Analysis and Optimization of the Impact of Coupling Wind, Solar and Hydrogen Storage Systems in Different Extreme Environments

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Abstract. With the development of the global world, the demand for a low-carbon lifestyle increases. The current electrical power system is developing towards new energy. Wind power and photovoltaic power are the main representatives of new energy. However, wind power and photovoltaic power generation are intermittent and unpredictable, which will lead to a lack of stability and continuity in power generation and supply. Therefore, coupling wind, solar, and hydrogen storage systems can achieve energy complementarity, thereby realizing the full utilization of energy. Hydrogen is the cleanest energy storage option and is suitable for long-term storage compared to other traditional energy storage methods. The paper begins with a brief description of the system structure for coupling wind, solar, and hydrogen storage systems. Next, the main content is divided into three sub-modules of wind power generation system, photovoltaic power generation system and hydrogen storage, which analysed sequentially to determine the impacts they receive in different extreme environments. The extreme environments mainly consist of extreme temperatures, high humidity, air pollution, and some natural disasters. Finally, the paper summarizes the reduction in system efficiency and the damage to components caused by extreme environmental influences; It is proposed that the whole wind-photovoltaic-hydrogen storage system can be simulated by adding different environmental factors in the future, which facilitates accurate prediction of how the efficiency of the system will be affected in different environments and enables the adaptability of the system for application in multiple environments.

INTRODUCTION

With the development of the world, there is a growing demand for low-carbon living. The current electrical power system is developing towards low-carbon development patterns and aims to achieve carbon neutrality [1]. The realization of the carbon neutrality goal lies in the application of new energy. Wind power and photovoltaic generation occupy an important position in the world. However, generating electricity relying on wind energy and solar energy has a lack of stability and continuity [2]. Therefore, there is now research to show that coupling wind, solar and hydrogen storage systems can achieve energy complementarity, thereby realizing the large-scale and high-quality development of renewable energy [3]. The higher calorific value and zero-carbon emissions are the two major environmental advantages of hydrogen storage technology compared to other traditional energy storage methods. Furthermore, battery storage is a short-term energy storage, while hydrogen energy storage is a long-term storage. Therefore, the use of a hydrogen storage system to participate synergistically in the operation of wind-solar coupled generation systems can improve the absorption capacity of renewable energy sources [4].

Currently, although some achievements have been made in the energy scheduling and capacity allocation of wind-solar coupled hydrogen storage systems in existing studies, the research on the dynamic response characteristics and optimal control of the system under complex environments or extreme weather conditions is relatively insufficient. This research is based on different extreme environmental scenarios and takes the wind-solar integrated hydrogen storage system as the research object to analyze and compare the operating characteristics and the difference of stability for the system in different extreme environments, and proposes control management and protection optimisation strategies for the system. Research shows that this strategy can improve the stability and utilization efficiency for a wind-solar-hydrogen coupled system, and provides a reference for the safe and stable operation of a new energy multi-energy complementary system.

SYSTEM STRUCTURE DESCRIPTION

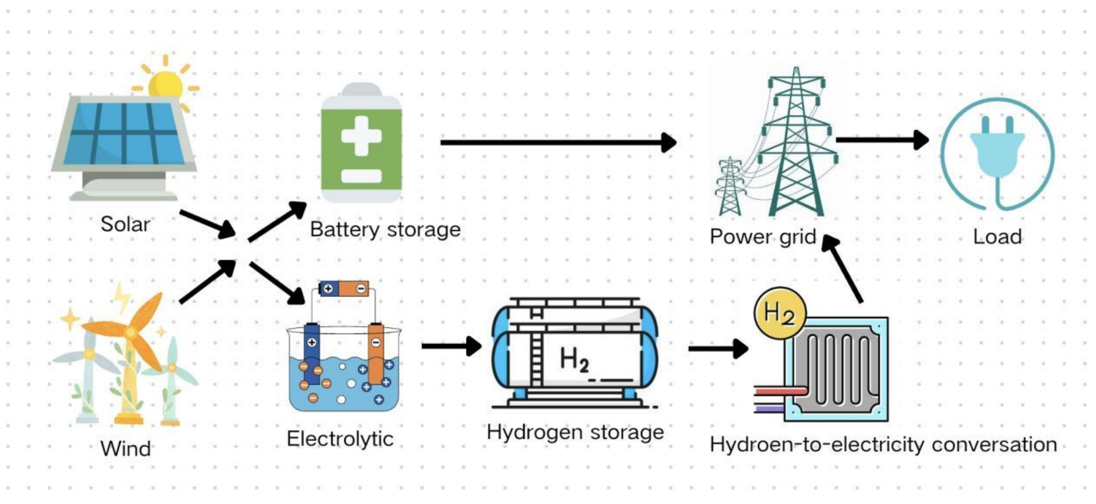

FIGURE 1. The main components and process of the wind-solar coupled power generation and hydrogen storage system

As shown in Figure 1, the wind-solar coupled power generation and hydrogen storage system mainly consists of a wind power generation system, a photovoltaic power generation system, a battery storage system, an electrolytic hydrogen production system, a hydrogen storage system, fuel cell power generation system, and a control and detection system. The figure also shows the overall process of the system operation. Firstly, electricity is generated from wind and solar energy. Next, electricity is stored by a battery storage system and a hydrogen production and storage system according to the load response. When the demand of load exceeds the power generation of wind and solar energy, the battery will make up for the power shortage. On the contrary, when solar energy and wind energy are abundant, the system will utilize them to produce hydrogen [2]. These system monitoring and energy management are performed by the control and detection system. Finally, there is a fuel power generation system to carry out hydrogen-to-electricity conversion. When wind power and photovoltaic power generation fail to meet the load, the hydrogen stored will be used to generate electricity through fuel cells.

ANALYSIS OF EXTREME ENVIRONMENTS

The impact of wind-solar coupled hydrogen storage systems in different extreme environments can be divided into two major categories, one kind comes from the energy required for their own power generation, such as storms and strong radiation, another one kind comes from the other extreme climate and weather,such as extreme temperature, high humidity, etc. In this study, the whole system is divided into three modules, namely wind power generation system, photovoltaic power generation system and hydrogen storage system, and their impacts in different extreme environments are compared and analysed separately.

Wind Power Generation System

Extreme Low Temperature

In a low-temperature environment, the fan blade of a wind power generation system will be frozen due to extremely low temperatures. The system will trigger the low-temperature protection mechanism at this time and stop operation [5]. Generally, wind turbines have a temperature limit for normal operation. The minimum operating temperatures of the wind turbines are -10 °C, -30 °C and -40 °C for ambient, cryogenic and ultra-cryogenic wind turbines, respectively

[5]. And the temperature of range where wind power generators are most susceptible to freezing is from 10°C to 0°C [6].

High Humidity and Low Temperature

Ice is formed by the solidification of water. The higher the humidity in the air, the higher the water content. In an environment of low temperature and high humidity, it seriously affects the safe start-up of wind turbines, power generation efficiency and the stability of power grid communication [7]. Bearing is an important component in a wind power generator, and is used to support rotating parts and reduce friction during operation. When the temperature is extreme, the bearing will lose the matched degree with the corresponding wind power generator because its size will expand and contract due to thermal expansion and contraction. This will not lead the wind power generator to rotate smoothly, and can even damage [7]. The lubricant is usually applied between the components used to rotate the fan blades and helps reduce the friction between the components. Lubricants will become sticky at low temperatures, the friction between the components will increase when the wind power generator is operating, which will lead to intensified wear or overheating and failure of the bearing. The system is also affected by the low-temperature and high-humidity environment during the transmission process, and the most significant impact occurs on the transmission lines [7]. The wires will shrink due to icing, which leads to an increase in loss and a decrease in transmission efficiency. Meanwhile, in low temperature and high humidity environments, there will also be torrential rain and hailstorms. If combining the self-weight of hailstorms, its falling speed and the impact of the storm, the wires will be damaged or even broken [7]. This will lead to transmission interruption and directly cut off the power source, which is a serious impact. Therefore, the operation of the wind power system is affected due to the occurrence of any of these component problems at extreme temperatures and humidity, leading to a reduction in the efficiency of the wind power system.

Typhoon

Wind is an electricity source for wind power generation, but excessive wind speed is also a kind of hazard. Xun Lu et al. conducted typhoon simulations using an offshore wind farm as the measurement point[8]. This study indicates that the coming of a typhoon led to the fluctuation of wind direction, which has a huge impact on power generation, stability, and safety for the whole wind power generation system [8]. The difference in power generation from normal is 9412.1 MWh[8]. Therefore, the increase of wind speed in the short term seems conducive to the increase of power generation due to the arrival of the typhoon, but essentially, there are many hazards. When the wind speed is excessive, the bearing housing of the wind power generator will shift, leading to structural damage and even the fracture of the crank arm connecting the blades [7]. When the fluctuation of wind direction becomes large, the yaw system can be damaged [7].

Photovoltaic Power Generation System

Extreme Temperature

In daily life, mobile phones will heat up during prolonged use or exposure to sunlight, leading to the system running slowly or even automatically reducing the frequency. At this time, cooling heat dissipation is applied to the mobile phones to restore the state. Similarly, the power generation efficiency of photovoltaic(PV) components reduces due to the increase in internal impedance in high-temperature environments. A relatively low-temperature environment is conducive to its power generation. The increase in the temperature of the PV panels is mainly due to the enhanced intensity of solar radiation. Especially when the heat dissipation conditions are poor, the temperature of the PV panels' surface will increase significantly due to the high intensity of solar radiation, leading to a decrease in the efficiency of power generation. In the research by Nikolay Mestnikov et al. on the impact of the environment on the operation of photovoltaic installations in the northern part of the Russian Far East, the influence of temperature on the power generation performance of PV panels was determined through climate chamber experiments within the temperature range of -60 °C to +60°C [9]. It is found that high temperatures (especially above +30°C) will increase the internal resistance, resulting in a significant reduction in power generation efficiency. And the efficiency improves slightly under low-temperature conditions (especially below -40°C). The output of PV panels at 60°C is nearly 19% higher than that at +60°C [9]. The research conducted by Nikolay Mestnikov et al. and Mestnikov et al. shows that for every degree increase in temperature, the efficiency of photovoltaic power generation decreases by 0.5% [9][10]. Moreover, the Antarctic photovoltaic test also proved the reliable operation capability at -80°C [10].

Air Pollution

Solar radiation is an electricity source for a photovoltaic power generation system; the power generation efficiency of the system is directly related to the intensity of light. And because of this, the efficiency of PV components is also affected by air pollution. The intensity of solar radiation reaching the PV panel surface will be weakened significantly due to extreme air pollution(such as high-concentration PM2.5). PM2.5 is the core component of haze. A large amount of PM2.5 suspended in the air not only blocks sunlight but also acts as condensation nuclei, adsorbing water vapor and intensifying the formation and persistence of haze. The research of Liu H et al., by combining the data obtained from experiments of real monitoring systems and large-scale observation data from multiple actual photovoltaic power stations, indicates that when the concentration of PM2.5 reaches 100 $\mu g/m^3$, the output power of PV is relatively reduced by approximately 15%+-5%; When the concentration of PM2.5 exceeds 300 $\mu g/m^3$ (high polluted conditions), the impact tends to be saturated, manifested as a severe decline in the performance of photovoltaic power generation systems, or even failure [11].

Dust Cover

In addition to the impact of fine particulate air pollution on the power generation rate of photovoltaic systems, larger solid particulate matter such as sand and soil also has a significant influence on their power generation rate. The PV panels can be covered with dust, which hinders light and leads to a decrease in power generation rate. In the study of Sher A A et al, three main types of dust(sand, soil, ashes) were tested respectively [12]. The results indicate that the photovoltaic power generation efficiency will decrease with increasing the amount of dust. Ash has the greatest impact because its particles are the smallest and can cover the surface of the PV panels more comprehensively. Sand has the least impact because of its large particles and low surface coverage [12].

High Humidity

The influence of humidity on photovoltaic power generation systems has a certain degree of complexity and duality. Humidity can reduce power generation through short-term condensation effects, and brings a certain cooling effect at the same time. However, long-term exposure to high humidity will accelerate the deterioration of components, affecting the overall lifespan and reliability of photovoltaic systems. The research by Sher A A et al. tested photovoltaic power generation systems under different relative humidity levels ranging from 30% to 65%. It was found that when the humidity was lower than 50%, it had little impact on the power generation efficiency; When the humidity exceeded 50%, the power generation efficiency started decreasing. The higher the humidity, the more obvious the decline [12]. The research of Gao Y et al. indicates that high humidity environments can cause condensation or fogging, reducing the light transmittance and decreasing the number of photons leads to a decline in power generation [13]. Goswami A's research found that high humidity might also bring about a cooling effect and reduce the temperature of the PV panels [14]. Through the evaporation of water can take away part of the heat, to a certain extent, the PV conversion efficiency can be improved. However, a high-humidity environment will accelerate the aging and deterioration of photovoltaic component materials in terms of long-term impact [12]. Especially for some sealed devices, drying protection is required.

Hydrogen Storage System

As for the intermittency and instability of new energy power generation, the addition of the hydrogen storage system has played an important role. The hydrogen storage system is mainly divided into hydrogen production and hydrogen storage modules. When there is surplus electricity in the power grid load, the system converts the electricity into hydrogen through the chemical reaction of electrolyzing water for storage, so as to play a supplementary role in power generation when the load cannot be met during the intermittent power generation of the wind-solar coupled power generation system [15].

Extremely High Temperature

In the extremely high-temperature environment, the cooling burden will increase for the Electrolytic cell and compressor due to the high temperature. For example, a PEM electrolyzer generates hydrogen at a relatively low calorific value under a pressure of approximately 30 bar [16]. The power dissipation of the compressor increases rapidly with increasing environmental temperature, while the gas storage tank itself maintains a constant temperature. The heat generated during the compression process is difficult to release effectively, resulting in a decrease in compression efficiency [17]. Long-term high temperatures can lead to the aging and damage of components, thereby reducing the efficiency of the system. Air pressure can rise with increasing temperature. Increasing the air pressure will lead internal pressure of the hydrogen storage tank to increase, which poses a risk of tank explosion. At high temperatures, the evaporation of the electrolyte accelerates and the demand for water also increases. For some areas with high temperatures and drought, water resources are scarce, and electrolyzed water is difficult to operate continuously.

Extreme Low Temperature

In the extremely low-temperature environment, the electrolysis fails to start normally due to freezing of the electrolyte. Metals in high-pressure vessels are prone to brittle cracking at extremely low temperatures. The research by Wang P et al. shows that under low temperature storage stress (LTS), the metal materials (such as solder layers, bonding wires, and metallized layers) in the packaging of power devices will exhibit obvious interface failures, voids, and cracks. Similarly, metal materials in hydrogen storage systems may also exhibit higher brittleness and crack sensitivity in extremely low-temperature environments. Moreover, from a chemical perspective, electrolysis requires the absorption of heat. Low temperatures can reduce the migration of ions and the reaction rate, leading to a decrease in hydrogen production efficiency[18].

High Humidity and High Salinity

In a high-humidity coastal environment, air with high water content is prone to corrode the metal components of the electrolytic cell, resulting in a reduction in the service life of the equipment. In high-humidity environments, the transition metal oxides with layered structures are prone to ion exchange reactions, resulting in changes in the material structure and a decline in electrochemical performance [19]. For instance, if the electrode materials in a PEM electrolytic cell adopt similar layered transition metal oxides, long-term exposure to a high-humidity environment may weaken the electrode activity, thereby affecting the overall performance and reliability of the system. CHEN Mingzhe et al. 's research indicates that in seawater battery systems, there is a high interfacial impedance between the cathode electrode and the solid electrolyte, which severely limits the ion migration efficiency, and the metal electrode shows obvious signs of corrosion in high-salt electrolytes [19]. Similarly, the high humidity and salinity of the sea may also cause material corrosion or chemical stress on tanks, connecting pipework, and seals in the hydrogen storage system, increasing system ageing and performance degradation. The insulation performance(sealing property) of the equipment will decrease the potential risk of hydrogen leakage due to high humidity.

CONCLUSION

Through the retrieval and analysis of the impact of different extreme environments on the entire wind-solar coupled with a hydrogen storage system, the wind power generation module, photovoltaic power generation module, and hydrogen storage module will all be affected by different extreme environments, resulting in a decrease in system efficiency. Thus, the overall system efficiency will decrease.

Specifically, wind power generation systems are at risk of freezing and damage, leading to shutdown in extremely low-temperature and high-humidity environments. Additionally, the impact of typhoons causes wind direction fluctuations and excessive wind pressure, which poses a risk of yaw and damage to the system.

Photovoltaic (PV) power generation systems at extremely high temperatures will reduce their power generation efficiency due to the rise in their internal resistance, air pollution, sand and dust cover that weakens the intensity of solar radiation reaching the PV panels. The influence of humidity on the system is complex. It can bring some cooling benefits at low temperatures, but there is also a risk of freezing. The sealing of system components can also be damaged in a high-humidity environment, leading to their aging.

The electrolyte of the hydrogen storage system will consume a large amount due to evaporation in extremely high temperatures, making it difficult for arid regions to operate continually. The electrolytic cell and compressor will increase the cooling burden due to high temperatures. The increase in air pressure at high temperatures may cause the internal pressure of the hydrogen storage tank to rise, posing a risk of tank explosion. At extremely low temperatures, the electrolyte has the possibility of freezing, and the metal becomes more brittle, posing a risk of fracture. In the long term, the system components will be corroded and aged in the high-humidity coastal environment. The electrolytic activity also weakens accordingly, thereby affecting the overall performance.

These environmental factors are coupled with each other in different modules; the overall power generation efficiency and stable operation capacity of the system will be affected further.

Aiming at the problems of performance attenuation and insufficient adaptability existing in the operation of the wind-solar coupled with hydrogen storage system under extreme environments, the system in the future can be optimized based on the system construction and regulatory deployment. Firstly, the different environmental parameters can be added to form a simulation of system dynamic modeling, which can simulate and analyze the performance of the system, power generation rate, etc. are affected under different extreme climates, and can further predict the response capability of the system. Secondly, the system hardware devices can be enhanced and optimized, such as wind-resistant devices, devices with high sealing performance, high-temperature resistant components, cooling systems, etc. Thirdly, the control modules of the system can be optimized. Intelligent regulation and control can be introduced into the system, which can help the system adapt to different environments and maximize the response.

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