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Study on power-dividing thermal compensation strategy of wind-electricity-hydrogen storage system#

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ABSTRACT

Wind-powered hydrogen production is a promising method to enhance dispatch flexibility for renewable energy. However, frequent fluctuations of the wind power cause switching of electrolyzer states, resulting in instabilities in the hydrogen production process. Furthermore, the prolonged cold start leads to low operation temperature which thus leads to low energy utilization rate in the wind-powered hydrogen production system. For these concerns, this study proposes a solution for stabilizing the voltage output with variable system temperatures within different power ranges, so as to effectively minimize the frequency of start-stop cycles and enhance the efficiency of hydrogen production. Combined with computational fluid dynamics (CFD), a research model for the polarization characteristic curve of an alkaline electrolyzer (AE) under variable working temperature conditions, as well as a model of wind-powered hydrogen production system considering heat transfer are established. In addition, through non-dominated sorting genetic algorithm, the voltage output schemes, setting efficient and stable hydrogen production in different power intervals as the objective function, are optimized. The proposed strategy is applied to a wind power generation process with a design condition of 1 MW capacity under specific climatic conditions in Northeast China. The system energy efficiency analyses show that, compared with the traditional wind-powered hydrogen production system, the temperature compensation strategy is able to effectively improve the system energy utilization rate by 0.61%. Meanwhile, full-condition operation analyses demonstrate that the system start-stop frequency could be significantly reduced. This study provides a valuable reference program for efficient hydrogen production under variable temperature conditions.

Keywords: wind-powered hydrogen production, variable temperature, polarization curve, water electrolysis, power-dividing thermal compensation strategy

NONMENCLATURE

Abbreviations	
AE	alkaline electrolyzer
WT	wind turbine
BAT	battery
T	temperature
REF	reference
Symbols	
N	Number
P	Power, W
v	Wind speed, m/s
U	Voltage, V
I	Current, A
Q	Quantity of heat, W
η	Efficiency

1. INTRODUCTION

Based on the rapid growth of energy demand, and the International Energy Agency's net zero emission requirements for 2050, renewable energy power generation will play a central role in the energy system over the next decade [1]. Among them, wind power has attracted international attentions owing to its wide distribution and rich resources. However, wind power has strong intense and uncertainties, which challenges the effective and stable utilization of the wind energy. Through electrolytic hydrogen technology, fluctuating wind energy can be converted into high-quality hydrogen energy, achieving large-scale storage and utilization, showing great potentials in deep decarburization and enhancing wind power dispatching flexibility [2].

AE and proton exchange membrane electrolyzer (PEM) are two mature and commercialized technologies for hydrogen production. Among them, the AE has more prominent economic benefits and advantages regarding safety and stability. However, the intermittent nature of wind-generated electricity challenges the stable operation and efficient hydrogen production of AE. Currently, multi-type optimization strategy is the focus of research by both

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academia and industries. For instance, Loiy et al. [3-5] combined the electrolytic cell with additional energy storage methods to form a multi-energy complementary control strategy, converting unstable wind energy into hydrogen. In addition, this strategy is able to use various energy storage methods such as lava heat storage and power storage to make up for the energy supply window period and improve scheduling flexibility. In maximizing the economic potential of wind-powered hydrogen production systems, scholars like Francesco et al. [6-8] have integrated accurate models of commercial electrolytic cells with real wind farms. By doing so, the cost of hydrogen production and load is minimized, so as to effectively balance the economic considerations with scheduling flexibility. Furthermore, Li et al. [9-11] introduced a multi-state conversion electrolytic cell control strategy. This strategy coordinates the electrolytic cell and the battery to match the fluctuating power levels, leading to flexible scheduling and efficient energy utilization within the system.

Despite the above achievements, they primarily focus on optimizing the hydrogen production performance and economic benefits of the system from the aspects of power output and capacity configuration, whereas giving less considerations to the influence of temperature regulation on the performance of the AE. Lower temperatures can increase resistance in the polarization process of the electrolytic cell, impeding the continuous electrolytic water hydrogen production process and reducing the cell's hydrogen production performance. Conversely, excessively high temperatures can shorten the cell's service life. That is, only with optimal reaction temperature could the AE yield the best performance. Therefore, this paper proposes a thermal compensation strategy within the power division interval to enhance hydrogen production performance by improving the operating environment.

2. SYSTEM LAYOUT DESCRIPTIONS

In order to enhance the operational flexibility of AE and improve the operating environment, a thermal compensation is added. In this section, the composition and mathematical modeling of the wind-powered hydrogen production system coupled with thermal compensation will be introduced in detail.

2.1 Wind-powered hydrogen production system based on thermal compensation

The designed wind-powered hydrogen production system is depicted in Fig. 1. The system mainly comprises modules of wind power generation, power distribution, power storage, thermal compensation and electrolytic water hydrogen production. Considering the impact of wind fluctuations on the grid load, the entire system adopts an off-grid operation mode. The ideal goal is to dispatch all wind power to produce hydrogen by electrolysis of water.

In practical engineering applications, maintaining the efficient electrolysis temperature in varying operating environments incurs significant energy costs. Additionally, it is difficult for the electrolyzer to meet the demand for hydrogen production under fluctuating conditions, resulting in energy waste during heat preservation and even extremely high-temperature conditions that damage its service life. In order to improve the working environment of the AE under fluctuating power conditions, this study develops a thermal compensation strategy with variable power intervals, which differs from the existing thermal insulation strategies. This proposed scheme considers the influence of wind fluctuations on the response characteristics of the hydrogen production system. By adjusting the energy distribution relationship between the hydrogen production system, thermal compensation, and electricity storage, the operating environment can be effectively improved, and the hydrogen production performance can thus be improved.

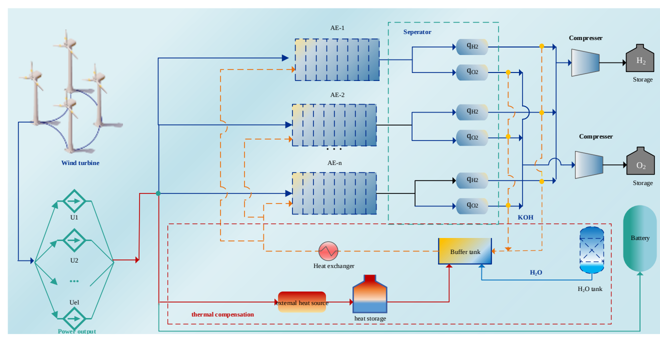

Fig. 1 Flow chart of wind-powered hydrogen production system with coupled thermal compensation

2.2 System modeling and analysis

The hydrogen production from electrolysis water driven by wind includes multiple energy conversion links, among which the leaf element momentum theory is the primary method to calculate wind speed conversion into power. The dynamic output model is shown in Eq. (1):

$$P_{WT} = \frac{1}{2}\rho S v^3 C_p \tag{1}$$

where, ρ is the air density, S is the swept area by the rotor, and C_p is the wind turbine's performance coefficient.

In the actual operation process, to protect the motor and avoid the phenomenon of overload at low speed and damage at high speed, the frequency converter is set to cut in and cut out the wind speed to limit the operation of the motor. The output model is shown in Eq. (2):

$$P_{WT}=\begin{cases}0 & 0\le v\le v_{in}\\ N_{WT}(\frac{P_{WTr}v^3}{v_r^3-v_{in}^3}-\frac{P_{WTr}v_{in}^3}{v_r^3-v_{in}^3}) & v_{in}\le v\le v_r\\ N_{WT}P_{WTr} & v_r\le v\le v_{out}\\ 0 & v>v_{out}\end{cases} \tag{2}$$

where v_{in} and v_{out} are the cut-in and cut-out wind speeds, respectively, v_r is the rated wind turbine speed, N_{WT} is the number of installed wind turbines, and P_{WTr} is rated wind turbine power.

Let m_{H2} be the hydrogen production rate, and the electrolysis efficiency η_{el} be the energy conversion efficiency of the electrolytic cell, which are shown in Eq. (3) and Eq. (4):

$$m_{H2}=\eta_F\frac{N_{AE}I_{AE}M_{AE}}{2F} \tag{3}$$

$$\eta_{AE}=\frac{m_{H_2}\Delta G}{P_{AE}M_{H_2}} \tag{4}$$

where N_{AE} is the number of the AEs, η_F is the Faraday efficiency defined as the ratio of the actual amount of hydrogen production, F is the Faraday constant, and ΔG is the Gibbs free energy of the electrochemical reaction.

When the response voltage of the electrolytic cell is higher than the thermal neutral voltage (U_{th}), the heat balance will be broken, and the electrolysis will become an exothermic process. The heat production Q_{gen} model is shown in Eq. (5) [12]:

$$Q_{gen}=(U_{el}\text{-}U_{th})N_{AE}I_{el} \tag{5}$$

where U_{el} and I_{el} represents the AE's voltage and current, respectively.

The heat exchange quantity Q_{loss} between the electrolytic cell and the environment is expressed by Eq. (6):

$$Q_{loss}=(T-T_{abs})/R_t \tag{6}$$

where T and T_{abs} are the AE's operating temperature and ambient temperature, respectively, and R_t is the total thermal resistance.

In addition to environmental cooling, the cooling process also includes two parts: cold water replenishment and heat exchange. The mathematical model is given by:

$$\begin{aligned}\rho_{KOH}V\frac{dT_{out}}{dt}&=q_{in}C_{KOH}(T_{in}-T_{out})\\&+q_{H_2O}(C_{H_2O}T_{H_2O}-C_{KOH}T_{KOH})\\&+(q_{in}C_{KOH}+q_{H_2O}C_{H_2O}-q_{out}C_{KOH})T_{ref}\end{aligned} \tag{7}$$

The electrolytic tank heat transfer link is mainly realized by countercurrent heat transfer, through rapid flow of low-temperature water to take away the heat energy in the electrolyte, to achieve effective cooling, to reduce the emergence of the phenomenon of overheating, the heat transfer process is Eq. (8):

$$\begin{cases}\rho_{KOH}V_hC_{KOH}\frac{dT_{KOH,out}}{dt}=q_{KOH}C_{KOH}(T_{KOH,in}-T_{KOH,out})-UAT_{LMTD}\\ \rho_{H_2O}V_cC_{H_2O}\frac{dT_{KOH,out}}{dt}=q_{H_2O}C_{H_2O}(T_{H_2O,in}-T_{H_2O,out})+UAT_{LMTD}\\ T_{LMTD}=\frac{(T_{KOH,out}-T_{H_2O,out})-(T_{KOH,in}-T_{H_2O,in})}{\ln(\frac{T_{KOH,out}-T_{H_2O,out}}{T_{KOH,in}-T_{H_2O,in}})}\end{cases} \tag{8}$$

where ρ_{KOH} and ρ_{H2O}, are the density of potassium hydroxide solution and cooling water, V_h *and* V_c are the volume of hot and cold parts in heat exchanger. q_{KOH} and q_{H2O}, represent flow rates of solution and cooling water. T_{LTMD} is the temperature difference for countercurrent flow. In addition, C_{KOH} and C_{H2O} represents heat capacity of Potassium hydroxide solution and cooling water.

2.3 Constant voltage thermal compensation strategy in the variable power range

According to the influence of the temperature of the electrolytic cell on the polarization characteristics and the control constraints, the thermal compensation strategy of the variable power interval of the electrolytic cell is further developed, which is shown in Fig. 2 and elaborated as follows.

Firstly, the frame of the external heat source in series with the AE is established, as shown in Eq. (9):

$$Q_h=\sum_{t=1}^{t=t_i}(U-U_{el})I_{el} \tag{9}$$

Then determine the operating conditions of the electrolytic cell array and calculate the wind power generation $P_{wind}(t)$ within the thermal compensation time interval which is given by Eq. (10):

$$P_{in}(t)=P_{wind}(t)+P_{bat}(t) \tag{10}$$

In addition, the thermal compensation voltage is designed in different power intervals. According to these power intervals, the multi-objective genetic algorithm (NSGA-II) is used to optimize the global performance of the thermal compensation voltage, as shown in Eq. (11):

$$\begin{cases}\min(\frac{1}{N_{H_2}})=[\sum_{t=1}^{t_{step}}\sum_{i=1}^{N_{max}}m_{H_2}(t,i)]^{-1}\\ \min(1-\eta_{AE})=1-\sum_{i=1}^{i=N_{max}}\frac{\int_{t=1}^{t=t_{step}}m_{H_2}(t,i)C_{H_2}dt}{\int_{t=1}^{t=t_{step}}P_{AE}(t,i)dt}/N_{max}\end{cases} \tag{11}$$

where $m_{H2}(t,\ i)$ is the hydrogen production rate at time t, considering the temperature factor, and $P_{AE}(t,\ i)$ is the AE's load power at time t. N_{H2} and η_{AE} represents the annual hydrogen production amount and hydrogen production efficiency.

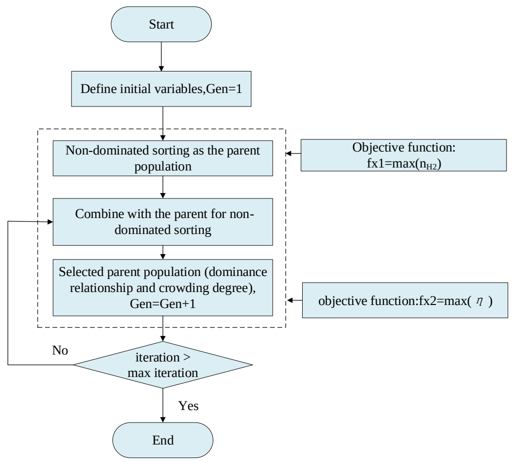

Fig. 2 Flowchart of the power-dividing thermal compensation strategy optimization process

The objective of voltage optimization is to maximize the hydrogen production and energy utilization rate.

3. RESULTS AND DISCUSSIONS

3.1 Validation of AE response model to fluctuating power under variable temperature conditions

In order to avoid overheating, the operating temperature of the AE is generally between 313.15 K and 353.15 K. By solving the multiphasic field coupling, the polarization characteristics of the AE with a capacity of 10 kW in the operating temperature range are obtained.

The model is verified with experimental data, and good agreement is obtained, as shown in Fig. 3. The low relative error in a wide current range is strong evidence for the simulation results. The model's reliability is demonstrated by polarization characteristic curve [13]. When the current density is high, the simulation trend is closer.

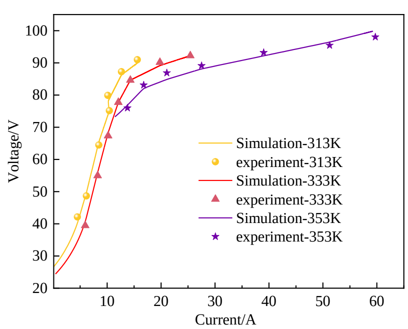

Fig. 3 Validation of model polarization properties at operating temperature

As indicated in Eq. (3), the hydrogen production rate of the AE is positively correlated with the current. However, the thermal effect induced by parasitic currents in practical conditions leads to energy wastage in the form of thermal energy. To further improve the energy utilization rate and reduce the influence of parasitic current, the influence of current on the electrolytic efficiency of the system under different temperature conditions is simulated, and the results are depicted in Fig. 4.

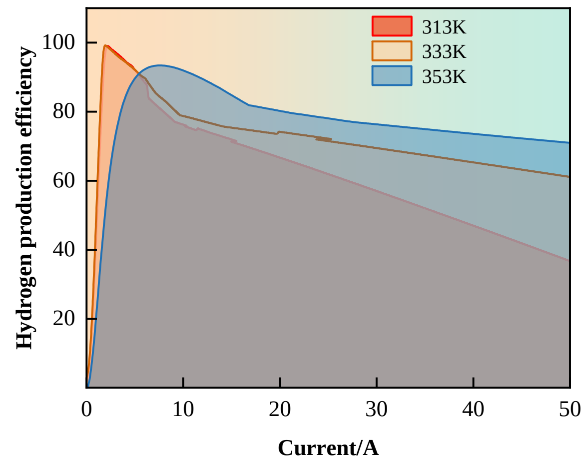

Fig. 4 Effect of operating temperature on hydrogen production performance

3.2 Sensitivity analysis of AE working temperature influencing factors

The cold water flow rate depends on the hydrogen production consumption, and the flow rate is between 0 m/s and 0.5 m/s. These two links will have a synergistic effect on the system temperature. In addition, the thermal effect in water electrolysis process is also a key influencing factor. Therefore, this paper studies the influence of various control parameters on the stack's temperature, and conducts a double-sensitivity analysis on the synergistic effect of critical parameters.

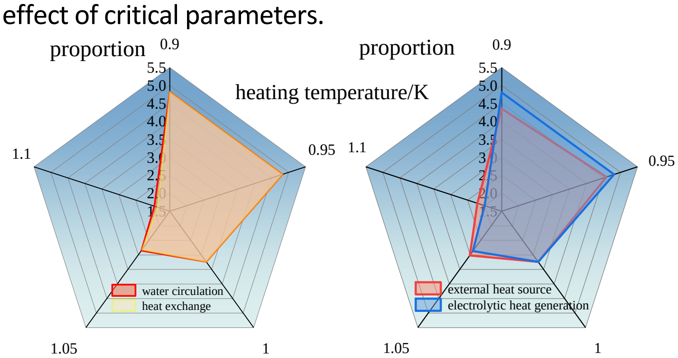

Fig. 5 Sensitivity analysis of factors affecting working temperature

The electrolyte input temperature is determined as monotonically increasing value points. This research carries out one-factor sensitivity analysis on 20 sample size groups under the corresponding conditions. Then the results show that, thermal compensation, and electrolytic heat generation on the system temperature plays a more important role. However, since the enhance of electrolytic heat generation reduces hydrogen production efficiency, and it is difficult to control, thus electrolytic heat generation is not considered a key impact factor in the sensitivity analysis. Therefore, external heat source and heat exchange are conducted to examine the effects of simultaneous changes in these two factors on the system operating environment.

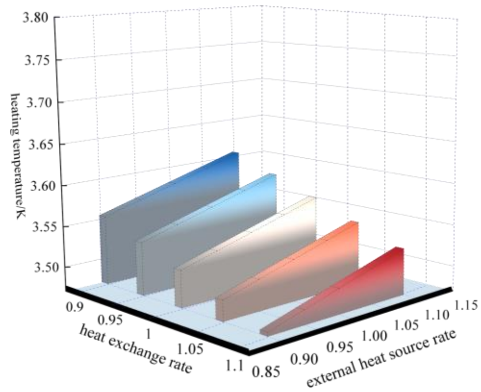

Fig. 6 Sensitivity analysis of heat exchange, compensation

The analysis diagram is shown in Fig. 6. It can be seen that, compared with external heat source, heat exchange has less effect on temperature rise. It is of great significance to carry out reasonable design of external heat source input scheme. Based on these, the paper proposed an optimization algorithm to realize the efficient control of external heat source.

3.3 Analysis of optimization results of the thermal compensation strategy

Based on the principle of thermal compensation and local weather data, the optimization of the thermal compensation strategy for the optimal sub-power interval for this case study is determined with the objectives of maximizing the hydrogen production rate and the average energy utilization of the system. The optimization results are shown in Table 1.

Table 1 Power-dividing thermal compensation voltage

Application range /W	thermal compensation voltage /V
0-2000	98.70
2000-3000	124.55
3000-4000	84.95
4000-5000	129.02
5000-6000	97.41
6000-7000	118.31
7000-8000	124.40
8000-9000	103.48
9000-10000	130.42

Four days per quarter, for 16 days, are selected as typical case days. The system operating temperature on typical days is shown in Fig. 7, and the ambient temperature is generally recognized as 293.15 K. Based on the performance of system, the average temperature of the electrolyzer running at full power in the system without thermal compensation strategy is 340.85 K. When the operation states are fluctuation, the average temperature of the electrolyzer running at 325.86 K, which performs relatively poor temperature returns. Compared with the system using thermal compensation strategy, the average temperature of the electrolyzer is 344.16 K under full power operation and 329.12 K under dynamic operation, meanwhile the average temperature of the electrolyzer under dynamic operation has been increased by 3.31 K. Therefore, the optimized power-sharing thermal compensation strategy can adjust the energy scheduling relationship between the electrolyzer and the thermal compensation and improve the operation environment.

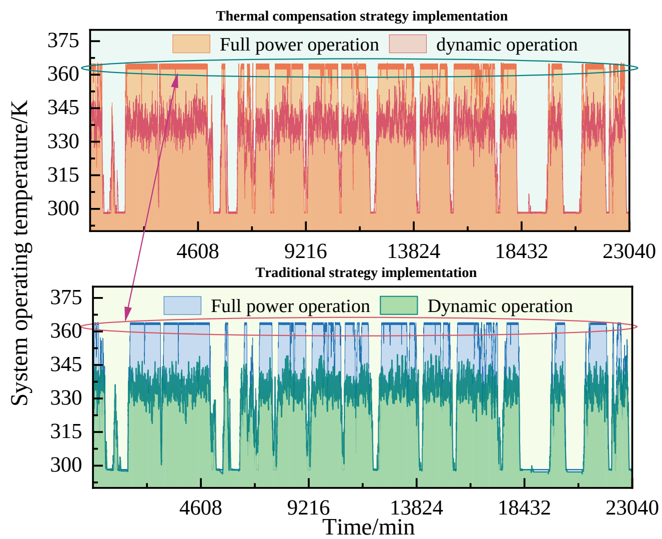

Fig. 7 Impact of the thermal compensation strategy on the system operating environment

In addition, the hydrogen production performance of applying the conventional hydrogen production strategy and the thermal compensation with split power interval in the case study is compared to illustrate the advantages of the strategy proposed in this paper. In 16 typical days of the whole year, the hydrogen production with the optimized strategy and the conventional strategy are 463.77 kg and 459.77 kg, respectively, and an improvement of 0.87% in the hydrogen production rate is achieved through the optimization of the operating environment. Meanwhile, in terms of the capacity utilization, the average energy rate with the optimized thermal compensation strategy is 58.31%, which achieves an improvement of 0.61% compared to the average energy utilization rate (57.7%) of the conventional strategy. Therefore, the system's performance in hydrogen production and energy utilization can be effectively improved by adopting the power-dividing heat compensation strategy, and the efficient utilization of wind energy can be realized.

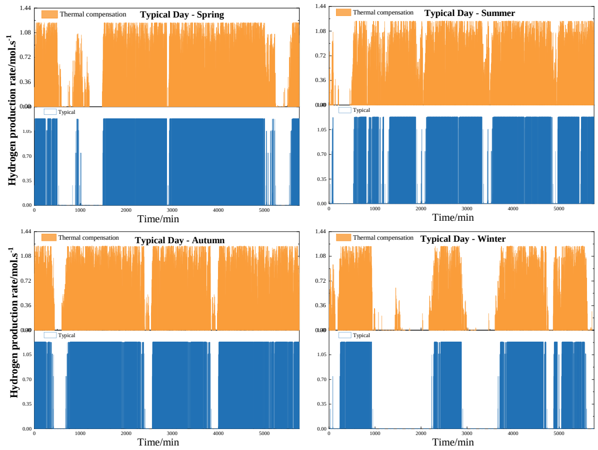

Fig. 8 The hydrogen production performance by using power-dividing thermal compensation strategy, and traditional strategy

4. CONCLUSIONS

In order to improve the operating environment of the AE in the wind-powered hydrogen production system and improve the performance of hydrogen production, a power division thermal compensation strategy is proposed, which is applied to specific working conditions. The main working is summarized as follows:

(1) This paper has built a 10 kW AE polarization characteristic curve model, which is based on the CFD method. Combined with the experimental results, the model can simulate the response of the AE at full working temperature more realistically with an error of around5%.

(2) Through sensitivity analysis, it is determined that the most critical factor in the temperature control scheme is the external heat source parameter. It provides theoretical support for the design of thermal compensation scheme.

(3) By adopting the strategy of power-dividing thermal compensation, the hydrogen production capacity is increased by 0.87%, and the energy utilization rate is increased by 0.61%.

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