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Research on the Reliability of Onshore DC Collection Multi-terminal DC Wind Power Systems

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ABSTRACT

Against the backdrop of clean energy development, wind energy, as a clean and renewable source of energy, plays a significant role in reducing carbon emissions, achieving dual-carbon goals, and transforming the energy structure. Offshore wind power is valued for its abundant resources and stability, while high-voltage direct current (HVDC) transmission has become a hot research field due to its cost-effectiveness and efficiency. This paper systematically identifies and analyzes various factors that may lead to failures in the onshore direct current (DC) collection of multi-terminal DC wind power systems using the Fault Tree Analysis (FTA) method.Overall, this paper provides theoretical support for the development of stable technology in offshore wind power HVDC transmission systems and offers guidance for future research and practice.

Introduction

In offshore wind power transmission, DC system has attracted attention due to the reduction of submarine cable construction. The multi terminal DC wind power system uses the multi terminal DC transmission system (MTDC) technology to connect multiple wind farms to the grid, and realizes energy transmission through VSC or LCC[1]. It has high flexibility and reliability, and is suitable for large-scale wind power grid connection and long-distance transmission. MTDC can effectively transmit electric energy to the load center and reduce the problem of grid stability. Multi terminal HVDC system (MT-HVDC) uses VSC technology, which has technical and economic advantages compared with traditional HVAC system[2]. MT-HVDC can effectively connect decentralized wind farms to the power grid, and cope with wind power fluctuations through control strategies[3].

Fault analysis is very important for system maintenance. It is the key to improve efficiency, reduce cost and ensure stable operation to determine the root cause of the problem, reduce faults, optimize design and improve reliability. In this paper, the fault tree analysis (FTA) method is used to systematically identify and analyze the factors that may lead to the failure of multi terminal DC wind power system with onshore DC collection, evaluate the possibility of failure and its impact on system reliability, and provide theoretical support for the development of the system stability technology[4].

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1.Analysis of multi terminal DC wind power structure with onshore DC convergence

The composition of multi terminal DC wind power system with onshore DC collection includes multiple wind turbines, transformers, converters, HVDC transmission cables, etc. The wind turbine converts the wind energy into mechanical energy through the wind turbine, and then into electrical energy through the generator[5]; The power generation side transformer remits the AC generated by the wind turbine generator at each end into the AC bus with the same frequency; The electric energy collected by the AC bus is converted into DC power through the converter (rectifier); The DC power is transmitted to the public DC collection bus through the high-voltage DC transmission cable to realize the onshore collection of DC power of converters at each generation side[6]; The grid side converter (inverter) converts DC power into AC power that is consistent with the grid frequency and voltage to realize grid connection. Its structural diagram is shown in Figure 1.

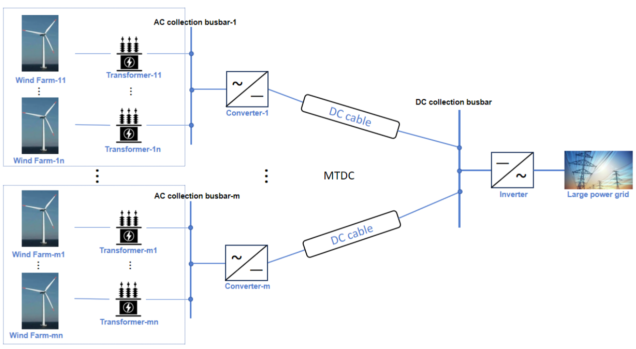

Figure 1. Structural diagram of multi terminal DC wind power system with onshore DC convergence

Fault tree analysis (FTA) is a structured method to identify system faults. It starts from the top-level fault and gradually analyzes to the root cause, which helps to understand the potential fault path [6]. Combining qualitative and quantitative analysis, FTA can effectively identify the causes and probabilities of key events, especially for fault diagnosis of complex systems [7]. It has been widely used in many industrial fields.

In the multi terminal DC wind power system with onshore DC convergence, FTA describes the macro fault phenomenon through the top event, the bottom event describes the fault cause, and the intermediate event describes the intermediate state of the fault, and constructs the fault tree model. This provides a rapid judgment method for system fault diagnosis and helps to quickly analyze fault types and phenomena.

In the actual analysis process of this paper, the top event of the fault tree is the multi terminal DC wind power system fault collected by the onshore DC, and the intermediate event is the main component fault, system fault and light fault; According to different fault sources, the fault sources of main components can be divided into four types: wind turbine, converter, inverter and bus; Loop faults can be divided into 4 types: power side combiner system, shore DC combiner system, cable and insulation system. Minor faults can be divided into 4 types: sensors, relays, connectors slightly loose, and bracket surface slightly corroded. These 12 types of faults are taken as the base event. The system fault tree is established based on various fault subdivisions and their logical relationships.

2.Topology analysis of multi terminal DC transmission system

In the multi terminal DC wind power system with onshore DC convergence, the multi terminal DC convergence system as the main source of power plays a core role. The system structure is diverse, and the transmission efficiency and reliability are different due to different structures. The common structures are ring, star and chain topology. The ring structure is widely used because of its stability and flexibility[8]. In particular, ring topology is used in offshore wind farms, which reduces the number of circuit breakers and enhances system redundancy and flexibility[9]. Series multi terminal DC transmission system has attracted attention in the field of cross sea interconnection and Hybrid DC transmission system[10]. With the expansion of renewable energy grid connected scale, the research on multi terminal DC transmission system will be more in-depth, focusing on improving system flexibility, reducing losses and optimizing control strategies. The substation ring topology (SSRT)[11] and Two wind farms and substation ring topology (2WF-SSRT) are common structures[12].

The 2WF-SSRT topology combines the ring structure of two wind farms and an onshore substation. Each wind farm side VSC is connected to an onshore VSC station via a DC link, forming a substation ring structure. This structure enhances the system’s stability and efficiency by reducing the number of DC connectors (DCCBs) and offshore stations, as illustrated in the structural diagram shown in Figure 2 [12].

3. System Failure Rate Analysis

Based on the 2WF-SSRT multi-terminal DC topology with high stability in existing research, and considering the shore-based DC collection system and high-voltage inverter grid connection comprehensively, a reliability

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analysis is conducted on the multi-terminal DC wind power system with shore-based DC collection. The sources of system failures include wind turbine failures, power side collection system failures, shore-based DC collection system failures, and high-voltage inverter grid connection system failures. There has been extensive research on the failure analysis of wind turbines and high-voltage inverter systems. This paper mainly focuses on a detailed analysis of faults in the 2WF-SSRT structure circuit and shore-based DC collection system, establishing a fault tree.

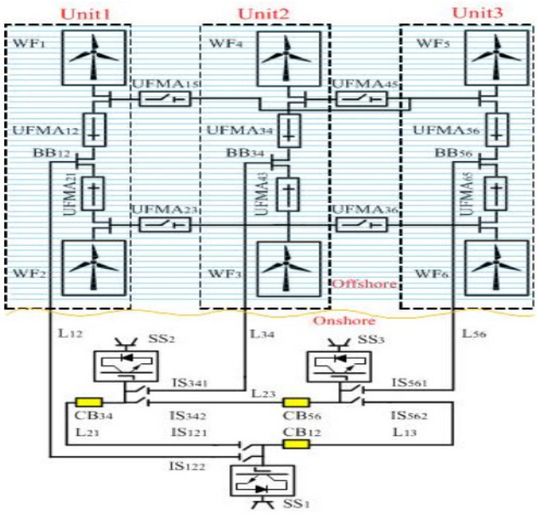

Figure 2. 2WF-SSRT topology[12]

3.1 Wind Turbine Generators

Wind turbine generators are the main source of power in wind power systems. Their working principle is as follows: the wind wheel captures wind energy and converts it into mechanical energy for the rotation of the shaft; through a speed increaser, the increased speed drives the generator, converting mechanical energy into electrical energy.

The average failure rate of wind turbine generators is about 2.5%-3% [14]. Zhiwei Gao and others have conducted a more systematic analysis and research on the failures of wind turbine generators. Among the failures of wind turbine generators, the electrical system has the highest failure rate, reaching 23%; in addition, the control system failure rate is 18%, sensor failure rate is 10%, hydraulic system failure rate is 9%, yaw system failure rate is 8%, rotor failure rate is 7%, and other failures including generators, gearboxes, and transmission systems are approximately 2%-6%.

3.2 Power Side Collection System

This paper analyzes the power side collection system, taking the 2WF-SSRT structure as an example. The structure consists of three interrelated units. Each unit includes two wind turbines and one substation, and the three units form a complete 2WF-SSRT structure. Within the 2WF-SSRT structure, there are 6 wind turbines and 3 substations. Each wind turbine is connected to 3 substations through a ring structure, ensuring that each wind turbine has three independent power output paths.

The sources of faults in the 2WF-SSRT structure circuit include main components and power transmission lines. A fault tree is established for each of the three output paths of each wind turbine, divided into the WF1-SS1 circuit, WF1-SS2 circuit, and WF1-SS3 circuit. Therefore, the circuit fault of the 2WF-SSRT topology is constituted by the AND gate of the faults in the WF1-SS1 circuit, WF1-SS2 circuit, and WF1-SS3 circuit.

Create a fault tree for the WF1-SS1 circuit, as shown in Figure 3. The main components include wind turbine generators, normally closed UFMA, and rectifiers; the transmission lines include the AC circuit, BB busbar, and CB circuit breaker. If any component fails, the circuit cannot operate normally. Let the probability of a fault occurring in the WF1-SS1 circuit be denoted as P_1 , and the probability that each component does not fail as P_i（where i=1 to 5)，then $P_1=1-\prod_1^5 P_i$）。

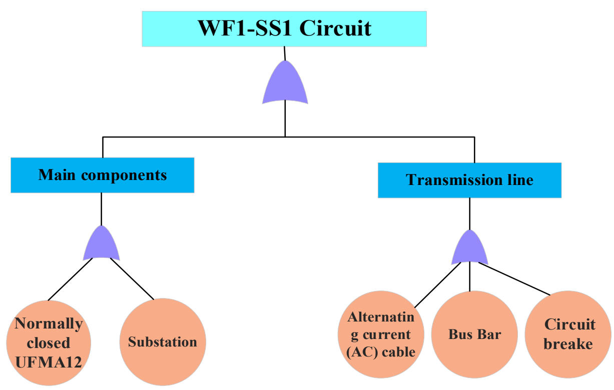

Figure 3. Fault Tree of WF1-SS1 Circuit

Create a fault tree for the WF1-SS2 circuit, as shown in Figure 4. The main components include wind turbine generators, normally closed UFMA,2 sets of normally open UFMA and rectifiers; the transmission lines include the AC circuit, BB busbar, and CB circuit breaker. If any component fails, the circuit cannot operate normally. Let the probability of a fault occurring in the WF1-SS2 circuit be denoted as P_2 , and the probability that each component does not fail as P_i（where i=1 to 7)，then $P_2=1-\prod_1^7 P_i$）。

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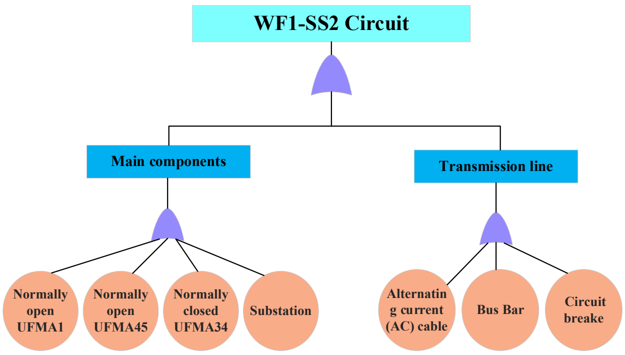

Figure 4. Fault Tree of WF1-SS2 Circuit

Create a fault tree for the WF1-SS3 circuit, as shown in Figure 5. The main components include wind turbine generators,a normally closed UFMA,a normally open UFMA and rectifiers; the transmission lines include the AC circuit, BB busbar, and CB circuit breaker. If any component fails, the circuit cannot operate normally. Let the probability of a fault occurring in the WF1-SS3 circuit be denoted as P_3 , and the probability that each component does not fail as P_i（where i=1 to 6), then$P_3=1-\prod_1^6 P_i$）。

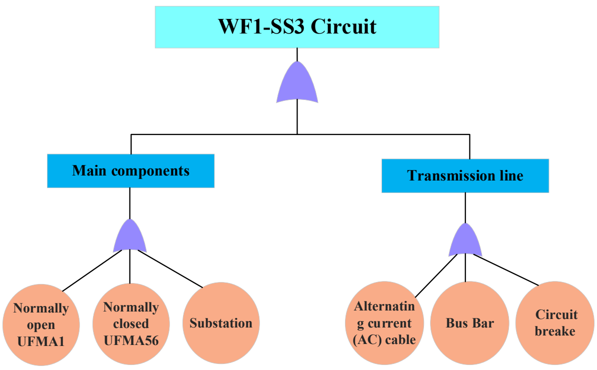

Figure 5. Fault Tree of WF1-SS3 Circuit

3.3 Shore-based DC Collection System

The shore-based DC collection system refers to the system where electrical energy, after being transmitted through high-voltage direct current (HVDC) transmission from the output end of a substation, is collected into the shore-based DC busbar. The schematic diagram of the system structure collected by n single-terminal DC transmission lines is shown in Figure 10. The electrical energy of the single-terminal DC transmission line is output by m groups of 2WF-SSRT structured wind turbine generators and collected through the DC busbar. The collected electrical energy is then stepped up by a DC boosting station and transmitted through a DC cable in single-terminal high-voltage direct current transmission. For an n-terminal DC transmission cluster, the high-voltage direct current from each terminal is collected by a gathering busbar and then grid-connected through a high-voltage inverter grid-connection system.

Create a fault tree for the shore-based DC collection system, as shown in Figure 6. It mainly includes faults on the DC collection bus side, faults in the multi-terminal DC transmission system, and faults in the shore-based collection bus; the main components include the DC busbar, capacitors, DC/DC boosting modules, high-voltage DC transmission cables, collected DC busbar, and collected busbar capacitors. Any failure of these components will prevent the normal collection of current. Let the probability of faults occurring in the shore-based DC collection system be denoted as P_4, and the probability that each component will not fail be denoted as P_i（i=1~6), then $P_4=1-\prod_1^6 P_i$）。

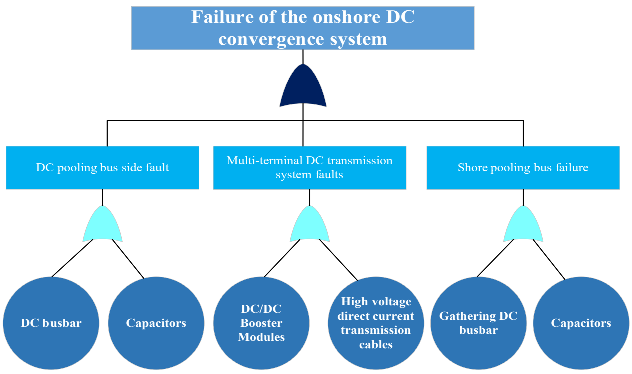

Figure 6. Fault Tree of Shore-based DC Collection System

3.4 High-voltage Inverter Grid-connection System

In the multi-terminal DC wind power generation system with shore-based DC collection, electrical energy is collected through a high-voltage DC bus, and then integrated into the power grid through a high-voltage inverter grid connection system. The high-voltage inverter converts direct current (DC) into alternating current (AC). Offshore wind power grid connection systems often use a hybrid structure of Modular Multilevel Converters (MMC) and Diode Rectifiers (DR) to enhance stability and economy. For example, in large-scale offshore wind power grid connection scenarios, a single DC voltage level system composed of cascaded DR and MMC can achieve efficient electrical energy transmission and control [15].

Liang Fang and others have studied the impact of Distributed Generation (DG) in port-based distributed power systems, assessing the enhancement of system reliability by solar energy, wind energy, Energy Storage Systems (ESS), Combined Cooling Heat and Power (CCHP) systems, and commercial electricity. The study employed a Markov chain model to evaluate the stochastic characteristics of DG components, and the results showed that the

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average failure rate of the DC/AC inverter is 0.143 times per year[16].

The average failure rate of 0.143 times per year means that there are 0.143 failures on average each year. Assuming that the failures are independent random events, the time to failure can be modeled using the exponential distribution, $P(t)=1-e^{-\lambda t}$, where λ is the failure rate and t is the time.For a period of one year, the failure rate$P(1)=1-e^{-0.143*1}=1-0.866=0.134=13.4\%$.

3.5 Fault Analysis of Multi-Terminal Direct Current Offshore Wind Power Collection Systems

The failure of the multi-terminal direct current (DC) wind power system with onshore DC collection is defined as the inability to stably output electrical energy and achieve grid connection.Failures may be caused by wind turbine unit failures, 2WF-SSRT structure loop failures, onshore DC collection system failures, or high-voltage inverter grid-connection system failures.

As shown in Figure 12, taking a single-terminal high-voltage direct current (HVDC) transmission circuit as an example for fault analysis, minor faults that do not lead to overall system failure are disregarded. Let

(1) The failure rate of the high-voltage inverter on the grid side is λ_a;

(2) The failure rate of the Onshore DC Collection Busbar is λ_1;

(3) The failure rate of the HVDC transmission cable is λ_2;

(4) The failure rate of the DC/DC Boost Converter Module is λ_3;

(5) The failure rate of the low-voltage side DC collection busbar is λ_4;

The probability that the onshore DC collection system cannot transmit electrical energy normally is λ_b, then

$$\lambda_b=P_4=\lambda_1+\lambda_2+\lambda_3+\lambda_4-\lambda_1\lambda_2\lambda_3\lambda_4 \quad ①$$

(6) The probability of a single wind turbine power output circuit failure in the 2WF-SSRT structure is λ_5, then

$$\lambda_5=P_1 * P_2 * P_3 \quad ②$$

A 2WF-SSRT structure consists of 6 wind turbines, then the failure rate of the 2WF-SSRT structure cannot output electrical energy stably is λ_c, then

$$\lambda_c=6 * \lambda_5-\lambda_5^6 \quad ③$$

(7) The failure rate of the Wind Turbine is λ_d。

The probability of a fault occurring where the single-terminal high-voltage direct current transmission circuit with m sets of 2WF-SSRT structures cannot stably integrate into the grid is λ_A,then

$$\lambda_A=1-[(1-\lambda a)*(1-\lambda_b)*(1-\lambda_c^m)*(1-\lambda_d)] \quad ④$$

When the onshore DC collection multi-terminal DC wind power system has n high-voltage DC transmission circuits, the probability of the entire system's electrical energy being unable to stably output and connect to the grid is λ_I, and the probability of the entire system's electrical energy being unable to output and achieve grid connection is λ_{II}, then

$$\lambda_I=1-(1-\lambda_A)^n \quad ⑤$$

$$\lambda_{II}=\lambda_A^n \quad ⑥$$

3.6 Example Calculation

This paper conducts a reliability analysis of multi-terminal HVDC wind power with onshore DC collection. Based on the establishment of a fault tree, the overall system reliability of multi-terminal HVDC wind power with onshore DC collection is comparatively analyzed in response to changes in the number of HVDC transmission terminals and the number of wind turbine units corresponding to a single terminal.

The lower the failure rate, the higher the reliability of the corresponding component or the overall system. By searching and calculating the failure rates of each basic component and fundamental loop according to formulas ①②③ , the data in Table 1 can be obtained.

Table 1. Case Study Failure Rates.

λ_a	0.134	P_1	0.03
λ_1	0.03	P_2	0.035
λ_2	0.05	P_3	0.04
λ_3	0.05	λ_5	0.000042
λ_4	0.03	λ_c	0.000252
λ_b	0.159998	λ_d	0.025

Based on the calculations using formulas ④ , ⑤ , and ⑥ , the variations of λ_A, λ_I, and λ_{II} with respect to the parameter m and the number of DC terminals n are obtained, as shown in Tables 2 and 3.

Table 2. Table of Failure Rate Variation with Respect to the Value of m.

m	n	λ_A	λ_I	λ_{II}
2	2	0.29074415	0.49695613	0.08453216
3	2	0.29074410	0.49695613	0.08453216
4	2	0.29074410	0.49695613	0.08453216
5	2	0.29074410	0.49695613	0.08453216

Table 3. Table of Failure Rate Variation with Respect to the Value of n.

m	n	λ_A	λ_I	λ_{II}
4	3	0.29074410	0.64321319	0.02457723
4	4	0.29074410	0.74694687	0.00714569
4	5	0.29074410	0.82052058	0.00207757
4	6	0.29074410	0.87270317	0.00060404

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4.Conclusions

Offshore wind power is highly favored for its abundant resources and excellent stability, while direct current (DC) transmission technology has become a hot research topic due to its significant cost-effectiveness and high efficiency. This study delves into the reliability of onshore DC collection in multi-terminal DC wind power systems and arrives at the following conclusions:

Wind turbine units exhibit a low failure rate, but the operation of large-scale wind farms still needs to pay attention to their potential impacts. The 2WF-SSRT ring structure stands out for its low failure rate and stable wind energy output capability.

A single DC transmission line can effectively collect energy from multiple 2WF-SSRT ring structures (m-value), and as the m-value increases, the overall failure rate λ_A of the single DC transmission line remains essentially unchanged. This indicates that within the load capacity of a single DC cable, it is possible to collect and transmit wind energy to the maximum extent, thereby reducing investment costs and improving power transmission efficiency.

In summary, this study provides an in-depth analysis of the reliability of offshore wind power high-voltage DC transmission systems and offers valuable references for future technological development and practical applications.

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References:

[1] Xu Weikai. Analysis and Discussion on the Development Trend of Offshore Wind Power. Resources Conservation and Environmental Protection, 2023.

[2] M. A. Koondhar, G. S. Kaloi et al. "Critical Technical Issues with a Voltage-Source-Converter-Based High Voltage Direct Current Transmission System for the Onshore Integration of Offshore Wind Farms." Sustainability, 2023.

[3] L. F. N. Lourenço, Amira Louni et al. "A Review on Multi-Terminal High Voltage Direct Current Networks for Wind Power Integration." Energies, 2022.

[4] Jiang Daozhuo, Gu Hongjie, Yin Rui, et al. Current Status and Prospects of Offshore DC Wind Power Field Research. Power System Technology, 2015.

[5] Guo Lingyu, Yao Gang, Zhou Lidan. A Review of High Step-Up Ratio DC/DC Conversion Technology for All-DC Offshore Wind Farms. Power System Protection and Control, 2018.

[6] Bimby Khrisdamara, Deny Andesta. "Analysis of Head Truck-B44 Failure Causes Using FMEA and FTA Methods (Case Study: PT. Bima, Site Pelabuhan Berlian)." Jurnal Serambi Engineering, 2022.

[7] Xie Yi, Lu Zhenbang. Improved Software Fault Tree Analysis. Reliability and Environmental Testing of Electronic Products, 2016.

[8] Fu Songtao, Su Xunwen, Song Haiming, et al. Simulation Comparison and Analysis under Faults of Two Multi-Terminal DC Topologies. Smart Grid, 2017.

[9] Wu Guoxiang, Sun Jiguo, Wu Guoqing, et al. Optimization Design of Multi-Terminal DC Network Topology for Large-Scale Offshore Wind Farms. Journal of Electrical Machines and Control, 2015.

[10] Zou Qiang, Ma Yunlong, Yang Jianming, et al. Research on Grounding Pole Topology of Series Multi-Terminal DC Transmission System. Electric Power Engineering Technology, 2018.

[11] Raza, A.; Dianguo, X.; Xunwen, S.; Weixing, L.; Williams, B.W. A Novel Multi-terminal VSC-HVDC Transmission Topology for Offshore Wind Farms. IEEE Trans. Ind. Appl. 2016, 53, 1316–1325.

[12] Ali Raza, Muhammad Younis, Yuchao Liu, Ali Altalbe, Kumars Rouzbehi, Ghulam Abbas. A Multi-Terminal HVdc Grid Topology Proposal for Offshore Wind Farms.

[13] Zhiwei Gao, Xiaoxu Liu. An Overview on Fault Diagnosis, Prognosis and Resilient Control for Wind Turbine Systems.

[14] Regarding the link provided, there seems to have been an issue with accessing the content. It could be related to the link itself or a network-related problem. Please check the legitimacy of the web link and try accessing it again if necessary.

[15] Di Shimin. Research on Topology and Control Strategy of Large-Scale Offshore Wind Power DC Grid-Connected System. Huazhong University of Science and Technology, 2023.

[16] Liang Fang, Xiaoyan Xu, et al. "Reliability assessment of the port power system based on integrated energy hybrid system." Bulletin of the Polish Academy of Sciences Technical Sciences, 2023.