground pipe network and visualized 3D operation guidance system.

Fig. 4. Intelligent power plant management and control system based on five-dimension DT

3.1.3.1.1. Visualized intelligent real-time monitoring of shaft system of steam turbine generator set

Based on the collected real-time data, historical data and expert experience, the system constructs a 3D visualization virtual model of steam turbine shafting with high fidelity in the virtual space to observe the internal operation state of the steam turbine. The system can evaluate the state of the steam turbine in real-time, so as to accurately warn and prevent accidents such as turbine over-speed, turbine shaft breakage, permanent bending of large bearing, bush burning, oil film instability, etc. At the same time,
it can help to optimize bearing design, valve sequence and opening and operation parameters. These advantages can greatly improve the operation reliability of the steam turbine generator set. The design framework is shown in Fig. 4.

3.1.3.1.2. Visualized online precision diagnosis of large-scale rotator
With the virtual model and analysis results of twin data, the system can remotely display the state of equipment and component, the severity of the problem, the description of the fault, the processing method and so on in real-time. Thus, remote and online diagnosis of equipment can be realized. The operators responsible for maintenance can access the e-mails, pages and dynamic websites sent by the online system alarm, and simultaneously they also can view the details of the rotator status through the virtual model running online.

3.1.3.1.3. Visualized management of underground pipe network
This is to achieve a complete and accurate 3D model of the underground pipe network through laser scanning technology, combined with the plane design.

3.1.3.1.4. A visualized 3D operation guidance system
Based on the real-time data, historical data, domain knowledge and 3D laser scanning technology, the complete and accurate 3D model of equipment has the following functions. First, the model can be linked with training courses to form vivid training materials, which can help new employees to master the equipment structure quickly. Second, it can be associated with the maintenance work instruction to form a 3D operation instruction to standardize the operation of employees. Finally, it can also be used as a tool for training and assessment for employees.

On the whole, the intelligent power plant management and control system based on 5D DT realizes the perspective monitoring of crucial equipment, precise and remote diagnosis of the fault, visualized management and accurate simulation of employee operations, etc., which can meet the various requirements such as equipment condition monitoring, remote diagnosis, operation and maintenance and so on and to realize the intuitive visual interaction between the users.

3.1.3.2. PHM of Wind Turbine (WT) gearbox based on five-dimension DT
Based on the 5D DT model, the PHM of WT is discussed. As shown in Fig. 5, the functions can be packaged into services and provided to users in the form of application software.

- Sensors are deployed on the gearbox, motor, spindle, bearing and other vital parts of the physical WT for real-time data acquisition and monitoring.
Based on the collected real-time data, historical data and domain knowledge, a multi-dimensional virtual model of geometry-physics-behavior-rule for virtual WT can be built to achieve a more realistic virtual mapping of physical WT.

With synchronous operation and interaction of physical WT and virtual WT, the former oriented state detection, fault prediction, and maintenance strategy design can be realized through interaction and comparison between physical state and simulation state, fusion analysis between physical data and simulation data as well as virtual model verification.

3.1.4. Online analysis of power grid

Online Dynamic Security Assessment (DSA) analysis has been widely used in the power dispatching control centers in China since 2016. When the control center of dipath processes the large-scale power grid models, it performs regular online DSA analysis at 15-minute intervals [16]. Considering the complexity of the faults and their repairs on the power grid and the huge impact on people's ordinary lives, it is increasingly important to shorten the round-trip response time of the entire online analysis system to better monitor and present early-warning of the faults on the power grid. [17-19] discussed the online analysis methods based on in-memory computing and twin NN to be suitable for the second-level online analysis system architecture.

In 2019, the research team of Chief Scientist Mike Zhou coming from the China State Grid Electric Power Research Institute of China (CSGEPRI) introduced a DT framework into the application environment of online grid analysis (as shown in Fig.6), which included an Online Analysis Digital Twin (OADT) method and a high-level solution architecture of the future real-time online analysis system to support the realization of the new grid online analysis solution architecture [20-21].

OADT had some outstanding built-in features, including in-memory computing, high-performance parallel computing, Complex Event Processing (CEP), and Machine Learning (ML) based on the security assessment. As illustrated in Fig.6, after the transmission of online measurement information from the RTU to the data bus of the dispatching center, the network analysis model (NAM) hosted in the data grid continuously updates by itself with a sub-second delay to track the operating status of the mirrored grid. If an critical situation is detected, the CEP engine is used to perform situational awareness analysis and a snapshot of load flow with second-level delay related to online measurement information will be established to drive the downstream online analysis applications such as NN model.

![Fig.6. The architecture of future real-time online analysis system combined with DT](image)

3.2. Power system framework design based on digital twin

From the above applications of DT on the power industry, it can be seen that different from the traditional power system driven by model and expert system, the power system based on DT takes the data-driven as the core. The dependence on physical systems is small, but mainly relying on massive data, Machine/Deep Learning (ML/DL), high-dimensional statistical analysis, stream computing,
knowledge graph and other artificial intelligence algorithms or tools matching with the massive data. The power system design framework based on DT can be shown in Fig.7.

Fig. 7. Power system framework design based on DT

The power system based on DT can ensure the consistency of the virtual system and the real system more accurately and quickly by comparing/adjusting with the real value at run time. The three major characteristics of the system are data-driven, closed-loop feedback and real-time interaction.

- Data-driven benefits from the power grid's massive data and the gradual improvement of the big data mining system, which makes the PSDT technology more suitable for the complex power industry.
- Closed-loop feedback enables the system's data model to update and optimize adaptively by actively learning a large amount of data after it is put into operation, and the effect of learning can be improved steadily as the amount of the data increases.
- Real-time interactive links data-driven and closed-loop feedback further enhances the function of the real-time situational awareness and the super-real-time virtual test of PSDT, so that the PSDT can control the situation of the system accurately and simulate the feasible/optimized decision-making solutions quickly not only under the routine operation but also in an emergency.

3.3. The future development trend and implementation path of DT

The landing of DT applications on the power industry mainly depends on the implementation of services such as Cyber-Physical System (CPS), multi-dimension virtual models, twin data-driven, and dynamic real-time interactive connection, and the core technologies are mainly reflected in DT modeling, CPS, interaction method between the virtual model and the real-world entity and so on. According to the above in-depth analysis of the power of DT applications, the future development trend and implementation path of power of DT are analyzed as follows.

3.3.1. DT modeling

Preliminary researches and applications have been made on the methods and processes of DT modeling on the power industry. In some aspects such as physical behavior research, non-destructive material measurement technology, quantification error and error confidence assessment-related theoretical research have made sure progress. These auxiliary technologies will help the determination of the power of DT model parameters, the construction of behavior constraints, and the verification of model accuracy. In the future, it will be necessary to start from theoretical research on the consistency
of model framework and model process and provide theoretical guarantees of model accuracy and practical accuracy.

3.3.2 CPS
At present, the research on the theory and technology of the CPS is still in the initial stage, and the CPS of the power industry is focusing on the integration and fusion of sensor data and collected system data and the dimension reduction processing of data fusion. In the future, based on the demand of virtual-real interaction in the power of DT, from four perspectives of physical integration, model integration, data integration and service integration to extract the scientific information of CPS and design the corresponding reference framework for the system implementation, which can provide theoretical and technical reference for DT practice in power industry.

3.3.3 Interaction and collaboration
A dynamic real-time interactive connection connects physical entities, virtual models, and service systems into an organic whole, which enables the information and data can be exchanged and transmitted between various parts. So it can be seen as the "vessel" of DT applications. Therefore, without the interaction between the components, the applications of DT will lose vitality, just like a person cutting off his artery. The DT on the power industry has initially realized the interaction, collaboration between the physical world and the virtual world, but the research on the interaction and collaboration between machines (equipment) and services will be the critical technical guarantee and the trend of future technology development for the successful application of DT on the power industry, which has little progress so far.

4. Conclusion
Through in-depth analysis and summary, it can be seen that the research of DT is shifting from the research of concept and application framework to the research of more profound core technology. The characteristics of data-driven, real-time interaction and closed-loop feedback, as well as its real-time perception and the deduction means of virtual reality technology will inevitably be applied in-depth on the power industry. At the same time, the research of DT technology and its application on power industry should be closely linked with big data mining and analysis technologies, which can reduce the dependence of PSDT on its physical entity to a greater extent, and strengthen the study of the data-driven model, so as to solve the related problems of uncertainty and error better during the application on the power industry.

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