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STOCHASTIC ENERGY NETWORK EXPANSION PROGRAMMING FOR DISTRICT INTEGRATED HEAT AND POWER SYSTEM BASED ON CHANCE CONSTRAINTS METHOD

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ABSTRACT

In the context of a high proportion of renewable energy and multi-energy load access to energy system, the stochastic characteristics of energy supply side and load side need to be considered. In this paper, a district integrated heat and power system (DIHPS) model including wind turbine, photovoltaic, CHP, HP and gas boiler is established. Based on the chance-constrained programming model of DIHPS, this paper studies the changes of electric power and mass flow of energy network in DIHPS under stochastic conditions, and the changes of expansion schemes when energy stations connected. The results show that considering the randomness of energy supply side and load side, the expansion cost of power lines and thermal pipelines can be effectively reduced.

Keywords: DIHPS, stochastic characteristics, chance-constrained programming, energy network expansion planning

1. INTRODUCTION

With the high proportion multi-energy coupling equipment and new energy sources accessing, district integrated energy system (DIES) has gradually presented stochastic characteristics.

Therefore, the planning of DIES considering uncertainties has attracted more and more attention [1]. Sun et al considering the uncertainty of wind power generation and load forecasting, and proposed a natural gas-electricity coupling system probabilistic optimal power flow model [2]. Wu et al proposes a day-ahead stochastic scheduling model in electricity markets. A chance-constrained stochastic programming formulation with economic and reliability metrics is presented for the day-ahead scheduling [3]. Some researches have been conducted for the DIHPS with high-penetration wind power [4].

In this paper, a stochastic expansion planning method of DIHPS based on chance-constraints is proposed. The paper considers the uncertainty of new energy and multi-energy load, using chance-constrained stochastic programming model and Monte Carlo simulation method to study the influence of uncertainty characteristics of DIHPS on expansion planning.

2. MODELING OF DIHPS

2.1 Model of Energy Network

District integrated heat and power system (DIHPS) consists of energy station, energy network, renewable energy and load. Energy network includes power distribution network and district heating network (DHN).The DHN model is divided into hydraulic model and thermodynamic model.

According to the Kirchhoff laws, the mass flow rate entering a heat node is equal to the mass flow rate leaving the heat node, and the sum of pressure losses around a closed loop must be equal to zero.

$$\begin{cases} Am = m_{\mathrm{q}} \\ Bh_{\mathrm{f}} = 0 \end{cases} \tag{1}$$

Where, A is heating network connection matrix, m is the mass flow in each pipe, m_{q} is the mass Flow of Each Node, B is the basic Loop Matrix, h_{f} is head loss.

The hydraulic model is solved by Newton-Raphson method to obtain the mass flow rate of the pipeline, which is provided to the thermodynamic model for

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calculation. The thermodynamic model is shown in the following Eq. (2).

$$\begin{cases}\phi = C_{\mathrm{p}} m_{\mathrm{q}}^{\mathrm{node}} (T_{\mathrm{s,load}} - T_{\mathrm{o,load}}) \\ C_{\mathrm{p}} (\sum m_{\mathrm{out}}) T_{\mathrm{out}} = C_{\mathrm{p}} \sum (m_{\mathrm{in}} T_{\mathrm{in}}) \\ T_{\mathrm{end}} = (T_{\mathrm{start}} - T_{\mathrm{a}}) \mathrm{e}^{\lambda L_{\mathrm{pipe}} / (C_{\mathrm{p}} m_{\mathrm{pipe}})} + T_{\mathrm{a}} \end{cases} \tag{2}$$

Where, ϕ is the thermal power of heat load node, C_{p} is the specific heat capacity of water, $m_{\mathrm{q}}^{\mathrm{node}}$ is the injecting mass flow into the node, $T_{\mathrm{s,load}}$ is load water supply temperature, $T_{\mathrm{o,load}}$ is load outlet temperature, T_{out} is mixing Temperature of nodes, m_{out} is the mass flow rate of outgoing nodes in pipeline, T_{in} is the temperature of water flow at the end of intake pipe, m_{in} is mass flow of inbound nodes in pipeline, T_{strart} and T_{end} is the temperature of pipeline start and end, T_{a} is ambient temperature, λ is the heat transfer coefficient of pipeline, L_{pipe} is pipeline length, m_{pipe} is the mass flow in pipeline.

Linear equations of water supply temperature and return water temperature can be obtained by Eq. (2) and solved by Newton-Raphson method.

For detailed model about the electric network, refer to previous study [5].

2.2 Uncertain Model of DIHPS

The uncertainty of DIHPS comes from two aspects, one is the energy supply side, the other is the load side.

2.1.1 Uncertainty of Energy Supply Side

Uncertainty on the DIHPS energy supply side is mainly about renewable energy, such as wind turbines and photovoltaics. The output of photovoltaic is related to the intensity of illumination. Beta distribution is often used to express the randomness of the intensity of illumination. The wind turbines output power is related to the wind speed, which obeys the Weibull distribution, and its uncertainty modeling is shown in [1].

2.1.2 Uncertainty of Energy Load Side

Some references show that for the same period of time in different periods, the electric and thermal load levels are generally normal distribution. However, due to the existence of maximum and minimum loads in reality, the normal distribution model with boundaries should be used to describe the uncertainty of electric and thermal loads.

If the forecasting value of electric load is P_0 and the actual value is P_{d}, the minimum and maximum loads in this period are $P_{\mathrm{d,min}}$ and $P_{\mathrm{d,max}}$, and P_{d} obey the normal distribution with standard deviation of σ_{d1}, then the probability density function (PDF) of the actual load P_{d} in the interval $[P_{\mathrm{d,min}}, P_{\mathrm{d,max}}]$ is as follows:

$$f_{\mathrm{d}}(P_{\mathrm{d}}) = \frac{\exp\left[-\dfrac{(P_{\mathrm{d}} - P_0)^2}{2\sigma_{\mathrm{d1}}^2}\right]}{\int_{P_{\mathrm{d,min}}}^{P_{\mathrm{d,max}}} \exp\left[-\dfrac{(P_{\mathrm{d}} - P_0)^2}{2\sigma_{\mathrm{d1}}^2}\right] \mathrm{d}P_{\mathrm{d}}} \tag{3}$$

For thermal load, the PDF of thermal load is similar to the electric load, because the uncertainty of thermal load is closely related to the temperature inside and outside, the thermal load should also satisfy the constraints of Eq. (4)-(7).

$$C \cdot \frac{dT_t^{in}}{dt} = P_t^{heat} - \lambda \cdot (T_t^{in} - T_t^{out}) \tag{4}$$

$$C \cdot (T_t^{in} - T_{t-1}^{in}) = P_t^{heat} - \lambda \cdot (T_t^{in} - T_t^{out}) \tag{5}$$

$$T_{\mathrm{min}}^{in} \le T^{in} \le T_{\mathrm{max}}^{in} \tag{6}$$

$$T_t^{in} - T_{t-1}^{in} \le \Delta T_{\mathrm{max}} \tag{7}$$

Where, P_t^{heat} is the heating power in t period, C is equivalent heat capacity of building aggregation model, T_t^{in} is the indoor average temperature in t period, T_t^{out} is the outdoor average temperature in t period, ΔT_{max} is the maximum temperature variation in t period, and λ is thermal conversion coefficient.

Uncertainty in the above model is sampled by Monte Carlo method.

2.3 Energy Station

In this paper, three common energy conversion devices widely used in the DHS as heat sources are considered. The energy station I is CHP unit, energy station II is heat pump and energy station III is gas boilers. For detailed model about the energy station, refer to previous study [4].

2.4 Objective Function

The objective is to minimize the daily operation cost and line/pipe expansion cost of the DIHPS, which is described in Eq. (8). The optimal variable is the output of energy station and expansion line/pipe type of DIHPS.

$$
\begin{aligned}
&\min C_{total} = C_{opt} + C_{upgrade\_Line} + C_{upgrade\_Pipe} \\
&C_{opt} = \sum_{t=1}^{N} (C_t^{N_{esI}} + C_t^{N_{esII}} + C_t^{N_{esIII}} + C_t^{loss}) \\
&C_t^{N_{esI}} = C_t^{g} \cdot P_t^{g,I} - C_t^{e} \cdot P_t^{e,I} \\
&C_t^{N_{esII}} = C_t^{e} \cdot P_t^{e,II} \\
&C_t^{N_{esIII}} = C_t^{g} \cdot P_t^{g,III}
\end{aligned}
\tag{8}
$$

The objective function includes the total operation cost C_{opt} and the expansion cost of line/pipeline $C_{upgrade}$. $C_t^{N_{esI}}$ is the operation cost of energy station I. C_t^{g} and C_t^{e} is the gas price and electric price during t period. $P_t^{g,I}$ is the total amount of natural gas purchased by energy station I in t period. C_t^{loss} is the network loss cost of DIHPS.

2.5 Constraint

The constraints in model include electric power, thermal power flow constraints, equipment output constraints and chance constraints.

The chance constraint in this paper is that the probability of power transmission in cable line and mass flow in thermal pipeline is less than its upper limit, which meets the confidence requirement. As shown in Eq. (9). Monte Carlo sampling method is used to test whether chance constraints are satisfied.

$$
\begin{cases}
\Pr\left\{S_i \le S_i^{\max}\right\} \ge \alpha \\
\Pr\left\{m_i \le m_i^{\max}\right\} \ge \alpha
\end{cases}
\tag{9}
$$

Where, the S_i and m_i is ith cable line power and pipeline mass flow, $S_i^{\max}$ and $m_i^{\max}$ is the maximum power and mass flow in ith cable line and pipeline, the α is confidence level.

3. CASE STUDY

The case study is based on a modified district integrated heat and power system as shown in Fig. 1 [4]. The expansion types of cable and pipe are shown in Table 1 and 2.

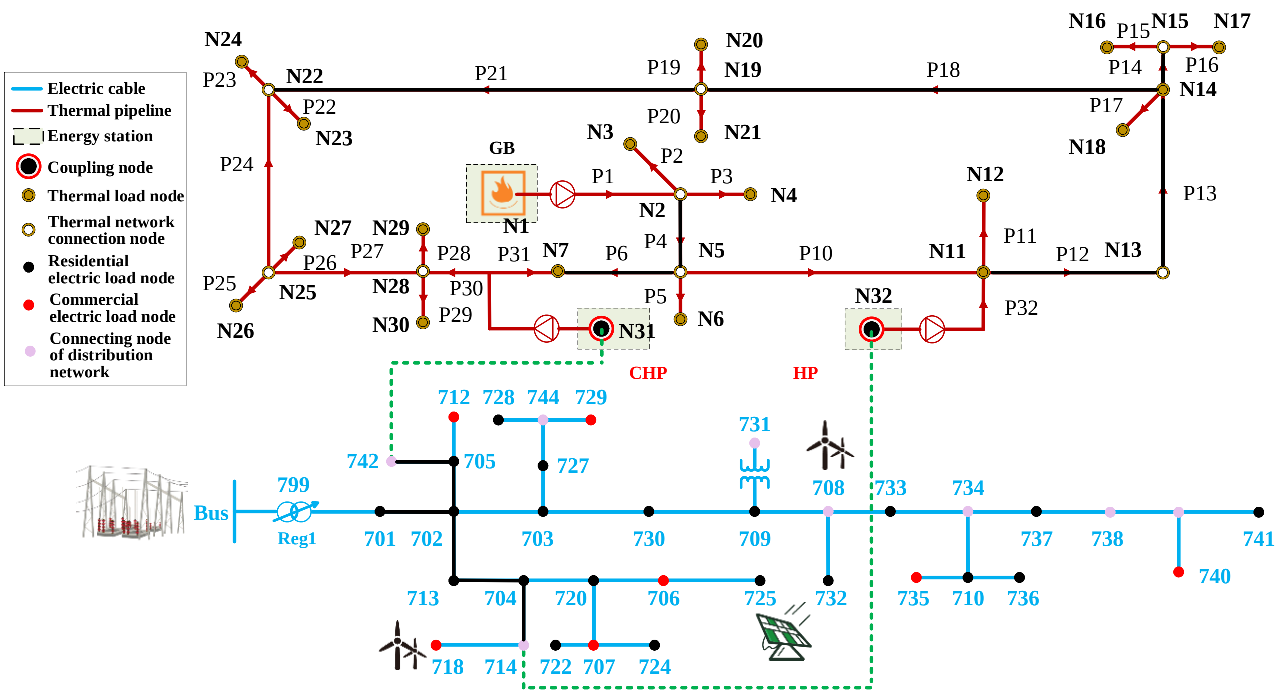

Fig 1 The modified district integrated heat and power system.

Table 1 The expansion types of electric cable

ID	Type	Line capacity (kVA)	Cost (10^3RMB/km)
1	LGJ-25	1114.86	1500
2	LGJ-35	1403.89	1800
3	LGJ-50	1816.81	2200
4	LGJ-70	2271.01	2500
5	LGJ-95	2766.51	3000
6	LGJ-120	3138.13	3300
7	LGJ-150	3674.91	3700
8	LGJ-185	4252.99	4000
9	LGJ-240	5037.52	4500
10	LGJ-300	5863.34	5200

Table 2 The expansion types of pipe

ID	Type	$m^{\max}$ (kg/s)	Cost (10^3RMB/km)
1	DN-20	0.126	2100
2	DN-25	0.295	2500
3	DN-32	0.482	2800
4	DN-40	1.005	3400
5	DN-50	1.571	4200
6	DN-65	2.655	5000

7	DN-80	5.027	6000
8	DN-100	9.425	7200
9	DN-125	14.726	8500
10	DN-150	24.740	10000

Table 3 Cable expansion scheme with α variation

From	702,	713,	701,	742,	705,	704,
To	713	704	702	705	702	714
α=1	5→8	5→8	9→10	1→2	1→2	2→4
cost	133.2	192.4	456.0	52.8	66.0	18.6
α=0.95	5→8	5→8	9→10	-	1→2	2→4
cost	133.2	192.4	456.0	0	66.0	18.6
α=0.87	5→7	5→7	9→10	-	-	2→4
cost	122.4	176.8	456.0	0	0	18.6
α=0.83	5→7	5→7	9→10	-	-	2→3
cost	122.4	176.8	456.0	0	0	16.6

Note: 5→8 means that the original cable is type 5 and the expanded cable is type 8; The unit of cost is 10^4 RMB.

Table 4 Pipe expansion scheme with α variation

Pipenum	4	10	12	13	18	32
α=1	7→9	7→9	7→9	7→9	6→9	8→9
cost	47.0	127.0	147.0	107.6	35.9	156.6
α=0.88	7→8	7→8	7→9	7→9	6→8	8→9
cost	39.3	106.1	147	107.6	30.1	156.6

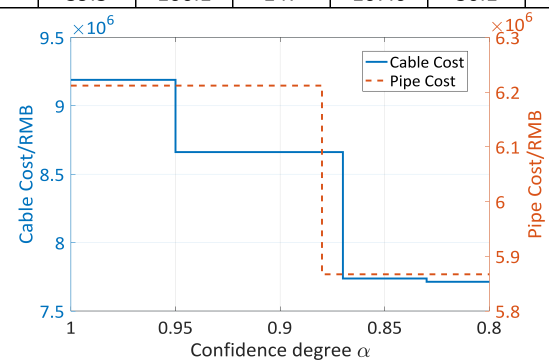

Fig 2 Cable and pipeline expansion cost

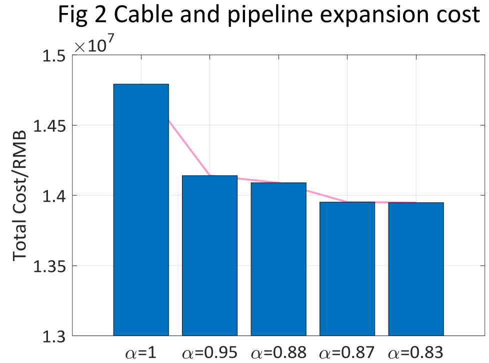

Fig 3 Total cost varies with confidence degree

As shown in Fig 3, whether considering the uncertainty of DIHPS has an impact on the total cost. As confidence degree decreases, the total cost tends to decrease. From Fig 2, we can see that the cost of expansion decreases stepwise with the decrease of confidence degree. The cost of cable line expansion planning changes at confidence degree equal to 0.95, 0.87 and 0.83 respectively, and the cost at 0.95 and 0.87 decreases significantly. This is because the optimized CHP feeding power of the energy station only occasionally exceeds the upper limit of the cable line. When the confidence decreases and the CHP output is optimized, the output of heat pump and gas boiler is increased, and the CHP output is slightly reduced. The constraints of 742-705 and 705-702 lines can be met, thus the cost can be reduced. Similarly, the variation of pipeline expansion cost occurs at confidence degree equal to 0.88.

For the stochastic energy network expansion planning proposed in this paper, it can be seen that with the decrease of confidence, the cost decreases in a step-by-step, and the probability of cable and pipe exceeding the limit will also increase, which will take more risks. Therefore, if we pay more attention to the economic cost, we can save more cost and benefit by choosing the scheme with confidence of 0.87. If we consider the security of energy network expansion planning more conservatively, choosing the scheme with confidence of 0.95 will give better consideration to the risk.

4. CONCLUSIONS

Considering the uncertainty of energy supply side and load side will reduce the expansion cost of cable line and pipeline after energy station access, and the cost of expansion will decrease stepwise with the decrease of confidence degree.

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REFERENCE

[1] Zou K , Agalgaonkar A P , Muttaqi K M , et al. Distribution System Planning With Incorporating DG Reactive Capability and System Uncertainties[J]. IEEE Transactions on Sustainable Energy, 2012, 3(1):112-123.

[2] Sun G , Chen S , Zhinong WEI…. Multi-period integrated natural gas and electric power system probabilistic optimal power flow incorporating power-to-gas units[J]. Journal of Modern Power Systems and Clean Energy, 2017, 5(3):412-423.

[3] Wu H , Shahidehpour M , Li Z , et al. Chance-Constrained Day-Ahead Scheduling in Stochastic Power System Operation[J]. IEEE Transactions on Power Systems, 2014, 29(4):1583-1591.
[4] Yunqiang Zhi, Dan Wang, Hongjie Jia, et al. Optimal Scheduling Strategy of District Integrated Heat and Power System with Multiple Energy Stations under Different Heating Regulation Modes[J]. Applied Energy, 2019, 240:341-358.
[5] Lin W , Jin X , Mu Y , et al. A two-stage multi-objective scheduling method for integrated community energy system[J]. Applied Energy, 2018, 216:428-441.