Optimal Energy Dispatch of the Energy Hubs Considering Off-design Characteristics of Generation Units

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Abstract. This paper proposes the off-design mathematical model of generation units for the optimal energy dispatch of the energy hubs (EHs). EHs are usually operated under off-design condition as the widely fluctuating energy demands of residence. In order to investigate the impacts of the off-design characteristics on the operation strategy of EHs, we test the off-design model in the integrated energy system with three EHs. The simulation result shows that ignoring the off-design characteristics of EHs may lead to the inaccurate result of the optimal energy dispatch of EHs.

1. Introduction
With the increasing seriously environmental pollution problems, researchers are attention to the development and utilization of multiple energy systems [1, 2, 3]. Energy hub (EH) is acted as an interconnection point between various energy systems [4, 5]. The conversion of power between different EHs establishes a coupling of the corresponding energy flow resulting in system interactions. As shown in Figure 1, we establish the energy conversion topology considering various kinds of renewable and non-renewable energy resources including coal, gas, oil, wind and solar, which is mainly focused on the energy conversion efficiency through different energy generation technologies. Electricity is not the only energy carrier in the modern system, heating and cooling technologies are also taken into consideration in this topology [6].

It is worth mentioning that a suitable simulation model is a key factor in improving the performance of the EH in regard to reducing energy cost. EHs have been mostly served as combined heating and power (CHP) systems in the integrated energy systems, as the EH is commonly applied to the end users directly [7, 8]. As we know, the efficiencies of equipments have a great impact on the simulation models, but the design model of equipments in the EH is used more widely than the off-design model owing to the superiority of computation, which may lead to the reduction of accuracy of the operation strategy. In this paper, we present the off-design model of equipments for the optimal operation of the EHs with the target of minimizing the daily operation cost. In order to investigate the impacts of the off-design characteristics on the operation strategy, we have tested the off-design model in the integrated energy system with three EHs.

In the following Section, Section 2 presents a general energy hub model considering the off-design characteristics of generation units. The optimal energy dispatch problem as well as some constraints is
introduced in Section 3. Section 4 compares the difference of operation strategy of the EHs for the off-design model. Finally, Section 5 draws the conclusions.

Figure 1. The topology of energy conversion efficiency

2. Mathematical model

In this section, the mathematical models of the equipments in the energy hub are provided, which is shown in Figure 2. It is worth mentioning that the equipments performance curves are obtained from related documents. The detail depiction of the general form of the models are presented in the following.

Microturbine (GT) is generally used in power generation unit for simultaneous production of electricity and recoverable heat. As far as the off-design characteristics are concerned, the GT performance based on the off-design characteristics are in the form of the relations between the electric input $P_{MT}$ and thermal output $Q_{MT}$ as well as that between the gas consumption $P_{NG}$ and thermal output $Q_{MT}$:

\[
P_{MT} (t) = K_1 Q_{MT}^2 (t) + K_2 Q_{MT} (t) + K_3
\]

\[
P_{NG} (t) = K_4 Q_{MT}^2 (t) + K_5 Q_{MT} (t) + K_6
\]

Where $P_{NG}$ is the gas consumption power of GT. $P_{GT}$ refers to the electric input. $K_1$ to $K_6$ are assumed to be fixed values.
Due to the part load-ratio characteristic of gas-fired boiler and heat exchanger (HE) is unremarkable, a fixed thermal efficiency is used:

\[
\eta_{\text{GBN}} = \eta_{\text{HEN}} = \frac{P_{\text{HEout}}(t)}{P_{\text{HEin}}(t)} = \frac{P_{\text{GBout}}(t)}{P_{\text{GBin}}(t)}
\]

(3)

Where \( \eta_{\text{GBN}} \) and \( \eta_{\text{HEN}} \) denote the efficiencies of the gas-boiler and the heat exchanger, respectively.

3. Optimal energy dispatch

3.1. Objective

In this paper, the objective function is the minimization of total operation cost for the energy hubs, which is presented as follows:

\[
C_{\text{op}} = \sum_{i=1}^{24} C_{\text{NG}} (P_{\text{NG}}(t) + P_{\text{GBin}}(t)) + C_{\text{E}} P_{\text{E}}(t) + C_{\text{H}} P_{\text{HEin}}(t)
\]

(4)

Where \( C_{\text{op}} \) refers to the total operation cost related to the EHs, \( C_{\text{NG}}, C_{\text{E}}, C_{\text{H}} \) are the energy price of natural gas, electricity and heat exchanger, respectively.

3.2. Constraints

The energy balance constraint is as follows:

\[
P_{\text{MT}} + P_{\text{E}} = L_{\text{E}}
\]

(5)

\[
Q_{\text{MT}}(t) + P_{\text{HEout}}(t) = L_{\text{H}}
\]

(6)

3.3. Solution method

The aforementioned formulation results in a mixed integer nonlinear programming (MINLP) model, because the equipment performance characteristics will introduce nonlinear terms into the optimization problem. The proposed MINLP problem is solved on the platform of Matlab with SCIP as the solver, which is capable of efficiently solving linear and nonlinear optimization problems that contain a large number of variables.

4. Example

Consider the system in Figure 3 consisting of three equal hubs as shown in Figure 2, each of them equipped with a microturbine, a gas boiler and a heat exchanger. The electricity network, heat network and natural gas network are connected by the EHs. This 3-hub system exchanges power with adjacent systems via slack node.
In this optimization model, $K_i$ to $K_6$ of the microturbine is -0.00004, 1.0585, -1448, 0.000001, 1.7751, 1474, respectively. The energy prices are assumed fixed for all carriers, which is presented in Table 1. The load demand are assumed to be the same for all the EHs, which are shown in Figure 4.

Table 1. Assumed energy prices.

| Energy carrier | p.u. |
|----------------|------|
| electricity    | 0.6  |
| natural gas    | 3.5  |
| district heat  | 4    |

To evaluate the effects of simulation model of EHs on the optimal operation strategy, the optimal operation based on the off-design models are presented in the form of diagram as shown in Figures 5, 6, 7. As shown in Figure 5, hub 1 is directly connected to the slack node 1 and the input of natural gas is empty, it’s optimal supply is independent of the network and the consumption of the other hubs. As the input of natural gas is empty all over the day, and the electricity can only be supplied by the power grid, the input power of electricity of hub 1 is little higher than that of hub 2 and hub 3. This is due to the fact that the microturbine can product electricity and heat at the same time.
The optimal operation strategy of hubs 2 and 3 are pictured in Figure 6-7. We can see that in the different hubs, optimal energy dispatch is due to the location of the energy system. Focusing on electricity balance, it should be noted that MT and HE are switched on all the day. Before 9am, the input power of electricity, heat and natural gas is all the same, while after 9 am, the optimal result of hub 2 and hub 3 is quite different with the increasing energy demand. At 9 pm, there is the largest heating and electricity demand, and the electricity demand is supplied by power grid. At the same time, the input of natural gas of hub 3 is lower than hub 2, this is due to the higher efficiency of MT in hub3 than the efficiency of MT in hub 2. Hence, the less input natural gas is needed. We can see from the Figure 6 and Figure 7 that the off-design model is important of the EH for the optimal energy dispatch.

5. Conclusion
In this paper, we have proposed the off-design model of an energy hub for the optimal energy dispatch with the target of minimizing the optimal operation cost. Thereafter, a simulation case has been carried out to investigate the impact the of off-design characteristics on the optimal operation strategy of the EHs. As for the optimal operation strategy, the off-design model is more reasonable than the constant efficiency model to meet the fluctuating energy demands in the integrated energy system. In summary, we should not simply use the constant efficiency model for the optimal operation of the EHs, especially when the energy demands of the users are widely fluctuating.
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