Station-grid Co-planning of Integrated Energy System with Consideration of Multi-energy storage and Reliability Cost

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Abstract. In order to improve the reliability of integrated energy system, the station-grid co-planning model and its solution method are proposed. The planning model considers the constraints of distribution network, gas distribution network, heat distribution network and energy station, and aims at minimizing the total planning cost within the planning period including investment cost, maintenance cost and reliability cost. It realizes the optimal planning for the types and locations of energy supply sources, distribution pipelines, energy stations and energy storage devices, such as electricity storage devices, gas storage devices, heat storage devices and cooling storage devices. The model is a mixed integer quadratic programming problem, which is solved by Gurobi. The case study uses the modified electricity-gas-heat integrated energy system to analyse the system planning scheme and planning cost under two scenarios. The results show that the proposed model can reasonably plan the integrated energy system and further improve the reliability of the integrated energy system.

1. Introduction

Under the background of global energy crisis and environmental pollution, integrated energy system is needed to improve energy efficiency and achieve low-carbon development. Power distribution network, gas distribution network and heat distribution network are coupled together though energy stations. In order to achieve high-reliability and security of integrated energy system, it is necessary to realize the station-grid co-planning of integrated energy system with consideration of multi-energy storage and reliability cost.

In recent years, there have been a series of basic researches on the planning of energy station of integrated energy system. Ref. [1] presented a framework in order to optimally design and size interconnected energy hubs, determining which components should be allocated to each hub and in what capacity. Ref. [2] established an optimal planning model for energy station location and pipe network path layout based on the p-median model. Under the target of the lowest total cost of investment and operation, the optimal capacity of combined heat and power, electric boiler, refrigerator and other equipment in the energy station is planned in ref. [3]. Furthermore, scholars at home and abroad have carried out relevant researches on the grid planning of integrated energy system. Ref. [4] established an integrated energy system optimal allocation model that can be realized from the beginning. In ref. [5], an integrated energy system planning model is proposed to obtain the optimal structure configuration and energy management strategy. In ref. [6], a capacity allocation planning model for grid-connected integrated energy system is proposed, which considers both price demand.
response and incentive demand response. In addition, some scholars have studied the reliability assessment of integrated energy system. In order to meet the requirements of high penetration renewable energy access, Ref. [7] proposed an energy hub planning method aiming at optimal reliability. In Ref. [8-9], the N-1 reliability check result is regarded as a penalty term to influence the planning result of regional integrated energy system. But there are few researches on station-grid co-planning of integrated energy system considering multi-energy storage and reliability cost.

Therefore, this paper establishes the station-grid co-planning model of integrated energy system. The main contributions of this paper are as follows:

• The station-grid co-planning model of integrated energy system can improve the reliability of integrated energy system by considering the reliability cost.

• With consideration of multi-energy storage devices, such as electricity storage devices, gas storage devices, heat storage devices and cooling storage devices, the station-grid co-planning model of integrated energy system can decrease the planning cost of integrated energy system.

The remainder of the paper is organized as follows. Section 2 introduces the station-grid co-planning model and its solution method of integrated energy system. Section 3 uses the modified case of electricity-gas-heat integrated energy system to analyse the system planning scheme and planning cost under two scenarios. Finally, conclusions are drawn in section 4.

2. Planning model of integrated energy system

Integrated energy system includes power distribution network (PDN), gas distribution network (GDN), heat distribution network (HDN) and energy station (ES). Among them, PDN includes distribution substations, power distribution lines, photovoltaics (PVs), wind turbines (WTs) and electricity loads; GDN includes gas distribution stations, gas distribution pipelines, and gas loads; and HDN includes heat distribution stations, heat distribution pipelines, and heat loads. There are five kinds of energy conversion devices in ES, including power to gas (P2G), combined heat and power (CHP), gas boiler (GB), electrical chiller (EC) and absorption chiller (AC). Furthermore, there are four kinds of energy conversion devices of integrated energy system, such as electricity storage devices, gas storage devices, heat storage devices and cooling storage devices.

2.1. Objective Function

The planning objective function of the integrated energy system is to minimize the total cost within the planning period, as

\[
\min C_{TOTAL} = C_I + C_M + C_R
\]

\[
C_I = \sum_{y} D_y \left( \sum_{s \in \Omega_s} c_{I,s} x_{s,y} + \sum_{m \in \Omega_c} c_{I,m} C_m \left( x_{m,y} - x_{m,y-1} \right) + \sum_{k \in \Omega_k} c_{I,k} L_k \left( x_{k,y} - x_{k,y-1} \right) \right)
\]

\[
C_M = \sum_{y} D_y \left( \sum_{s \in \Omega_s} c_{M,s} x_{s,y} + \sum_{m \in \Omega_c} c_{M,m} C_m x_{m,y} + \sum_{k \in \Omega_k} c_{M,k} L_k x_{k,y} \right)
\]

\[
C_R = \sum_{y} D_y \sum_s \sum_{f \in \Omega_f} \left( \sum_{l \in \Omega_l} c^s_{I,l} P_{I,l}^f + \sum_{l \in \Omega_l} c^s_{I,l} P_{I,l}^f + \sum_{l \in \Omega_l} c^s_{I,l} P_{I,l}^f + \sum_{l \in \Omega_l} c^s_{I,l} P_{I,l}^f \right)
\]

where, \( C_I \) is the investment cost; \( C_M \) is the maintenance cost; \( C_R \) is the reliability cost. \( y \) represents year \( y \) of the planning. \( D_y = 1/(1+d)^{y-1} \) is net present value coefficient. \( d \) is the discount rate. \( \Omega_s, \Omega_c, \Omega_k \) and \( \Omega_e \) are a collection of candidate sets of energy sources, energy conversion devices, energy storage devices and energy distribution pipelines, respectively. \( c_{I,s}, c_{I,m}, c_{I,k} \) and \( c_{I,k} \) are the investment cost of
per unit capacity energy distribution sources, energy conversion devices, energy storage devices and per unit length energy distribution pipelines, respectively. \( C_s, C_n \) and \( C_c \) are new-built capacity of devices and \( l_n \) is the new-built length of devices. \( x_{m,y}, y_{m,y}, x_{n,y} \) and \( x_{k,y} \) are whether the \( s \)-type energy distribution source, \( m \)-type energy conversion device, \( n \)-type energy storage device and \( k \)-type energy distribution pipeline exist in the \( y \)-year, respectively. If they exist, take 1; if they don't exist, take 0. \( C_{M,s}, C_{M,m}, C_{M,n} \) and \( C_{M,k} \) are the maintenance cost of per unit capacity \( s \)-type energy distribution source, \( m \)-type energy conversion device, \( n \)-type energy storage device and per unit length \( n \)-type pipeline, respectively. \( i_e, i_g, i_h \) and \( i_c \) are the numbers of the electricity, gas, heat and cooling load node, respectively. \( c_{ij}, c_{ij}^f, c_{ij}^g \) and \( c_{ij}^h \) are the energy interruption cost of per unit electricity, gas, heat and cooling load, respectively. \( P_{ij}^e, P_{ij}^g, P_{ij}^h \) and \( P_{ij}^c \) are the short supply of electricity, gas, heat and cooling load.

2.2. Constraints

2.2.1. Constraints related to power distribution network

\[
P_{PV,i}^e + P_{WT,i}^e + P_{net,i}^e + P_{dis,i}^e = P_{cha,i}^e + L_i^e
\]
(5)

\[
Q_{PV,i}^e + Q_{WT,i}^e + Q_{net,i}^e + Q_{dis,i}^e = Q_{cha,i}^e + L_i^e
\]
(6)

\[
P_{G,i}^{min} \leq P_{G,i}^e \leq P_{G,i}^{max}
\]
(7)

\[
-P_{ij}^{max} \leq P_{ij}^e \leq P_{ij}^{max}
\]
(8)

\[
0 \leq P_{ij}^e \leq \lambda_{ij}^{e,max} L_i^e
\]
(9)

where, equation (5)-(6) are the node power balance constraints of power distribution network. \( P_{PV,i}^e \) and \( P_{WT,i}^e \) are the active power from photovoltaic and wind power. \( P_{ij}^e \) is the active load reduction for the nodes of power distribution network. \( L_i^e \) is the active node load of power distribution network. \( Q_{PV,i}^e \) and \( Q_{WT,i}^e \) are the reactive power from PV and wind power. \( Q_{net,i}^e \) is the reactive power exchanged between power distribution network node and external network. \( Q_{ij}^e \) is the reactive load reduction for the nodes of power distribution network. \( Q_{ij}^e \) is the reactive node load of power distribution network. Equation (7) is the output of generator unit constraints. \( P_{G,i}^{max} \) and \( P_{G,i}^{min} \) are the upper and lower limits of the generator output in node \( i \), respectively. Equation (8) is the transmission power of branch constraints. \( P_{ij}^{max} \) is the maximum transmission power of branch \( ij \). Equation (9) is the electricity load reduction constraint. \( \lambda_{ij}^{e,max} \) is the maximum reduction ratio of electricity. \( P_{cha,i}^e \) and \( P_{dis,i}^e \) are the storing and releasing electricity power of electricity storage device at time \( t \), respectively.

2.2.2. Constraints related to gas distribution network

\[
P_{net,i}^g + P_{L,i}^g = P_{cha,i}^g + L_i^g
\]
(10)

\[
P_{W,i}^{min} \leq P_{W,i}^g \leq P_{W,i}^{max}
\]
(11)

\[
V_{ij}^{min} \leq V_{ij}^g \leq V_{ij}^{max}
\]
(12)

\[
0 \leq P_{ij}^g \leq \lambda_{ij}^{g,max} L_i^g
\]
(13)
where, equation (10) is the node power balance constraints of gas distribution network. \( P^h_{i,t} \) is the load reduction for the nodes of gas distribution network. \( L^h_i \) is the node load of gas distribution network. Equation (11) is the output of gas well constraints. \( P^\text{max}_{W,i} \) and \( P^\text{min}_{W,i} \) are the upper and lower limits of the gas well output in node \( i \), respectively. Equation (12) is the pipeline flow constraints. \( V^h_{ij} \) is the flow rate of distribution pipeline \( ij \). \( V^\text{max}_{ij} \) and \( V^\text{min}_{ij} \) are the upper and lower limits of the flow rate of distribution pipeline \( ij \), respectively. Equation (13) is the gas load reduction constraint. \( \lambda_{i}^{g,\text{max}} \) is the maximum reduction ratio of gas load. \( P^g_{\text{cha},i,t} \) and \( P^g_{\text{dis},i,t} \) are the storing and releasing gas power of gas storage device at time \( t \), respectively.

2.2.3. Constraints related to heat distribution network

\[
P^h_{\text{net},i,t} + P^l_{i,t} + P^h_{\text{dis},i,t} = P^h_{\text{cha},i,t} + L^h_i \tag{14}
\]

\[
P^\text{min}_{S,i} \leq P^l_{i,t} \leq P^\text{max}_{S,i} \tag{15}
\]

\[
P^h_{ij,\text{min}} \leq P^h_{ij,t} \leq P^h_{ij,\text{max}} \tag{16}
\]

\[
0 \leq P^h_{ij,t} \leq \lambda^h_{i} \max L^h_i \tag{17}
\]

where, equation (14) is the node power balance constraints of heat distribution network. \( P^h_{i,t} \) is the load reduction for the nodes of heat distribution network. \( L^h_i \) is the node load of heat distribution network. Equation (15) is the output of heat source constraints. \( P^\text{max}_{S,i} \) and \( P^\text{min}_{S,i} \) are the upper and lower output limits of heat source at node \( i \), respectively. Equation (16) is the pipeline transmission heat power constraints. \( P^h_{ij,\text{min}} \) and \( P^h_{ij,\text{max}} \) are the minimum and maximum available heat power that can be transmitted by the heat distribution pipelines, respectively. Equation (17) is the heat load reduction constraint. \( \lambda^h_{i} \max \) is the maximum reduction ratio of heat load. \( P^h_{\text{cha},i,t} \) and \( P^h_{\text{dis},i,t} \) are the storing and releasing heat power of heat storage device at time \( t \), respectively.

2.2.4. Constraints related to energy station

\[
\eta^h_{\text{CHP}} P^h_{\text{CHP},i,t} + P^\text{net}_{i,t} + P^l_{i,t} + P^h_{\text{dis},i,t} = P^h_{\text{cha},i,t} + P^h_{\text{F2G},i,t} + P^h_{\text{EC},i,t} + L^h_i \tag{18}
\]

\[
\eta^h_{\text{F2G}} P^h_{\text{F2G},i,t} + P^\text{net}_{i,t} + P^l_{i,t} + P^h_{\text{dis},i,t} = P^g_{\text{cha},i,t} + P^h_{\text{F2G},i,t} + P^g_{\text{CHP},i,t} + P^g_{\text{GB},i,t} + L^h_i \tag{19}
\]

\[
\eta^h_{\text{CHP}} P^h_{\text{CHP},i,t} + \eta^g_{\text{CHP}} P^g_{\text{GB},i,t} + P^\text{net}_{i,t} + P^l_{i,t} + P^h_{\text{dis},i,t} = P^h_{\text{cha},i,t} + P^h_{\text{AC},i,t} + L^h_i \tag{20}
\]

\[
\eta^h_{\text{AC}} P^h_{\text{AC},i,t} + \eta^g_{\text{AC}} P^g_{\text{EC},i,t} + P^\text{net}_{i,t} + P^l_{i,t} + P^h_{\text{dis},i,t} = P^g_{\text{cha},i,t} + L^h_i \tag{21}
\]

\[
\chi_i C^\text{min}_i \leq C_i \leq \chi_i C^\text{max}_i \tag{22}
\]

\[
0 \leq P^h_{i,t} \leq \lambda^h_{i} \max L^h_i \tag{23}
\]

where, equation (18)-(21) are the electricity, gas, heat and cooling power balance constraints of energy station. \( P^h_{i,t} \) is the cooling load reduction. \( L^h_i \) is the cooling load. Equation (22) is the devices capacity constraints. Equation (23) is the cooling load reduction constraint. \( \lambda^h_{i} \max \) is the maximum reduction ratio of cooling load. \( P^h_{\text{cha},i,t} \) and \( P^h_{\text{dis},i,t} \) are the storing and releasing cooling power of cooling storage device at time \( t \), respectively.
2.2.5. Constraints related to multi-energy storage

\[ E_t^\kappa = E_{t-1}^\kappa + \left( P_{cha,t}^\kappa \eta_{cha} + P_{dis,t}^\kappa \eta_{dis} \right) \Delta t \]  \hspace{1cm} (24)

\[ 0 \leq P_{cha,t}^\kappa \leq P_{cha,max}^\kappa \] \hspace{1cm} (25)

\[ 0 \leq P_{dis,t}^\kappa \leq P_{dis,max}^\kappa \] \hspace{1cm} (26)

\[ E_{min}^\kappa \leq E_t^\kappa \leq E_{max}^\kappa \] \hspace{1cm} (27)

\[ E_0^\kappa = E_{24}^\kappa \] \hspace{1cm} (28)

where, \( \kappa \) is the type of energy storage devices, including electricity storage devices, gas storage devices, heat storage devices and cooling storage devices. \( P_{cha,t}^\kappa \) and \( P_{dis,t}^\kappa \) are the storing and releasing power of energy storage devices at time \( t \), respectively. \( \eta_{cha} \) and \( \eta_{dis} \) are the storing and releasing efficiency of energy storage devices at time \( t \), respectively. \( P_{cha,max}^\kappa \) and \( P_{dis,max}^\kappa \) are the maximum storing and releasing power of energy storage devices, respectively. \( E_{min}^\kappa \) and \( E_{max}^\kappa \) are the upper and lower capacity bounds of energy storage devices, respectively.

2.2.6. Constraints related to state variables

\[ x_{c,y,t} \leq x_{c,y} \] \hspace{1cm} (29)

where, the equation (29) indicates once the candidate devices and pipelines are installed, they won’t be removed in the future.

2.3. Solution Method

There are lots of nonlinear terms of multiplication of two variables in the planning model of integrated energy system. In order to solve the problem conveniently, real auxiliary variables are introduced into the model and the original mixed integer nonlinear programming model is transformed into the mixed integer quadratic programming model. The mixed integer quadratic programming model in this paper is solved by using Gurobi.

3. Case Study

In order to solve the planning model of integrated energy system, an improved ease of integrated energy system is established, which includes 54-node power distribution system, 50-node gas distribution system, 38-node heat distribution system and 3 energy stations. Energy station 1 connects the electricity node 6, the gas node 30 and the heat node 10. Energy station 2 connects the electricity node 16, the gas node 3 and the heat node 3. Energy station 3 connects the electricity node 31, the gas node 50 and the heat node 35. Electricity storage devices and cooling storage devices are installed inside the energy station. Gas storage devices are installed at gas node 17, 21 and 49. Heat storage devices are installed at heat node 1, 14 and 27. The total planning period is 10 years, which is divided into two stages, and each of which is 5 years. The data of integrated energy system can be found in Ref. [10-12]. This paper considers the following 2 scenarios and compares their planning results. Scenario 1 realizes the station-grid co-planning of integrated energy system based on three energy stations composed of five energy conversion devices. Scenario 2 adds multi-energy storage devices based on scenario 1. The planning schemes and planning cost are shown in table 1-2 and figure 1-2.
Table 1. Planning Cost of Scenario 1-2 (MUSD)

| Scenario | Stage | Investment Cost | Maintenance Cost | Reliability Cost | Total Cost |
|----------|-------|-----------------|------------------|-----------------|------------|
| Scenario 1 | Stage 1 | 17.65 | 12.61 | 0 | 79.48 |
| Scenario 1 | Stage 2 | 17.74 | 18.75 | 12.73 | 61.64 |
| Scenario 2 | Stage 1 | 15.46 | 11.56 | 0 | 55.12 |
| Scenario 2 | Stage 2 | 17.04 | 17.57 | 0 | 81.64 |

Figure 1. The Planning Scheme of Scenario 1

Figure 2. The Planning Scheme of Scenario 2
Table 2. Planning Schemes of Energy stations of Scenario 1-2

| Scenario   | Stage | P2G | CHP   | GB   | EC   | AC   |
|------------|-------|-----|-------|------|------|------|
|            | Stage 1 | /   | /     | EH1(0) | EH2(0) | /   |
| Scenario 1 | Stage 2 | EH1(2) | EH2(1) | EH3(1) | EH3(1) | EH2(2) |
|            | Stage 1 | /   | /     | EH1(0) | EH2(0) | /   |
| Scenario 2 | Stage 2 | /   | /     | /     | EH3(1) | EH2(2) |

Comparing scenario 1 and scenario 2, it can be seen that after installing energy storage devices, 22 power source of the distribution network is replaced by a power source with smaller generation capacity, and many distribution electricity/gas/heat pipelines are also replaced by pipelines with smaller capacity, and some new pipelines are removed. The kinds of devices inside energy station are decrease. Comparing the planning cost of scenario 1 and scenario 2, it can be seen that due to the influence of replacing pipelines/power sources and removing pipelines, the investment cost and maintenance cost in the planning decrease slightly, and the reliability cost greatly reduced. Above all, the change of the planning scheme and the decrease of the total planning cost can show that the installation of energy storage devices can improve the reliability of integrated energy system.

4. Conclusions
This paper proposes the station-grid co-planning model of integrated energy system to realize the optimal planning for the types and locations of energy supply sources, distribution pipelines, energy stations and energy storage devices, aiming at minimizing the total planning cost within the planning period including investment cost, maintenance cost and reliability cost. The planning model is a mixed integer quadratic programming problem and is solved by Gurobi. The case study uses the modified electricity-gas-heat integrated energy system to analyse the system planning scheme and planning cost under two scenarios. The simulation results lead to some conclusions as follows:

1) The proposed model can reasonably plan the integrated energy system, realizing the optimal planning for the types and locations of energy stations and grids.

2) The installation of energy storage device can not only decrease the investment cost and maintenance cost, but also greatly reduce the reliability cost and improve the reliability of the integrated energy system.

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References
[1] Salimi, M., Ghasemi, H., Adelpour, M., et al. (2015) Optimal planning of energy hubs in interconnected energy systems: a case study for natural gas and electricity. IET Gener. Transm. Dis., 9: 695–707.
[2] Yi, W.F., Yu, Y.Z., Zhang, Y.W., et al. (2019) P-median model based optimal planning of energy station for regional integrated energy systems. Autom. of Electr. Power Syst., 43: 154–160.
[3] Sheikhi, A., Rayati, M., Ranjbar, A.M. (2015) Energy hub optimal sizing in the smart grid: machine learning approach. In: Innovative Smart Grid Technologies Conference. Denver. pp. 1-5.
[4] Wang, Y., Zhang, N., Zhuo, Z.Y., et al. (2018) Mixed-integer linear programming-based optimal configuration planning for energy hub: Starting from scratch. Appl. Energy, 210: 1141–1150.
[5] Ma, T.F., Wu, J.Y., Hao, L.L., et al. (2018) The optimal structure planning and energy management strategies of smart multi energy system. Energy, 160: 122–141.

[6] Xiang, Y., Cai, H.H., Gu, C.H., et al. (2020) Cost-benefit analysis of integrated energy system planning considering demand response. Energy, 192: 116632.

[7] Xu, X.D., Hou, K., Jia, H.J., et al. (2015) A reliability assessment approach for the urban energy system and its application in energy hub planning. In: IEEE Power and Energy Society General Meeting. Denver. pp. 1-5.

[8] Hu, Y., Bie, Z.H., Ding, T., et al. (2016) An NSGA-II based multi-objective optimization for combined gas and electricity network expansion planning. Appl. Energy, 167: 280–293.

[9] Barati, F., Seifi, H., Sepasian, M.S., et al. (2015) Multi-Period Integrated Framework of Generation, Transmission, and Natural Gas Grid Expansion Planning for Large-Scale Systems. IEEE T. Power Syst., 30: 2527–2537.

[10] Saldarriaga, C.A., Hincapie, R.A., Salazar H. (2013) A holistic approach for planning natural gas and electricity distribution networks. IEEE T. Power Syst., 28: 4052–4063.

[11] Yildirim, N., Toksoy, M., Gokcen, G. (2010) Piping network design of geothermal district heating systems: Case study for a university campus. Energy, 35: 3256–3262.

[12] Zhou, X.Z., Guo, C.X., Dong, S.F., et al. (2019) Expansion planning of urban multi-energy electricity-gas-heating distribution network incorporating electrical reconfiguration. Autom. of Electr. Power Syst., 43: 23–33.