Modeling and operation domain analysis of wind-photovoltaic-hydrogen coupled energy block system

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Abstract: With the rapid development of my country's new energy field, higher requirements have been put forward for the wind-photovoltaic-hydrogen coupled absorption and capacity configuration of the power system. Therefore, the physical nature and regular characteristics of energy conversion, storage, and coupling between wind-photovoltaic-hydrogen multi-differential energy sources are different. This article first starts from the perspective of power/energy supply and demand balance, and comprehensively considers system output, conversion efficiency, energy loss and other factors to establish a wind-photovoltaic-hydrogen coupling system analysis model. Then, according to the relationship between power and time, the system's model operation domain is comprehensively analyzed. Finally, combined with the actual measured data of wind power and load in a certain area, using simulation software, the system's operating domain and spatial flexibility are analyzed, and the validity of the system model constructed in this paper is verified.

1. Introduction
With the fourteenth five-year plan, my country's "dual carbon target" has ushered in a blowout development in the new energy field [1-2]. Due to the uncertainty of renewable energy power generation, the large-scale grid connection of renewable energy has a profound impact on the planning and operation of the power system. As a clean energy, hydrogen energy has the characteristics of high energy density, convenience, storage and transportation, and has become one of the preferred solutions for efficient use and green storage of wind power and photovoltaic energy. With the continuous progress of hydrogen energy technology, effective technical support has been provided for the realization of wind-photovoltaic-hydrogen coupled power generation systems. However, at present, effective and unified modeling and analysis methods for the physical nature and basic laws of energy conversion, storage, and coupling between a variety of heterogeneous energy sources need to be studied in depth.

Aiming at the model construction of different systems, literature [3] proposed an improved disturbance observation maximum power tracking algorithm based on the rate of power change, and established a large-scale wind and solar grid-connected power generation system dynamic analysis model. Literature [4] studies the unit commitment problem of power systems with wind power, and evaluates the impact of wind power forecasting and load forecasting uncertainty on the system unit commitment and dispatching. Literature [5] aims to maximize the low-carbon benefits of renewable energy grid-connected, establishes a simulation model of annual time series production that takes into account large-scale wind and solar power generation, and uses the branch and bound method to solve the model.
Although some methods for constructing new energy system models have been proposed in the above-mentioned documents, they still need to be improved to a certain extent. Therefore, this article uses a unified model structure to characterize the components in the wind-solar-hydrogen coupled power generation system, constructs a wind-photovoltaic-hydrogen coupled energy block system model, and uses different parameters to describe the differentiated characteristics. Finally, the operating domain of the system model is analyzed.

2. Coupling energy block system model construction

The wind-photovoltaic-hydrogen coupling system involves different physical media and different technical characteristics. Therefore, it is necessary to establish a unified model framework to simplify processing of its key information according to its complex parameters and boundary conditions. Combined with the output power characteristics of the system, the existing data are reasonably corrected and processed scientifically. According to the obtained data, the input and output power characteristics of each element are analyzed and compared, and their internal relationship is found, so as to construct the wind light hydrogen coupling energy block system model.

In order to ensure the unity of the constructed model, this paper takes the energy flow/power flow in a certain time scale as the boundary condition of the model, and according to the direction and nature of the energy flow in the system, the model is divided into three regions (respectively external domain, operation domain and power grid domain).

The external domain includes the supply process \( \zeta >0 \) and demand process \( \zeta <0 \) of energy, which indicates that energy is input to or consumed from the operation domain. The system operation domain is the connection hub between the external domain and the power grid domain. The mutual conversion, connection and storage of energy are carried out inside it. It is the core of the solar hydrogen energy block system model. By using different data to describe the parameters in the operation domain, the model can characterize the components of the wind light hydrogen coupled power generation system. Grid domain refers to the transmission network connected to the model. Including the input \( P_{\text{load}}<0 \) and output \( P_{\text{load}} > 0 \) processes of electric energy.

According to the power balance relationship of each model in the time scale \( t \), the model constructed in this paper can be expressed as shown in equation (1) at the same time:

\[
C_i dx_i = \int \eta_{\text{ex},i} \zeta_i dt - \int \eta_{\text{load},i} P_{\text{load},i} dt - \int \eta_{\text{gen},i} P_{\text{gen},i} dt - l_i
\]  

(1)

Where: \( i \in N \), \( N = \{1, \ldots, i, \ldots n\} \), \( N \) is the total number of system models; \( C \) is energy storage capacity, kW·h; \( dx \) is the change value of state of charge (SOC) of energy storage; \( \eta_{\text{gen}} \) is the output efficiency; \( P_{\text{gen}} \) is the output power; \( \eta_{\text{load}} \) is the load efficiency; \( P_{\text{load}} \) is load power, kW; \( \eta_{\text{ex}} \) is the conversion efficiency of external energy; \( \zeta \) is the output / consumption of external energy, kW; \( l \) is the energy loss including energy storage system, kW·h.

The wind farm model can be expressed as shown in formula (2):

\[
0 = \int \zeta_1 dt - \int \eta_{\text{gen}} P_{\text{gen}} dt
\]  

(2)

Where: \( \zeta_1 \) is the wind energy collected by the wind farm for the collection and calculation of wind speed data, \( \zeta_1 = f(t) \), kW; \( \eta_{\text{gen}} \) represents the power generation efficiency of the wind farm itself, \( \eta_{\text{gen}} = f(P_{\text{gen}}) \).

The photovoltaic model can be expressed as:

\[
0 = \int \zeta_2 dt - \int \eta_{\text{gen}} P_{\text{gen}} dt
\]  

(3)

Where: \( \zeta_2 \) is the solar energy collected by the photovoltaic station for the collection and calculation of irradiation data, \( \zeta_2 = f(t) \), kW; \( \eta_{\text{gen}} \) represents the power generation efficiency of the wind farm itself, \( \eta_{\text{gen}} = f(P_{\text{gen}}) \).

\[
C_3 dx_3 = -\int \eta_{\text{load}} P_{\text{load}} dt - l_3
\]  

(4)
Where: \( C_3 \) represents the capacity of hydrogen storage tank, kWꞏh; \( \eta_{\text{load}3} \) represents hydrogen production efficiency of electrolytic cell \( \eta_{\text{load}3} = f(p_{\text{load}3}) \), \( l_3 \) represents energy storage loss, \( l_3 = f(x_3) \), kWꞏh.

System constraints:

1. State of charge and energy storage capacity constraints:
   \[
   \begin{align*}
   C_i &> 0, \quad 0 \leq x_i \leq 1 \\
   C_i &= 0
   \end{align*}
   \] (5)
   Where: \( C_i > 0 \) is energy storage state, and \( C_i = 0 \) is no charge state.

2. Energy input and consumption constraints:
   \[
   \begin{align*}
   \zeta_i &> 0 \\
   \zeta_i &< 0
   \end{align*}
   \] (6)
   Where: when \( \zeta_i > 0 \) indicates the external input of energy, \( \zeta_i < 0 \) indicates external consumption of energy.

3. System load and output constraints:
   \[
   kP_{\text{load},i,\text{min}} \leq kP_{\text{load},i} \leq kP_{\text{load},i,\text{max}}
   \] (7)
   Where: \( P_{\text{load},i,\text{min}} \) and \( P_{\text{load},i,\text{max}} \) are the upper and lower limits of load demand respectively, kW; \( k \) is a binary number, where 1 indicates that there is a load demand and 0 indicates that there is no load demand.

4. Load and unit ramp rate constraints:
   \[
   dP_{\text{load},i,\text{min}} \leq dP_{\text{load},i} \leq dP_{\text{load},i,\text{max}}
   \] (9)
   \[
   dP_{\text{gen},i,\text{min}} \leq dP_{\text{gen},i} \leq dP_{\text{gen},i,\text{max}}
   \] (10)
   Where: \( dP_{\text{load},i,\text{min}} \) and \( dP_{\text{load},i,\text{max}} \) are the lower limit and upper limit of load climbing rate respectively, kW / min.

Where: \( P_{\text{gen},i,\text{min}} \) and \( P_{\text{gen},i,\text{max}} \) are the upper limit and lower limit of unit output respectively, kW; \( \eta_{\text{gen}}, \eta_{\text{load}}, \eta_{\text{ex}} \), which varies according to the change of input / output power, \( \eta_{\text{gen}} = f(p_{\text{gen}}) \), \( \eta_{\text{load}} = f(p_{\text{load}}) \), \( \eta_{\text{ex}} = f(\zeta) \).

3. Run domain analysis
   Select a specific time scale \( \triangle t \), establish corresponding indexes for the transmission power \( (p_{\text{gen}}, p_{\text{load}}) \) of the model and analyze them accordingly. The index analysis diagram of operation domain is shown in Figure 1.
The power change rate at time $t_1$ is shown in equation (11):

$$u_{gen,i,t_1} = \frac{p_{gen,i}(t_2) - p_{gen,i}(t_1)}{t}$$  \hspace{1cm} (11)

The output power at $t_1$ is shown in equation (12):

$$p_{gen,i,t_1} = p_{gen,i}(t_1)$$  \hspace{1cm} (12)

The power supply at time $t_1$ is shown in equation (13):

$$e_{gen,i,t_1} = \int_{t_1}^{t_2} p_{gen,i}(t) \, dt$$  \hspace{1cm} (13)

The three-dimensional coordinate system is established with the analysis index corresponding to equations (11) - (13) as the coordinate axis, and the analysis cube is established with the current operation index as the operation point and the corresponding constraint conditions as the boundary. In the established cube, the three parameters are constrained each other.

4. Simulation analysis

Combined with the actual historical data of a place, this paper uses the simulation software to simulate and analyze an example. The simulation model includes wind farm with unit capacity of 60kW, photovoltaic power plant with unit capacity of 60kW and electrolytic cell group with upper output limit of 100kW. The statistical data of annual wind speed and light intensity are shown in Figure 2. The simulation time step is 5min. 1440 time sections are counted. Combined with equation (2) and equation (3), the calculated wind power output and photovoltaic power generation output sequence are shown in Figure 3.

Combining formulas (11)-(13), analyze its operating domain indicators, as shown in Figure 4 and Figure 5. It can be seen from Figure 4 that the maximum climbing power is 8.3kW/min and the minimum is -8.1kW/min. The maximum output power is 58kW. The maximum power supply is 218kWh. On the scale of climbing power, the operating points are relatively concentrated, and 95% of the points are concentrated in the interval [-4, +4] (kW / min). For the other two scales, the operation points have no obvious concentration domain. Due to the strong randomness of wind speed distribution in the wind farm, there is no obvious correlation law at the operation point. It can be seen from Figure 5 that the maximum climbing power is 5.7kW/min and the minimum is -2.5kW/min. The maximum output power is 55kW. The maximum power supply is 203.5kWh. The climbing power changes little, and 98.3% of the operating points are concentrated in the interval [-1, +1] (kW / min). Due to the power generation characteristics of photovoltaic power generation, the operating points show a circular distribution law in the three-dimensional coordinate system.

According to the output conditions in Figure 4 and figure 5, combined with the constraints of the electrolytic cell itself as the boundary, the scatter analysis cubic diagram is drawn according to the conditions of each operating point, as shown in Figure 6.

The blue cube in Figure 6 is a flexible cube drawn according to the boundary conditions of the electrolytic cell. The maximum / minimum climbing power is ±8kW / min and the maximum output power is 100kW. The maximum power supply is 375kWh. Under the constraints, only the climbing constraints of individual points (1.8%) can’t be met, and the other scales can meet the constraints. The yellow cube is an ideal flexible cube drawn with the maximum and minimum values of each operating point as the boundary. The maximum climbing power is 8.8kW/min and the minimum is -7.2kW/min. The maximum output power is 97.3kW. The maximum power supply is 361.5kWh. Under ideal conditions, it can cover the operation indicators of wind power and photovoltaic units, so as to realize the consumption of renewable energy accepted by the system within the time interval.
Figure 2 statistical data of wind speed and irradiation history

Figure 3 wind power and photovoltaic output sequence

Figure 4 scatter diagram of wind power output

Figure 5 scatter diagram of photovoltaic output

Figure 6 Analytical cube diagram of electrolyzer operating area
5. Conclusion
In this paper, a wind-photovoltaic-hydrogen coupled energy block system model is established based on the power/energy balance principle of the system, and the operating domain is analyzed. Combining system output, conversion efficiency, energy storage loss and other factors, a method for establishing a unified model is proposed. According to the relationship between power and time, the model operating domain is analyzed from the perspectives of power change rate, power output, and input power. Analysis and evaluation of the system's ability to absorb intermittent renewable energy. The results of this paper will have certain significance for the research on the absorption and capacity allocation of wind-photovoltaic-hydrogen coupling systems in power systems.

In the future, more in-depth research can be carried out from the aspects of system transient model and capacity matching of wind-photovoltaic-hydrogen system.

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