Operational Optimization of Integrated Energy System Based on Coordinated Complementary of Cold, Heat and Electricity Loads

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Abstract: Integrated Energy Systems (Integrated Energy System, IES) to pluripotent and complementary energy ladder as the core, will greatly improve the system's energy efficiency, to achieve a variety of complementary energy flow optimization. By establishing a cold-heat-electricity integrated energy system, taking the lowest total operating cost of the system as the objective function, considering the equipment model constraints and power balance constraints, the day-to-day load simulation is used to optimize the economic operation of the integrated energy system; at the same time, the system operates in winter and summer. The operating conditions vary greatly, and the quarterly adjustment operation mode is adopted, and the branch and bound (BaB) algorithm is used to solve the optimization model. The simulation results show that the energy supply of the system is balanced, the "source-charge-storage" complementarity is strong, the system operates flexibly, cost-effectively, and at the same time, the system emits less polluting gas, which is beneficial to environmental protection.

1. Introduction
The energy industry as a key factor supporting daily life consumption, industrial production and other activities shows the characteristics of large energy demand, many types of energy, large differences in energy structure and rapid changes in energy flow. Most of the existing energy production structures are independent of each other and operate independently, which is prone to serious energy conversion losses, the sparse coupling relationship of each system and the single structure; on the energy consumption end, huge energy demand and rapid changes in energy consumption methods are constantly changing. The impact on the existing energy system structure poses a huge challenge to the stability and safety of the energy system. Therefore, it is extremely critical to strengthen the heterogeneous energy flow coupling and cooperation in the integrated energy system.

At present, many scholars have done more research on the optimization of integrated energy systems, but the optimal operation of the integrated "source-charge-storage" integrated energy system and the consideration of the seasonal operating conditions, especially the seasonal load differences are likely Less considerations are made to make the system difficult to operate stably. Therefore, this paper will conduct research on the multi-energy complementary optimization operation and seasonal load stability of the cold-heat-electricity integrated energy system.
2. Optimize Operation Strategy

2.1. Objective function
Based on the principle of economic optimality, this paper will take the annualized system cost as the objective function. The annualized system cost mainly includes the annualized equipment investment cost, operation and maintenance cost, energy consumption cost, demand response compensation cost and spare capacity cost. The comprehensive energy utilization rate is the highest, that is, the ratio of the total energy output by the integrated energy system to the total energy input is the highest.

\[
C_{\text{eng}} = \sum_{t=1}^{T} \left( \sum_{i=1}^{N} c_{\text{ng}}(t) \left( f_{i,t} x_{i,t} + \frac{f_{i,pv,t} P_i(t)}{\eta_i} \right) + P_e(t) C_g(t) \right)
\]  

(1)

\[
P_{\text{pv}} = f_{p,v} P_{r,pv} A_{A} \frac{1 + \delta_p \left(T_{pv} - T_p\right)}{A_{A}}
\]

(2)

A heat pump is an original that converts electrical energy into thermal energy, that is, an electric-to-heat original. The mathematical model is as follows:

\[
P_{\text{HP}}(t) = Q_{\text{HP}}(t) \cdot \eta_{\text{HP}}
\]

(3)

The electric boiler converts electrical energy into heat energy with a high and constant conversion efficiency. The mathematical model is as follows:

\[
P_{\text{EB}}(t) = Q_{\text{EB}}(t) \cdot \eta_{\text{EB}}
\]

(4)

The electric refrigerator uses electric energy to generate cooling capacity, and its mathematical model can be expressed as follows:

\[
P_{\text{ER}}(t) = Q_{\text{ER}}(t) \cdot \eta_{\text{ER}}
\]

(5)

The absorption chiller absorbs and recovers the waste heat to generate the cooling capacity, and its mathematical model can be expressed as follows:

\[
P_{\text{AR}}(t) = Q_{\text{AR}}(t) \cdot \eta_{\text{AR}}
\]

(6)

The gas-heat coupling equipment unit is mainly a gas boiler, and its typical physical model can be expressed as follows:

\[
P_{\text{GHB}}(t) = \frac{V_{\text{GHB}}(t) L_{\text{NG}} \eta_{\text{GHB}}}{\Delta t}
\]

(7)

Energy storage equipment (including energy storage batteries and heat storage tanks, etc.) is the heart of an integrated energy system and a key device for energy coupling and demand response. The mathematical model of its charging is as follows:

\[
SOC(t) = (1 - \delta) \cdot SOC(t-1) + P_n \cdot \Delta t \cdot \eta_{\text{in}} / E_{BD}^N
\]

(8)

The mathematical model of energy release is as follows:

\[
SOC(t) = (1 - \delta) \times SOC(t-1) - P_{\text{out}} \times \Delta t / (E_{BD}^N \times \eta_{\text{out}})
\]

(9)

2.2. Device model

2.3. Constraints
(1) Electric load balancing constraints

\[
P_{\text{grid} - \text{buy}}(t) + P_{\text{WT}}(t) + P_{\text{PV}}(t) + P_{\text{EES-out}}(t) = E_{\text{load}}(t) + P_{\text{EES-in}}(t) + Q_{\text{EB}}(t)
\]

(10)

(2) Thermal load balance constraints

\[
P_{\text{EB}}(t) + P_{\text{GHB}}(t) + P_{\text{TES-out}}(t) \gg \sigma H_{\text{load}}(t) + P_{\text{TES-in}}(t)
\]

(11)
(3) Cold load balance constraints

\[ P_{ER}(t) + P_{AR}(t) \geq \sigma C_{load}(t) \]  

(12)

2.4. Algorithm

This optimization model is a mixed integer nonlinear programming model. Its coupling relationship is complex and the nonlinear characteristics are obvious. Especially the multi-variable input and conversion of gas internal combustion engines and flue gas absorption heat pump equipment make the model show strong non-convex characteristics. General optimization Solvers (such as CPLEX, GUROBI, etc.) and ordinary algorithms cannot be solved, therefore, this paper adopts the branch definition method to solve the problem.

The branch-defining algorithm decomposes the original problem into many sub-problems by relaxing constraints, and adopts the method of solving the optimal solution of the sub-problem. When the optimal solution is the feasible solution of the original problem, the optimal solution is the optimal solution of the original problem; otherwise, the objective function is the optimal solution of the original boundary problem, the objective function maximum feasible solution the optimal solution for the lower bound of the original problem, continue to solve the program, when the upper bound is below the lower bound, the original optimal problem-free Solution.

3. Case

3.1. Device parameters

The cold-heat-electricity integrated energy system has a large difference in seasonal loads, especially in winter and summer. The demand for cold and heat loads is very different, and the system operating conditions are complicated. Under the condition that the cooling, heating and electric loads of the system are independent and uncertain, if the rice is operated in a single working condition for different seasons, there are situations where the system cannot meet the load demand and the equipment cannot operate. At this time, we should consider adjusting the system quarterly. This article adjusts the system equipment parameters, changes the system operating conditions, and adjusts the system to operate quarterly. Among them, some equipment model parameters of winter and summer are shown in Table 1.

| Parameters | Summer | Winter |
|------------|--------|--------|
| Q_{load}   | 80     | 100    |
| C_{load}   | 40     | 60     |
| \eta       | 0.2    | 0.8    |
| COP_{et}   | 1.8    | 2.8    |
| COP_{rec}  | 4.1    | 2.3    |

3.2. Results analysis

(1) The results of the summer day load on the operation of the integrated energy system are as follows: According to the cold-heat-electric load and the power output of each equipment before summer, the output power of the gas internal combustion engine basically bears the base load part of the electrical energy load; the photovoltaic power generation equipment is actively connected to the system and is completely consumed by the system. Absorbed electric power is reduced, especially at the peak period of 0 kW in the 9th, 11th and 12th hours, which fully reflects the system's effect of peak-shaving and valley-filling. The small degree of participation is conducive to improving the lifespan of power storage equipment. It also shows that the system can achieve self-consumption and the system has good stability.

According to the thermal power output of each equipment before the summer day, the thermal energy output of the cylinder liner water heat exchanger is stable, which can meet the daily heat load...
The heat load of the system exists in two peak load periods within a day. The flue gas absorption heat pump has flexible adjustment, which can realize the function of "with input and release, with output and stop" for the output of thermal energy. At the same time, the heat storage equipment maintains the power stability of the thermal system by absorbing and releasing heat, and effectively regulates the economic and stable operation of the thermal system.

According to the cold power output of each equipment before summer, the cold energy demand is the largest in summer. The cold energy load is mainly supplied by the flue gas absorption heat pump, and the flue gas absorption heat pump outputs stable cold power to meet the system cold energy load balance. The electric refrigerator operates flexibly. When the cooling power of the flue gas absorption heat pump is insufficient, it provides part of the cold energy to meet the load shortage of the cold power system, realize the "source-charge-storage" power balance, and the system operates stably.

(2) The results of the summer day load on the operation of the integrated energy system are as follows:

The cold winter days ago - thermal - electric loads and the power output of each device, the energy trough in the period (first 1-6 H and second 24 H Gas engine power output less) In this case, low-price power grid, the grid output power , it is conducive to economy running system; the peak power period (first 7-22 H ) gas engine with the electric power demand and where the negative power increases , which provides more than 50% of power load, and the output is stable. From the 9th to the 17th, the photovoltaic power generation has obvious output, the system can completely absorb the photovoltaic power, and the power received by the system from the grid during peak hours is reduced, especially at the 10th and 11th The power generation and consumption are completely autonomous, and the power of the grid is low during the peak period of power consumption (12th to 15th hours), so as to achieve the optimal system economy.

In the optimization before the winter, the charge and discharge power of the storage device are at a low level, which not only reduces the maintenance cost of the storage device, but also increases the service life of the device. The thermal power output of each equipment before winter is shown in Figure 8. The system uses a large amount of heat energy from the jacket water heat exchanger to supply the load for use. When the liner exchange water is insufficient heat to provide heating power, the flue gas is absorbed by the heat pump system, flexible electric boiler operation, and the heat load supplied vacancy when high energy output, the heat storage apparatus into operation, to heat or storage portion Part of the heat energy is emitted to regulate the operation of the system and realize the power balance of the heat energy system. According to recently cold winter power output of each device, the power demand is low due to the cold winter, the system is well absorbed by the flue gas heat pump to achieve for all of the cooling load of the cooling effect refrigerator and electric cooling operation should be.

4. Conclusion

(1) Based on the cold-heat-electric integrated energy system topology, coupling multiple energy production methods, including the power generation and cooling effects of gas internal combustion engines, good refrigeration and heating performance of flue gas absorption heat pumps, and numerous energy conversion devices and systems In order to ensure the stable operation of the system, heat storage/electricity storage equipment is added to increase the capacity margin of the system power, and the system is optimized for operation.

(2) Taking the optimization of the overall operating economy of the system as the optimization goal, considering the constraints of the equipment model and the power balance constraints, and using the winter and summer load parameters to optimize the calculation. Due to the large difference in load characteristics between winter and summer, the system operating conditions are complex. By adjusting the system equipment parameters, it can be operated under more suitable conditions. The built model has strong coupling, non-linear and strong non-convex features, and the branch definition algorithm is used to solve the model. The simulation results show that the system is power balanced and can run stably, and the overall system has good electricity, heating, and cooling effects to meet the load
demand. The complementary combination of "source-charge-storage" greatly improves the system's optimized operating capacity. The operation mode is flexible, the energy flow supply is changeable, and at the same time, the system emits less polluting gas and the treatment cost is lower, which can achieve the maximum economic benefit of the system and environmental protection.

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References
[1] Cheng H., Hu X., Wang L., etal. (2019) Review on research of regional integrated energy system planning. J. Automation of Electric Power Systems., 7: 2-13.
[2] Xie M., Ren D.C., Pu X.Z., etal. (2019) Review of development and application of cold, hot and electric triple supply system. J. Refrigeration., 1: 63-69.
[3] Deng X.Y., Ai X. (2019) Comprehensive benefit evaluation and incentive mechanism of distributed photovoltaic energy storage system. J. Power generation technology., 1: 30-36.
[4] Chen Q.Y. (2019) Research on the implementation strategy of ubiquitous electric power Internet of things. J. Power generation technology., 2: 99-106.
[5] Wang D., Liu L., Jia H., etal. (2018) Review of key problems related to integrated energy distribution systems. J. CSEE Journal of Power and energy systems., 2: 130-145.
[6] Wang W.L., Wang D., Jia H.J., etal. (2016) Steady state analysis of typical regional integrated energy systems in the context of energy Internet. J. Chinese journal of electrical engineering., 12: 3292-3306.
[7] Yang X., Zhang L.Q., Liu B.Y., etal. (2016) Literature review of distributed cold, heat and electricity supply system. J. Science and technology prospect., 3: 92-93.
[8] Sun H., Zhao G.P., Guo Q. (2016) Energy management for multi-energy flow: challenges and prospects. J. Automation of Electric Power Systems., 15: 1-8.
[9] Qi P. (2015) Overview of development of cold, hot and electric power supply system technology. J. Electromechanical information., 12: 173-175.
[10] Jia H.G., Dan W., Xu X.D., etal. (2015) Research on some problems of regional integrated energy system. J. Automation of electric power system., 7:198-207.