Optimal Operation Of Integrated Energy System Considering Demand Response

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Abstract—Due to the high cost of energy storage part in traditional integrated energy systems, the demand response effect is poor. The paper proposes electrolytic water hydrogen production technology and applies it to the optimal operation of integrated energy system. By optimizing the operating cost of the system through adaptive genetic algorithm, we show that when the load matching degree was increased from 50\% to 70\%, the system operating cost was reduced by about 15.8\%, and the carbon displacement was decreased by about 35\%. System operating costs, carbon emissions, and the amount of electrolytic water systems involved in the demand response have all decreased.

1. Introduction
Long-term use of fossil fuels has gradually caused problems such as energy security, greenhouse effects, and environmental deterioration, posing a serious threat to the global ecological environment\textsuperscript{[1]}. New energy represented by wind and solar energy has the advantages of wide distribution, sustainable, clean and environmental protection. However, the rapid development of renewable energy also brings challenges to the safety, stability and economic operation of the power system. Due to the high concentration of wind and light resources in China and the insufficient acceptance capacity of the power grid, the problem of abandoning wind and light gradually highlights, which seriously restricts the development of large-scale wind and optical energy\textsuperscript{[2-3]}.

Different from the above research, this paper introduces electrolysis water hydrogen production technology to produce hydrogen with excess power and stored in the gas storage device to participate in the system demand response, and the resulting hydrogen gas can also fuel the hydrogen fuel cell. Therefore, this paper first introduces the concept of load matching to optimize the operating cost and carbon dioxide emissions under different meteorological conditions.

2. Integrated energy system modeling

2.1 Comprehensive energy modeling thinking
Hydrogen is a kind of clean energy with many advantages of high energy thermal value, good stability, easy storage and transmission, and has a broad prospect of applying electrolytic water hydrogen production technology to the optimized operation of the comprehensive energy system.

At present, the comprehensive energy system modeling idea is mainly divided into two kinds: bus type and energy hub. The bus type takes electrical, flue gas, steam, hot water and air as the basic bus, establishing the dynamic economic scheduling model of typical heating and cooling power supply.
system\cite{4}; the energy hub can reduce the model complexity through automatic linearized modeling method, and quantitatively evaluate the flexibility of the energy hub based on the energy hub coupling matrix analysis\cite{5}.

2.2 Output model of each unit

a. Wind turbine generator unit

\[ P_{WT}^t = \begin{cases} 
0 & v_t \leq v_{in}, v \geq v_{out} \\
\frac{v_t - v_{in}}{v_r - v_{in}} P_{RWT} & v_{in} < v_t < v_r \\
\frac{P_{RWT}}{v_r} & v_r \leq v_t \leq v_{out} 
\end{cases} \]  

(1)

In the formula: $P_{WT}^t$ is the power output of the wind turbine at time t, $v_{in}$ is the wind turbine cut-in wind speed, $v_{out}$ is the wind turbine cut-out wind speed, $v_t$ is the wind turbine at time t, $v_r$ is the wind turbine rated wind speed; $P_{RWT}$ is wind turbine rated power (1000kW).

b. PV generator set

\[ P_{PV}^t = f_{PV} \cdot N \cdot P_{RPP} \cdot \frac{R_t}{R_{STC}} \left[ 1 + \alpha \left( T_{cell}^t - T_{STC} \right) \right] \]  

(2)

In the formula: $P_{PV}^t$ is the output power of the photovoltaic array at time t; $f_{PV}$ is the loss coefficient, which indicates the power reduction or power shortage caused by the inevitable factors such as the loss and aging of the photovoltaic panels, usually take 0.9; $N$ is the total number of photovoltaic panels; $P_{RPP}$ is the rated power of a single photovoltaic panel, $R_t$ is the actual radiation intensity at time t, $R_{STC}$ is the reference radiation intensity, usually take 1 kw/m$^2$, $\alpha$ is the temperature coefficient, take 0.47%/°C. $T_{cell}^t$ is the temperature of the photovoltaic panel at time t, and $T_{STC}$ is the reference temperature, usually take 25 °C.

c. Electrolyzer

\[ G_{EL}^t = \eta_{EL} P_{EL}^t \]  

(3)

In the formula: $G_{EL}^t$ is the standard cell output of gas power at time t, $P_{EL}^t$ is cell consumption of electric power at time t, $\eta_{EL}$ is the standard cell conversion efficiency, take 0.45.

d. Hydrogen fuel cell

\[ P_{HFC}^t = \frac{\eta_{HFC} V_{HFC}^t H_{H_2}}{k_{HFC}} \]  

(4)

In the formula: $P_{HFC}^t$ is the power output of hydrogen fuel cell, $\eta_{HFC}$ is the conversion efficiency of hydrogen fuel cell, take 0.7; $V_{HFC}^t$ is the hydrogen consumption rate of hydrogen fuel cell; $H_{H_2}$ is the heat value of hydrogen, take 2.82 × 105 J/ml; $k_{HFC}$ is the conversion constant, take 2.778 × 10^{-7} J/(kwh).

e. Cogeneration electric generator

\[ \begin{align*}
P_{CHIP}^t &= \eta_{CHIP}^e G_{CHIP}^t \\
H_{CHIP}^t &= \eta_{CHIP}^h G_{CHIP}^t
\end{align*} \]  

(5)

In the formula: $P_{CHIP}^t$ and $H_{CHIP}^t$ is cogeneration electric generator power and heat generation power at time t; $G_{CHIP}^t$ is cogeneration electric generator input power at time t; $\eta_{CHIP}^e$ and $\eta_{CHIP}^h$ is electric generator electricity conversion efficiency and heat conversion efficiency, respectively, 0.33 and 0.47.
f. Gas-fired boiler

\[
\begin{align*}
H_{GB}^t &= \eta_{GB}^t \cdot V_g^t \cdot H_g \\
H_{GB}^{\text{min}} &\leq H_{GB}^t \leq H_{GB}^{\text{max}}
\end{align*}
\]  

(6)

In the formula: \(H_{GB}^t\) is the output thermal power of gas-fired boiler, \(\eta_{GB}^t\) is the thermal efficiency of gas-fired boiler, take 0.9; \(V_g^t\) is the consumption rate of natural gas at time \(t\); \(H_g\) is the calorific value of natural gas, take 9.9 kWh/m\(^3\); \(H_{GB}^{\text{min}}\) is the minimum output power of gas-fired boiler; \(H_{GB}^{\text{max}}\) is the maximum output power of the gas-fired boiler.

g. Diesel engines

\[P_D^t = \eta_D G_D^t\]  

(7)

In the formula: \(P_D^t\) is the output power of the diesel generator at time \(t\), \(\eta_D\) is the energy efficiency of the diesel unit, take 0.5. \(G_D^t\) is the input power of the diesel generator at time \(t\).

3. Objective functions and constraints

The total operating costs of an integrated energy system \(M_c\) are expressed as the sum of the operating costs of each unit, that is, the purchase of natural gas \(M_{pg}\), the purchase of diesel \(M_D\), the purchase of electricity and scenery \(M_w\) and \(M_{pv}\), and the cost of carbon emissions \(M_{ce}\). The objective function is:

\[\min M_c = M_{pg} + M_D + M_w + M_{pv} + M_{ce}\]  

(8)

The details are as follows:

a. The cost of buying natural gas \(M_{pg}\).

Some of the gas purchased by the grid goes to the electric generator and some goes to gas fired boilers. If the price of natural gas is fixed, the purchase price of natural gas can be expressed as:

\[M_{pg} = r_g \cdot \sum_{t=1}^{T} (G_{CHP}^t + G_{GB}^t) \Delta t\]  

(9)

In the formula: \(G_{CHP}^t\), \(G_{GB}^t\) is cogeneration electric generator consumption of natural gas power and gas boiler consumption of natural gas power at time \(t\); \(r_g\) is gas price, take 0.13 Yuan/(kwh).

b. The cost of diesel fuel \(M_D\).

The diesel purchased by the Integrated Energy Network goes directly into the diesel generator for fuel. If the price of diesel is fixed, the purchase cost of diesel can be expressed as:

\[M_D = r_D \cdot \sum_{t=1}^{T} G_D^t \cdot \Delta t\]  

(10)

In the formula: \(G_D^t\) is the diesel power consumed by the diesel unit at time \(t\); \(r_D\) is the diesel price, take 0.75 yuan/(kwh).

c. The cost of wind power generation \(M_w\) and \(M_{pv}\).

If the price of wind power and photovoltaic electric generator \(r_{WT}\) and \(r_{PV}\) are set at 0.72 Yuan/(kwh) and 0.46 yuan/(kwh) respectively, the cost of wind and photovoltaic power generation can be expressed as:

\[M_w = r_{WT} \cdot \sum_{t=1}^{T} P_{WT}^t \cdot \Delta t\]  

(11)
In the formula: \( P_{WT}^t \) is wind turbine power at time \( t \); \( P_{PV}^t \) is photovoltaic unit power at time \( t \).

d. Carbon costs \( M_{ce} \).

The total carbon emissions defined in this paper are composed of the equivalent carbon emissions from the purchase of natural gas and the equivalent carbon emissions from the purchase of diesel. The equivalent emission coefficients for diesel and natural gas \( \beta_D \) and \( \beta_g \) are 0.26 kg/(kwh) and 0.24 kg/(kwh), respectively, \( \varepsilon \) represents the cost per unit mass of CO\(_2\) (0.03 yuan/kg), the cost of carbon emissions can be expressed as:

\[
M_{ce} = \varepsilon \cdot \sum_{t=1}^{T} \left[ \beta_D \cdot P_{WT}^t + \beta_g \cdot \left( G_{CHP}^t + G_{GB}^t \right) \right] \Delta t
\]

4. optimization algorithm

Adaptive genetic algorithms learn from the evolutionary methods of natural organisms, algorithmic the process of biological evolution, and implement simulation on a computer to solve optimization problems in real fields, which is a global search algorithm that can be avoided from being limited to the local maximum. It randomly generates different kinds of problem solutions, and selects more favorable problem solutions according to the principle of survival of the fittest, with further iteration and optimization through genetics and variation, similar to biological evolution in nature. It is the randomization of its initial selection scheme, coupled with constant variations in genetics, that makes it jump out of local optimum dilemmas and be suitable for global search and optimization. Therefore, in order to obtain the optimal operation cost of the integrated energy system, the adaptation function is represented by the countdown of the target function, and meanwhile, the hourly power output of each component in the integrated energy system is selected as the control variable to optimize the operating cost of the system through the adaptive genetic algorithm. The optimization flow chart of the algorithm is shown in Figure 1.

![Figure 1 The AGA optimization flow chart](image-url)
5. calculation example analysis

5.1 optimal operation results of integrated energy systems before and after demand response
This section takes a typical integrated energy system as an example to simulate the proposed optimal operation strategy. In order to understand the energy charge and discharge of the electrolytic water system in the integrated energy system after the demand response, Figure 2 shows the real-time energy interaction of the electrolytic water system (less than 0 means storage energy, more than 0 means release of electric energy). It can be seen from fig. 2 that after considering the demand response, the electrolytic cell performs energy storage at 7h and 11~14h, and the fuel cell releases electric energy at 2h,18.5h and 22~24h. According to the calculation, the electrolytic water system can fully convert the electricity of 3532.85 kW·h into hydrogen in the hydrogen storage system, which can release 1413.14 kW·h at the energy tension. This shows that the electrolytic water devices in demand-responsive systems have more flexibility than reckless integrated energy systems to help the system solve a portion of the tight energy requirements.

Fig2 Real-time energy interaction of electrolyzed water system after demand response

5.2. Operating cost and carbon exhaust optimization results of different matching systems
In order to reveal the impact of different meteorological conditions (wind speed and light) on the optimized operation of the system, this section studies the optimal operating cost, carbon displacement and operating changes of electrolytic water system under different matching degrees under the determined load demand (the load involved in the demand response). Table 1 shows the changes in the system operating costs and carbon displacement as the load matching degree increases from 50% to 70%.

| Parameter                  | Load matching/% |
|----------------------------|-----------------|
|                            | 50              | 55              | 60              | 65              | 70              |
| Running cost/dollar        | 57792           | 55469           | 52847           | 50096           | 48654           |
| Carbon emissions/kg        | 12551           | 10832           | 9875            | 8976            | 8153            |
According to Table 1, with the increase of load matching degree, the operating cost and carbon displacement of the integrated energy system are declining. That is, when load matching rises from 50% to 70%, the average daily operating cost decreased by about 15.8% and carbon displacement by about 35%. The reason for this change is that: with the increase of the load matching degree, the utilization rate of new energy power generation is getting bigger and bigger, and the electric load needed to transfer by the hydrogen storage system is gradually reduced. Calculating the energy interaction of the electrolytic water system at 5 matching degrees shows that as the load matching degree increases, the amount of electrolytic water hydrogen production gradually decreases, and less electric energy is released to the system. The calculations showed that the total electric power released was reduced by about 63% when the load matching degree rose from 50% to 70%. This is because the increasing load of new energy power generation can meet as the load matching degree increases, so the total amount of electricity that needs to be consumed by the electrolytic water system decreases, and the hydrogen involved in the demand response also decreases.

6. Conclusion
By introducing the technology of hydrogen production from electrolyzed water into the traditional integrated energy system and installing hydrogen storage device, the hydrogen will participate in the system demand response, which improves the system economy and reduces the output of standby power supply.

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