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Optimal Sizing Strategy for the Stand-Alone Hydrogen Production System Composed of Wind-PV-Energy Storage System

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ABSTRACT

Hydrogen production using a stand-alone microgrid composed of wind, photovoltaic, and energy storage systems is gaining growing attention due to its environmentally pollution-free feature. However, because of the intermittent and random characteristics of renewable energy, the sizing of the system highly influences its safe, stable, and economical operation. So far, this problem hasn't been addressed in both industry and academia. In this regard, an optimal sizing method for the electrolyzer and energy storage unit of a stand-alone microgrid with fixed wind and PV power generations is proposed. Under the constraints of the state of charge of the energy storage unit, the safe operation of the electrolyzer, and the optimal power allocation of the whole system, the best system profit and highly stable operation are achieved through optimization modeling and problem-solving. An example wind-PV-energy storage stand-alone hydrogen production system composed of 2MW wind power and 1MW PV power is developed. The electrolyzer, energy storage unit and hydrogen tank are sized following the proposed method.

Keywords: hydrogen product, capacity optimal sizing, mitigation technologies, intelligent energy, energy systems, climate change

1. INTRODUCTION

Hydrogen (H_2) is a promissing enviroment-friendly energy source and a widely used raw material. It's widely used in chemical industry, transportation and aerospace as a basic feedstock. Nowadays, with rapid development of economy and tecnology, green and low-carbon development has become the consensus of all countries. As a clean energy source, H_2 has gained more and more attention due to its superior characteristics of large energy capacity, long lifetime, easy to store and transport, high energy conversion rate[1]. Compared with traditional energy, H_2 shows a high energy density, 2.7 times of gasoline, 4.5 times of coal, and the energy density of lithium batteries is only 1/120 of fuel cells.

Fossil hydrogen production, industrial by-product hydrogen production and electrolysis hygrogen production are main hydrogen production methods currently[2]. Hygrogen production by fossil accounts for the majority of total hydrogen production amount, but with rising environmental costs and dwindling fossil fuels, it's considered that this approach is unsustainable. Industrial by-product hydrogen production only counts for a small part of ultimate production, and it's hard to improve its prodution in a large scale. Hygrogen production by electrolysis accounts for a small part too currently, but this approach is getting more and more attention.

Demands for H_2 are rising rapidly recent years due to the rapid growth of hydrogen equipments and users such as hydrogen powered vehicles, demostic hydrgen generators, more electric aircrafts (MEA). From 1970s, researchers have proposed the idea that combine the renewable energy (RE) generation tecnologies and the electrolysis together to produce H_2 in large scale[3]. In recent years, with the rapid development and large-scale application of RE generation technologies like wind power generation and photovoltaic power, this idea is coming a reality in many countries like Japan, Iran, and it has gained more and more attention worldwide.

When combining RE sources with electrolyzers, there has some problems about system design, energy management, stability analysis, etc, should be solved. Many efforts have been made on RE-H_2 system. In [4], a constrained multi-obejective optimization (CMO) approach based on the Electrolyzer Capacity Factor, Total H_2 Deficit, Energy Dump Possibility and Levelized Cost of H2 is proposed for the system design process.

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Xiong Wu, et al. proposed a cooperative operation model for the Wind Turbines and hydrogen fuelig stations considering indicidual benefit[5]. In [6], a comprehensive analysis study is conducted to investigate the impact of different electrolyzer sizes and system effificiencies on the cost of hydrogen. In [7], an optimal scheduling energy management system model is presented for industrial hydrogen facilities who have a hydrogen production system integrated with Photovoltaic arrars and Battery energy storagy system. The model minimizes the cost of hydrogen production through minimizing system net costs.

Despite numerous efforts to develop RE-H_2 system, there are shorten in the literature in considering the variation of electrolyzer efficiency and the negative impact caused by frequent shutdown and restart of electrolyzer under the condition of unstable RE sources. When designing a RE-H_2 system, how to optimize system capacity configuration to maximize the economic benefits is a problem demanding prompt solution.

The remaining of this paper is organized as follows: Section 2 describes the details of the proposed system and establishes mathmatical models of each unit in the system. Section 3 designs the optimal system operation strategy and establishes the optimization model of system capacity configuration. Section 4 presents the capacity configuration result and analysis the impact of system parameters and discusses the simulation results based on the capacity configuration result. Finally, section 6 gives the conclusion of the whole study.

2. GRID-OFF RE-H2 SYSTEM

2.1 System configuration

A combinatorial power system of a wind turbine(WT), a photovoltaic array(PV), a battery energy storage system(BESS) and alkaline electrolyzer(AEL) is detailedly described in this section. The simplified diagram of the system is shown in figure 1.

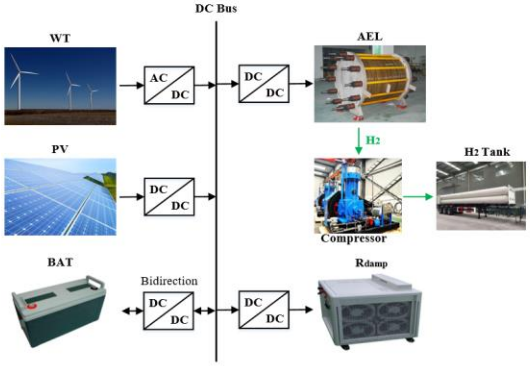

Fig. 1. System structure diagram

2.2 System modeling

The mathmatical model of main components of system are established in the following contents.

2.2.1 WT model

The output power of WT is closely related to wind speed and characteristics of the exact WT, which can be calculated as:

$$P_{WT}=\begin{cases}0 & ,v<v_{ci},v\geq v_o\\ P_{wtr}\cdot\dfrac{v^3}{v_r^3} & ,v_{ci}\leq v<v_r\\ P_{wtr} & ,v_r\leq v<v_o\end{cases}\tag{1}$$

where P_{wtr} is WT's rated output power at its rated wind speed, v_{ci}, v_r, v_{co} are WT's cut-in, rated and cut-out speed, v refers to wind speed at the height of WT's hub.

2.2.2 PV model

The output power of PV arrays is calculated as:

$$P_{PV}=P_{pvr}\frac{G}{G_{STC}}\left[1+k\left(T_{ct}-T_{STC}\right)\right]\tag{2}$$

where P_{pvr} is PV's rated output power, G is the solar radiation in the vertical direction of PV array's surface, G_{STC} and T_{STC} mean solar radiation and ambient temperature respectively under Standard Test Condition, k is PV's maximum power temperature coefficient, T_{ct} is the inner temperature of PV array.

2.2.3 BESS model

We build BESS's state of charge (SOC) model according to its charging and discharging process:

$$\begin{aligned}&SOC(t+\Delta t)=SOC(t)-P_{PAT}\cdot\Delta t\cdot\eta_c/C && ,P_{BAT}\leq 0\\ &SOC(t+\Delta t)=SOC(t)-\frac{P_{PAT}\cdot\Delta t}{\eta_d\cdot C} && ,P_{BAT}>0\end{aligned}\tag{3}$$

SOC(t) means BESS's real-time SOC value at time t, P_{BAT} means power absorbed or released by BESS on the DC bus side, η_c, η_d are charging and discharging efficiency of BESS during charging and discharging process respectively.

2.2.4 AEL model

This study adopts the electrical effificiency curve in [8] as AEL's dynamic electrical effificiency, the profile of the curve is shown in figure 2.

2.2. Hydrogen tank model

The amount of hydrogen stored in the tank at time t+Δt is calculated by the following equation:

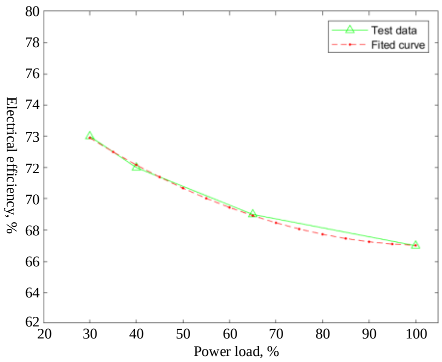

Fig. 2. Electrical effificiency under different power load

$$m_{tank}(t+\Delta t)=m_{tank}(t)+\eta_{AEL}\cdot P_{in}\cdot\Delta t/HHV \tag{4}$$

3. OPTIMAL SIZING STRATEGY

3.1 *Section of material and methods*

In order to maximize the overall economic benefit of the RE-H2 system， a new objective function that motivates the hydrogen produce is proposed in this work．The net economic benefit of the RE-H2 system is considered to define the objective function of the optimization problem that is to be maximized．

$$\max PRO = R_{H_2}(P_{AEL},C,N_{TANK})-C_{AEL}-C_{BAT}-C_{TANK}-C_{WT}-C_{PV}-C_{YS} \tag{5}$$

In objective function (5)，RH2(PAEL,C,Ntank) is the hydrogen production benefit of the system which is determined by AEL’s rated power PAEL，BESS’s capacity C and number of hydrogen storage tank Ntank．CAEL，CBAT，CTANK，CWT，CPV and CYS are total costs of AEL，BESS，hydrogen storage tank，WT，PV array and compressor respectively．The costs including investing costs, operating costs and replacing costs．

The objective function is subjected to the operational and capacity constraints blow．

(1) Combinatorial power system constraint

$$P_{AEL\_t}+P_{R_{ramp}\_t}=P_{WT\_t}+P_{PV\_t}+P_{BESS\_t} \tag{6}$$

(2) SOC constraint of BESS

$$SoC_{\min}\le SoC_t\le SoC_{\max} \tag{7}$$

(3) Power constraint of AEL

$$P_{AEL\min}\le P_{AEL\_t}\le P_{AEL\max} \tag{8}$$

(4) Capacity constraint of hydrogen tank

$$Q_{\min}\le Q_t\le Q_{\max} \tag{9}$$

3.2 *System Operation Strategy*

Rialiability of power supply is one of the most important way to maintain the RE-H_2 system runing reliably, it’s also significant to improve the energy coversion efficiency and revenue of the whole system. However, power supply from WT and PV is fluctuat and stochastic, which will lead to frequent start and stop of AEL. To avoid this, it’s necessary to adopt BESS as auxilliary power sourece to provide deficient power when power supply from RE sources can’t meet the power demand of AEL. The ESB accumulates surplus energy when the AEL is in shutdown state or the power supply from WT and PV excess the rated input power of AEL. To achive operational and economical benefits, an optimal energy management strategy is designed here to ensure smooth operation of the system. The optimal energy management strategy is defined as follows:

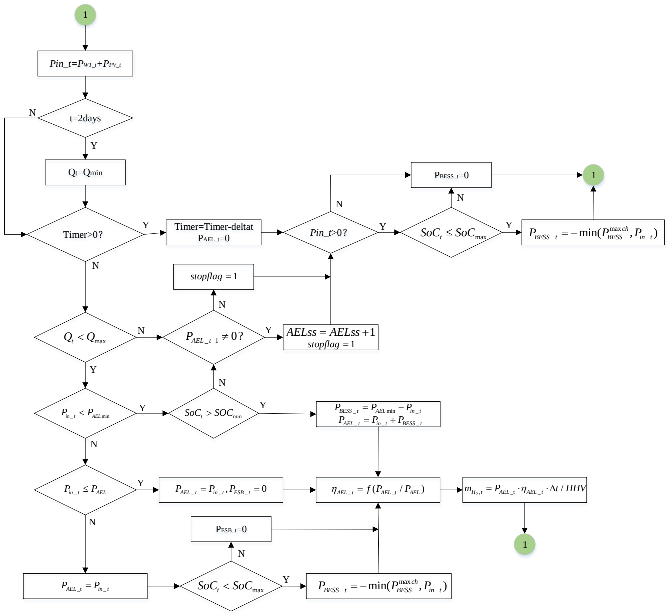

Fig. 3 Flow chart of system operation strategy

4. RESULTS AND DISCUSSION

This section presents the capacity configuration result of a case study where the system operates under afrementioned operation strategy and analyzes the influence of BESS on system capacity configuration results.

4.1 *Parameter setting and optimal sizing result*

We adopt wind speed, solar radiation and environmental temperature data recorded in a wind power plant in ChongQing province in entire 2020. The meteorological data are recorded every 5 minutes. Figure 4 presents the profile of the meteorological data.

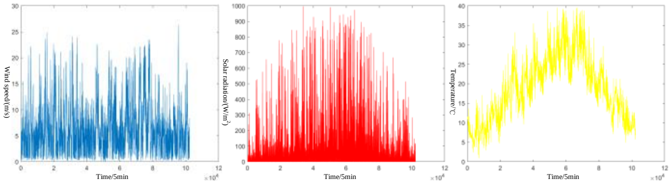

Fig. 4 Profile of meteorological data

The above data are preprocessed using funtion (1) - (3) to caculate the theoretical output power of WT and PV respectively, and the caculated results are displayed in figure 5. The annual power generations of the WT and PV are 5855448kWh and 866392kWh respectively.

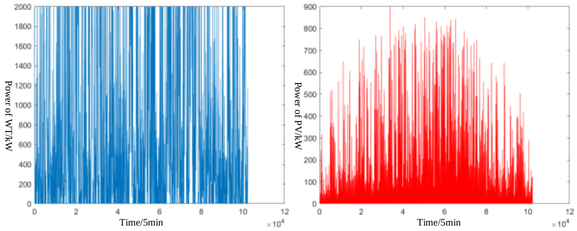

Fig. 5 Output power profile of WT and PV

Simulation program based on Particle Swarm Optimization(PSO) algorithm is devoloped and run in Matlab to solve the system capacity optimization problem proposed in section 3.1.

Table 1 System parameters and values

Parameter Name	Symbol	Value
Price of Hydrogen(￥)	Sh2	22
Investment cost of AEL(￥/kW)	C_{AELinv}	2400
Operation and Maintance cost of AEL(￥/kW/year)	C_{AELom}	96
Depreciation rate of AEL	r_{AEL}	10%
Lifetime of AEL(year)	AELlifetime	15
Investment cost of BAT(￥/kWh)	C_{BATinv}	2000
Operation and Maintance cost of BAT(￥kWh/year)	C_{BATom}	30
Minimun battery SoC	SOC_{min}	10%
Maximun battery SoC	SOC_{max}	100%
Cost of hydrogen tank(￥/per tank)	C_{tank}	100000
Minimun hydrogen storage capacity	Q_{min}	5%
Maximun hydrogen storage capacity	Q_{max}	100%
Investment cost of WT(￥/kW)	C_{WT2MW}	2000
Operation and Maintance cost of WT(￥/kW/year)	$C_{WT2MWom}$	50
Cost of PV(￥/kW)	C_{pv}	4000
Cost of hydrogen compressor system(￥)	C_{YS}	2000000
System life(year)	n	20

Table 2 gives the system parameters of each component like price, lifetime and son. Base on this，we can obtain the capacity configuration result by using the system operation strategy and PSO algorithm established above． Figure 6 shows the convergence process of the PSO algorithm in the optimization process. The algorithm converges to global optimum when at the 22th iterations.

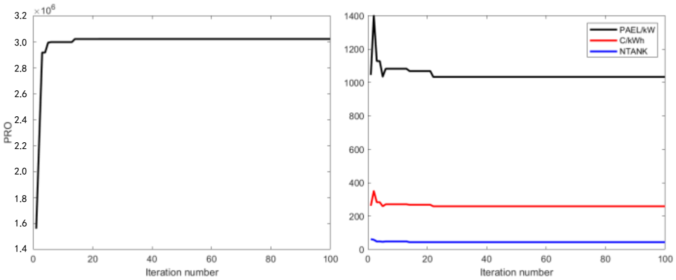

Fig. 6 Convergence of the PSO algorithm

The optimal solution of the system capacity optimization configuration is: PAEL=1034kW, capacity of BESS C=259kWh, NTANK=44. The optimal objective function value at the optimal solution is PRO=￥3023326. The annual hydrogen prduction amount of the whole system is QH2=73350kg. The conversion rate of RE sources of the system ηcon=42.99%.

4.2 Influence of the BESS

The BESS plays a key role in the grid-off RE-H2 system. It can accumulate surplus energy when the AEL can't consumed the RE completely, and the accumulated energy will be released to support the AEL when the generation power of WT and PV is insufficient. The use of the BESS not only smooths the fluctuations of RE power, but also decrease the number of shutdown of the AEL, which eventually improves system energy conversion efficiency and economic benefits.

For comparison, this paper conducts a system capacity configuration without BESS, all other conditions and parameters the same. The optimal solution of the system capacity optimization configuration is: PAEL=1212kW, NTANK=40. The optimal objective function value at the optimal solution is PRO=￥2191769. The annual H2 prduction amount of the whole system is QH2=70773kg. The conversion rate of RE sources of the system η con=41.48%.

The capacity of AEL in the condition without a BESS is larger than that with a BESS, which means there will be more H2 production sometimes, so the NATNK is also larger. However, the annual H2 prduction of the system is less than the condition with a BESS, it's because the number of shutdown of the AEL has increased without the power support from BESS. In other words, the running time of the AEL is reduced and the penalty cost of the system is increased.

5. CONCLUSION

In this paper, an optimization problem based on economic optimum is proposed to reliaze the optimal configuration of H2 production system capacity. Specially, this paper considers the dynamic H2 production efficiency model of AEL to describe the H2 production process of AEL more accurately. The PSO algorithm is used to solve the nonliner constrained optimization problem to get the optimal capacity configuration results.

The capacity configuration result confirms that the system can get optimal economic benefits. It's found that the prices of H2 and electrolyzer have the greatest influence on the configuration result through sensitivity analysis. The economic benefits of RE-H2 system will rise up greatly as the price of H2 goes up, and the capacity configuration results will become bigger. When the price of AEL drops down, the capacity configuration result of AEL will become bigger, which leads to a higher H2 production and a higher renewable energy conversion rate. However, if PAEL is too big, there will be a bigger number of shutdowns, which will accelerate degradation of the AEL, and finally leads to a higher penalty cost.

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