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Off-grid Wind-Solar Coupled Hydrogen Production System Architecture Optimization

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ABSTRACT

We analyze the structure of the wind-solar coupled hydrogen production system and optimized system architecture through performance comparison. To obtain the optimal architecture, we first compare the DC bus and AC bus systems to acquire an initial optimized system architecture, and secondly, we analyze the centralized and distributed structure of the system and compared them in five aspects: cost, reliability, system efficiency, stability, and control complexity. Finally, we verified the feasibility of the architecture by analyzing and calculating the performance of the system.

Keywords: wind-solar coupled system, hydrogen production, off-grid

NONMENCLATURE

Abbreviations	
EL	Electrolyzer
HHV	Hydrogen Heat Failure
MTTF	Mean Time To Failure
WT	Wind Turbine
BAT	Battery

1. INTRODUCTION

In resent year, many countries have propose zero-carbon targets and increasingly focused on environmental protection [1]. But traditional fossil energy are limited in supply and can cause serious environmental pollution. So, the demand for renewable energy which are environmentally friendly is growing. Wind and solar energy systems are the most well-known renewable energy which are used as power generation systems [2]. But renewable energy generation will produce the phenomenon of abandoned wind and solar [3], which will cause lots of waste of wind and solar energy. The wind-solar coupled hydrogen system can use the abandoned wind and solar to produce hydrogen [4], which reduces the waste of the energy and do not cause bad impact on the environment. Hydrogen can be used as a fuel to get a reliable power for almost every application that fossil fuels are used. Furthermore, hydrogen can be converted in other types of energy more efficiently than fossil fuels [5].

The selection of the architecture is significant to this system, as it determines the control strategy and the specific implementation of the energy management, the number of power converters, the choice of bus voltage level, and also affects the construction and maintenance costs of the system, as well as the hydrogen production and purity [6]. So it is necessary to analysis the architecture of the system. In this paper, several system architectures are analyzed to obtain an optimized structure of wind-solar coupled hydrogen production system. The results show that the system architecture has a high degree of stability, efficiency and reliability.

2. INITIAL ESTABLISHMENT OF THE SYSTEM STRUCTURE

For the wind-solar coupled hydrogen production system, the architectural analysis can be divide into grid-connected and off-grid, DC-bus type and AC-bus type structures. As shown in Fig.1.

DC-bus type system has many advantages compared with AC-bus type system: 1)no need to consider phase angle and frequency, 2)no need to consider reactive power compensation, 3)easy access to energy storage devices, 4)fewer AC/DC converters, 5) improved power supply reliability, etc. The DC-bus structure caters to the future trend of new energy generation and distributed power generation [7], so the off-grid DC-bus system is selected for comprehensive consideration.

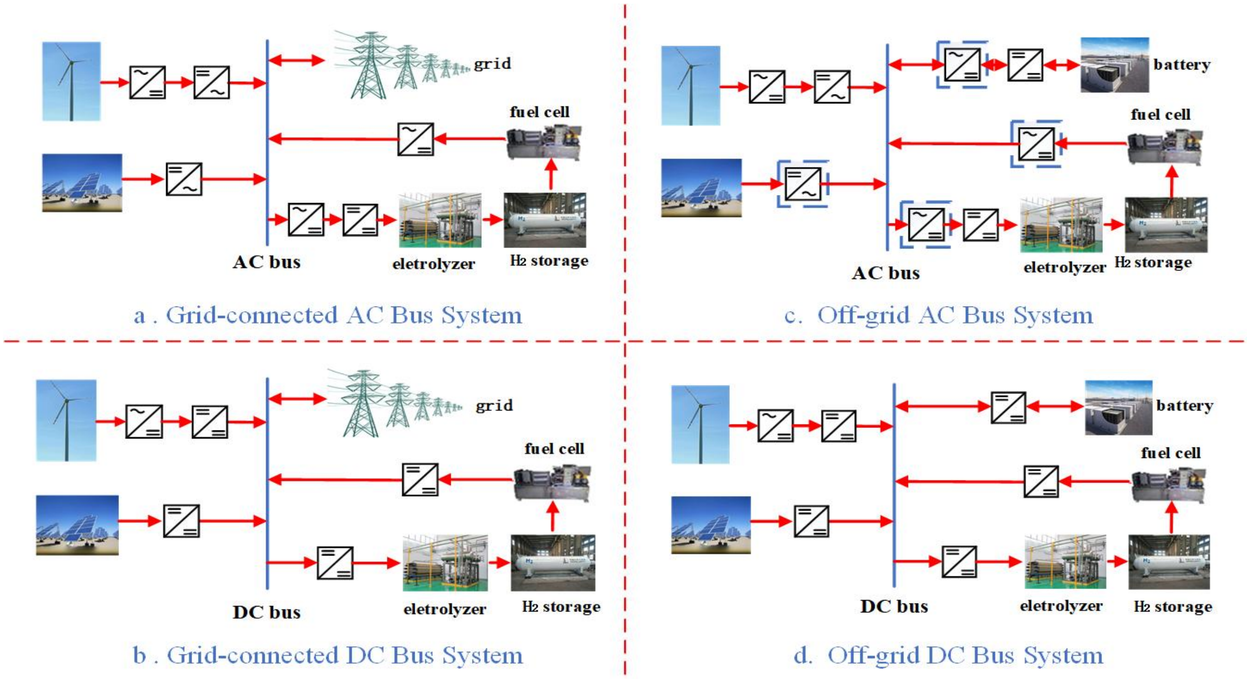


Fig.1 Basic structure of wind-solar coupled hydrogen production system system

3. OPTIMIZATION OF THE STRUCTURE OF WIND-SOLAR COUPLED HYDROGEN PRODUCTION SYSTEM

The distributed structure(structure1) and centralized structure(structure2) are shown in Fig.2, a 100MW installed wind power capacity with 50MW the 20MW battery system is analyzed as an example. The distributed architecture consists of two wind turbines connected to a small EL and a small BAT. The centralized structure is 10 wind turbines in parallel with big EL and big BAT to concentrate hydrogen production. The power of the small EL and large EL is 5MW and 50MW, the capacity of the small battery and big battery is 2MWh and 20MWh.

3.1 Cost analyze

NREL (National Renewable Energy Laboratory) has conducted a detailed analysis of alkaline EL costs [8]. The EL is divided into three classes according to the hydrogen production capacity: <10kg/day (small), 10kg/day-100kg/day (medium), >1000kg/day (large). As shows in *Tab.1.*

Tab.1

EL Grade	Price($/kg)
small	15.33
medium	8.42
large	5.56

It can be concluded that the cost per unit of hydrogen production in the EL decreases as the hydrogen production capacity of the EL increases. The power of the EL, the lower the cost of system. So, the largest power (5MW) EL is used to analyze. The cost of components in the structure1 and structure2 is given in Tab.2, the price data is provided by CSSC (CSIC offshore wind power company).

According to *Tab.2*, it can be seen that the cost of the centralized system saves 2.2% compared to the cost of the distributed system.

Tab.2 Cost of components

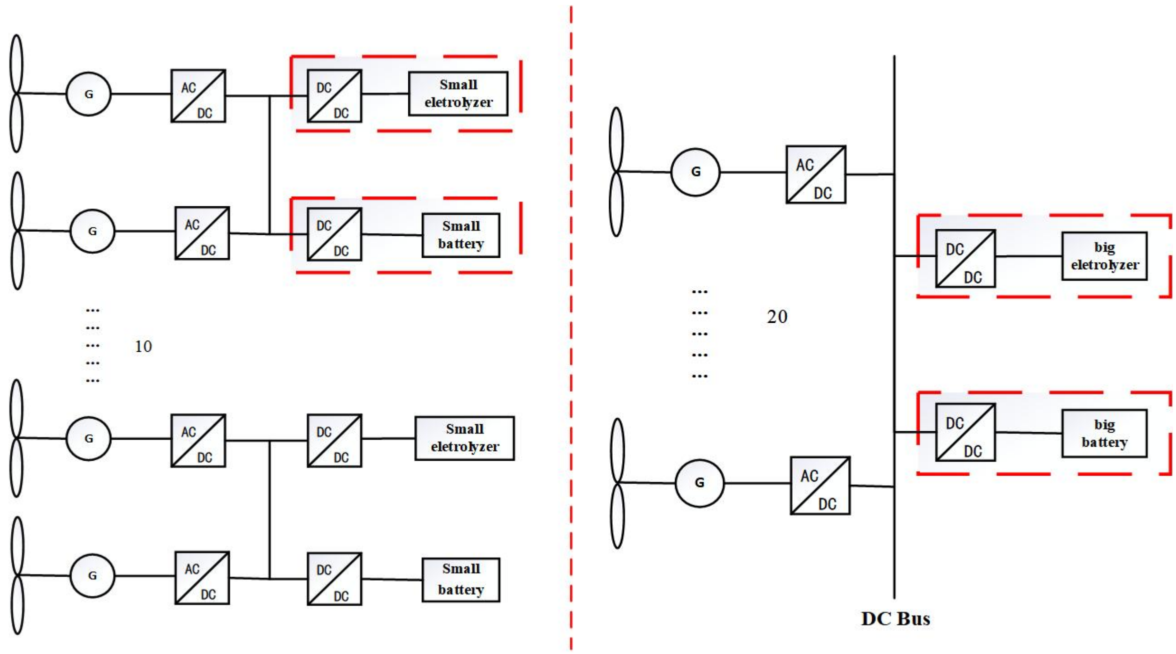
Cost $（million）	Distributed Structure	Centralized Structure
Electrolyzer	14849	14849
Wind Turbine	20046	20046
Battery	475*10	4157
Converter	2375+148*10+59*10	2375+1187+445
Total Cost	44090	43059

3.2 Reliability

Assuming that each component in the system is in stable operation in the life curve, its life follows exponential distribution, the reliability of the component at time *t* is：

$$R_i(t) = e^{-\lambda_i t} \tag{1}$$

$R_i(t)$ and λ_i is the reliability and the failure rate of the components.



a. Distributed Structure b. Centralized Structure

Fig.2 System architecture

According to the system reliability theory [9], the reliability Rs_d(t) (reliability of structure1) and Rs_c(t) (reliability of structure2) of two structure are as follows

$$\begin{cases} R_{s\_d}(t) = 1-(1-m^2)n_1 r_1 \\ m = 1-e^{-(\lambda_{wt}+\lambda_{ac})t} \\ n_1 = e^{-(\lambda_{dc1}+\lambda_{el})t} \\ r_1 = e^{-(\lambda_{bdc1}+\lambda_{bat})t} \end{cases} \quad (2)$$

$$\begin{cases} R_{s\_c}(t) = 1-(1-m n_2 r_2)^{20} \\ n_2 = e^{-(\lambda_{dc2}+\lambda_{el})t} \\ r_2 = e^{-(\lambda_{bdc2}+\lambda_{bat})t} \end{cases} \quad (3)$$

λ_{wt} ,λ_{bat} ,λ_{ac} ,λ_{el} is the failure rate of WT, BAT, WT converter and EL. λ_{dc1}, λ_{bdc1} is the failure rate of EL converter and BAT converter in structure1. λ_{dc2} ,λ_{bdc2} is the failure rate of EL converter and BAT converter in structure2. According to (3) - (4), the reliability curves of different system structures are plotted in Fig.3. The area enclosed by the reliability curve and the x-axis and y-axis is the system MTTF (Mean time to failure). The MTTF for the two architectures *MTTF*d (MTTF of structure1) and *MTTF*c (MTTF of structure2) is as follows.

$$MTTF_{\mathrm{d}} = \int_0^{\infty} R_{\mathrm{s\_d}}(t)dt = 9149.95h \quad (5)$$

$$MTTF_c = \int_0^{\infty} R_{\mathrm{s\_c}}(t)dt = 3432.61h \quad (6)$$

Tab.3 Failure rate(FR) of components

Components	FR	Components	FR
WT	1.6501	BAT	0.5
EL	0.8203	WT Converter	0.3025
BATConverter1	0.45108	BATConverter2	4.51
ELConverter1	0.3047	EL Converter2	3.047

From equations (5) and (6), the MTTF of strcuture1 is longer than structure2. System1 can System 1 can operate for an average of 9,149 hours without failure. But System 2 can only operate for an average of 3432 hours without failure. It can be seen that the choice of structure 1 can greatly improve the reliability of the system.

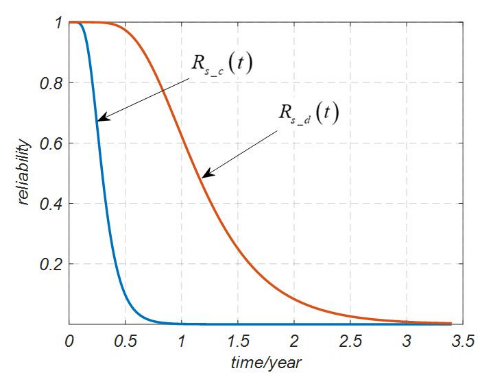


Fig.3 Reliability curve

3.3 Stability analysis

The WT rectifier mainly controls the wind turbine output power and the bus voltage is mainly controlled by the load, the wind turbine output can be modeled as the system impedance using Norton's equivalent.

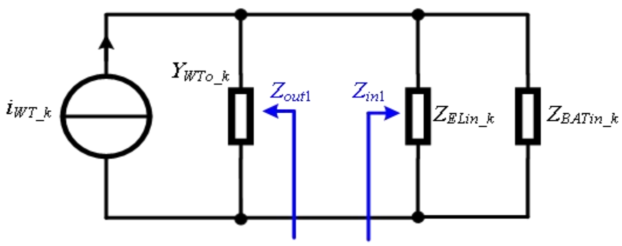


Fig.4 Equivalent circuit of structure1

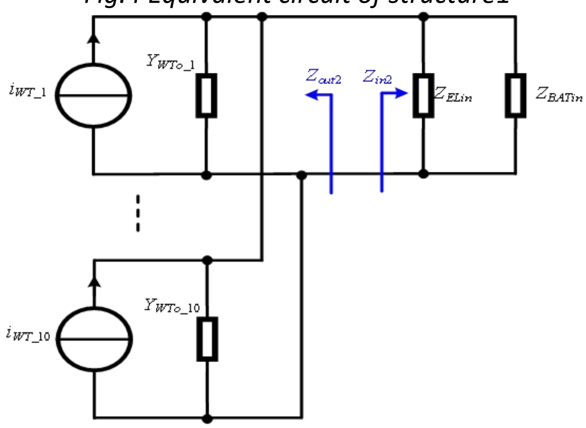


Fig.5 Equivalent circuit of structure2

Zin and *Zout* is total system input impedance and output impedance. Y_{WT}, Z_{EL} and Z_{BAT} is input impedance of WT, output impedance of EL and BAT.

Based on the MiddleBrook impedance criterion, the system is stable when Zin > Zout. Assuming that each WT is the same and the EL converter and BAT converter are the same, the output impedance of the system is Zout2=(1/10)Zout1, Zin2=(1/10)Zin1 because of wind turbines operate in parallel. But 1) considering the mutual crosstalk and line impedance between the WT, the stability of the structure2 will step down.2) When a wind turbine is damaged, the output impedance of the system shown in structure 2 will increase, resulting in a smaller stability margin of the system. Therefore, a comprehensive analysis shows that the stability of structure 1 is better than structure 2.

3.4 System efficiency

The model of WT in the two architectures is the same, and the operating environment of WT is comparable, so the WT efficiency is the same. The EL DC/DC converters of different power (50MW/5MW) of different structure is similar around the rated power. So, the efficiency of the system is mainly determined by the efficiency of the EL. The efficiency of the EL is equivalent to the system efficiency.

Assuming that the operating temperature and pressure of the EL are same in different structure, and work in rated power. The efficiency of the EL under the two architectures is

$$\begin{aligned}\eta_{el} &= \frac{E_{el}}{E_{in}} = \frac{HHV \cdot \rho \cdot V(\mathrm{Nm}^3/\mathrm{h})}{P_{in} \cdot 1h} \cdot 100\% \\ &= \frac{33 \cdot 0.0893 \cdot (10 \cdot 1000)}{50000} \cdot 100\% = 58.938\%\end{aligned} \tag{7}$$

P_{in} is the EL input power, V is the hydrogen production rate of EL is equal to 1000(Nm^3 /h), and ρ is the hydrogen density. The EL efficiency is basically same in both structure1 and structure2, so the system efficiency is basically the same.

3.5 Control Complexity

In structure 1, the subsystem is independent from each other, the complexity of controller design for the system is lower than structure2 because of the independent subsystems do not affect each other. In structure 2, multiple WT are connected in parallel to produce hydrogen, the controller design needs to consider various factors. A comparison of the two structures is shown in the *Tab.4*.

Compared with structure 1, structure 2 is more difficult to control and has a longer response time. So the control complexity of structure 1 is lower than structure 2.

Tab.4 Control complexity

Existing Problem	Structure1	Stucture2
Cooperative Control	● N	● Y
Crosstalk Between Loops	● Lower	● Higher
Control Efficiency	● Higher	● Lower
Response Time	● Faster	● Slower

4. CONCLUSION

Combining the evaluation results of different structures in five aspects: cost, reliability, system stability, system efficiency, and control complexity, a multi-dimensional performance indicator radar diagram can be drawn as shown in Fig.6. As shown in the figure, although the cost of structure 2 is lower than that of structure 1, the reliability, stability, and control complexity of the system are higher than structure2. Therefore, structure1 has a higher priority than structure2 for the wind-solar coupled hydrogen production system.

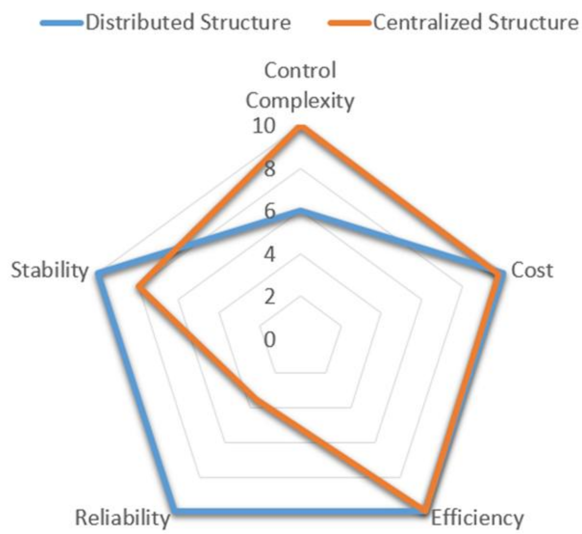


Fig.6 Radar diagram

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