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Optimal multi-time scale coordination method for electricity-heating integrated energy system scheduling

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Abstract. Considering that different energy subsystems have different control characteristics in equipment operations, an optimal multi-time scale coordination method for electricity-heating integrated system scheduling is proposed. It merges three optimal scheduling models based on three-time scales of day-ahead, rolling, and real-time. The coordinated optimization of electricity and heating energies with the same dispatch instruction is fulfilled in day-ahead scheduling. And all feasible scheduling instruction cycles are traversed in the rolling stage to improve the stability of system economic operation. The calculation examples show that the proposed overall strategy for multi-time scale scheduling can achieve multi-energy complementarity, and the optimization results have less deviation from the actual load.

1. Introduction

With the ever-increasing social energy demand, energy shortage and environmental pollution problems have become increasingly apparent. The construction of a multi-energy complementary integrated energy system(IES) can achieve the efficient and clean use of multi-energy, which is an inevitable choice for the development of the energy field[1-2]. However, there are significant differences in the control characteristics of the equipment in the various subsystems in the IES[3], coupled with the inaccuracy of renewable energy and load forecasting, making the system scheduling more difficult[4].

The existing researches on IES mainly focus on the schedule from the perspective of multi-time scale operation. A combined multi-time scale scheduling model of cooling, heating, and power microgrid is established in reference [5], which has good flexibility and economy; Reference [6] introduces hydropower into the IES and dispatches the wind-water-heat integrated power system. When the above-mentioned documents perform multi-time scale scheduling, the scheduling period of each subsystem in the same scheduling stage is usually the same, and the difference in the dynamic time scale of each subsystem is not taken into consideration.

Reference [7] uses the model resolution matching the dynamic process of gas and heating networks to describe the dynamic process of energy flow. Considering the thermal inertia characteristics of heat network transmission into the multi-time scale strategy, reference [8] modifies the model with delay. However, the devices' response characteristics in each subsystem to the scheduling instructions and their roles in optimizing scheduling are different [9], which also affects the safety and economy of the overall operation of the system.

Because of the shortcomings of the references mentioned above, a coordinated optimal multi-time scale scheduling model is established. It considers the adjustment characteristics of various types of equipment in various energy systems and the ability to operate under variable conditions and is suitable for the complementary operation characteristics of multi-energy interconnection.

2. Optimal multi-time scale optimal scheduling model

2.1. Overall strategy

Different subsystems adopt different operation optimization strategies during the scheduling according to the length of the dynamic time scale. The power system's dynamic time scale is short, and the three-stage dispatch model on time scales of day-ahead, rolling, and real-time is implemented. The thermal system has a relatively long dynamic time scale, and it is advisable to implement day-ahead scheduling model and rolling scheduling model.

Devices with different operating characteristics adopt different scheduling instruction cycles in each scheduling stage. Energy stations are usually equipped with energy production equipment, such as thermal power units (TH), gas turbines (GT), gas boilers (GB), wind power (WT); energy conversion equipment, such as CHP; energy storage equipment, such as electrical energy storage (EES), thermal energy storage (TES). Their adjustment characteristics, variable-condition operation capabilities, and roles in optimal scheduling are different. Even in the same scheduling stage, the scheduling period of each device is also different. Therefore, for devices with different control characteristics, it is necessary to determine each subsystem's optimal scheduling instruction cycle to achieve coordinated operation among multi-energy subsystems.

2.2. The day-ahead optimal scheduling model

2.2.1. Objective function. The day-ahead scheduling is based on the minimum cost of schedule as the objective function to formulate the next day scheduling optimization results.

$$\min F=\sum_{t=1}^{T}(\sum_{n=1}^{N_1}F_{TH}^{t,n}+\sum_{n=1}^{N_2}F_{CHP}^{t,n}+\sum_{n=1}^{N_3}F_{GT}^{t,n}+\sum_{n=1}^{N_4}F_{GB}^{t,n}+F_{grid}^{t})\Delta t \tag{1}$$

where F is the total cost of the system; T is the cycle of day-ahead scheduled scheduling for 24h; $F_{TH}^{t,n}$ is the generation cost of the Nth thermal power unit at time t; $F_{CHP}^{t,n}$ is the operating cost of the Nth CHP unit at t; $F_{GT}^{t,n}$ is the generation cost of the Nth gas turbine at t; $F_{GB}^{t,n}$ is the heat production cost of the Nth gas boiler at t; F_{grid}^{t} is the electricity purchase and sale cost at t. Electricity purchase and sale cost are as follows:

$$F_{grid}^{t}=p_t^{buy}\pi_t^{buy}-p_t^{sell}\pi_t^{sell} \tag{2}$$

where p_t^{buy} and p_t^{sell} are respectively the purchasing power and selling power of the energy station and the superior power grid at t; π_t^{buy} and π_t^{sell} are respectively the purchasing power and selling power at t.

2.2.2 Constrains. The day-ahead optimization model needs to satisfy the constraints of equipment model, system energy balance, power purchase and sale, and energy storage devices. The electrical and thermal energy supply and demand balance equation are as follows:

$$l_{dt}^{e} = p_{t,th} + p_{t,gt} + p_{t,wt} + p_{t,chp} + (p_{t,ess}^{disc} - p_{t,ess}^{ch}) + (p_{t}^{buy} - p_{t}^{sell}) \tag{3}$$

$$l_{dt}^{h} = h_{t,gb} + h_{t,chp} + (h_{t,tes}^{disc} - h_{t,tes}^{ch}) \tag{4}$$

where l_{dt}^{e} and l_{dt}^{h} are respectively the electrical and thermal loads of the energy station at t; $p_{t,j}$ and $h_{t,j}$ are respectively the electrical and thermal power produced or consumed by equipment i at t; Subscript j ={TH, GT, WT, CHP, GB} corresponds to TH, GT, WT, CHP, GB, respectively; $p_{t,ess}^{disc}$ and $p_{t,ess}^{ch}$ are respectively the discharging and charging power of the electrical energy storage device at t; $h_{t,tes}^{disc}$ and $h_{t,tes}^{ch}$ are respectively the discharging and charging power of the heat storage equipment at t.

2.3. The rolling optimal scheduling model

The objective function still selects the same objective function as the day-ahead optimization results, as shown in (1). The constraints of the rolling scheduling model include the constraints in the day-ahead scheduling model. In addition, the rolling scheduling model is made according to the basic operation points of the day-ahead optimization results to achieve a better connection between the two. Therefore, the constraint of deviation of the results between the rolling scheduling model and the day-ahead plan is added.

$$| p_{t,j,n}^{rolling} - p_{t,j,n}^{day} | \le \alpha P_{j,n}^{\max} \tag{5}$$

where, $p_{t,j,n}^{day}$ and $p_{t,j,n}^{rolling}$ are the day-ahead and rolling optimization results of the Nth device in the equipment j at t, respectively, α is the constraint multiplier.

2.4. The real-time optimal scheduling model

The real-time scheduling model is a single period of static optimization, and it is not easy to consider the interconnection between different periods. So the unit output is adjusted only based on the rolling results to ensure the power balance. The objective function is the minimum sum of the adjustment values of the output of each unit.

$$\mathrm{minP} = \sum_{n=1}^{N} | p_{t,j,n}^{real} - p_{t,j,n}^{rolling} | + \gamma (p_{t,wind} - p_{t,wt}) \tag{6}$$

where P is the sum of the output adjustment values of each equipment at t; $P_{t,j,n}^{real}$ is the real-time optimization results of the Nth equipment in the device j at t; Subscript j ={TH, GT, WT, CHP} corresponds to TH, GT, WT, CHP, respectively; γ is the wind abandoning penalty coefficient; $p_{t,wind}$ is the generating power of the wind farm at t.

The constraints of the real-time scheduling model include the constraints in the day-ahead scheduling model. On this basis, the real-time scheduling model is specified at the primary running point of the rolling optimization results, and the devices' output deviation constraint should also be considered.

$$| p_{t,j,n}^{real} - p_{t,j,n}^{rolling} | \le \beta P_{j,n}^{\max} \tag{7}$$

where β is the constraint multiplier.

3. The optimal multi-time scale coordination method for scheduling

Due to different working principles and control methods, different types of equipment have different control characteristics when responding to scheduling instructions. According to the operating characteristics of each subsystem equipment and its role in optimal scheduling, we can determine its scheduling instruction cycle.

(1) On the premise of meeting its operating constraints, the power supply equipment is optimized with a three-stage scheduling system of day-ahead, rolling, and real-time.

(2) CHP has a good rapid adjustment capability and a narrow adjustment capacity range. They participate in three-stage schemes.

(3) Combustion equipment (such as gas boilers) bear a larger proportion of heating load, have a slower adjustment rate and a larger adjustable capacity, and only participate in the two-stage scheduling of day-ahead and rolling. All feasible scheduling instruction cycles are traversed in the rolling stage, and the scheduling cycle obtained when the economy is optimal in the day is the optimal scheduling instruction cycle.

Figure 1 shows the time length of the scheduling schemes of each time scale in the document calculation example system. Assume that the optimal scheduling cycle command of the thermal system is 4h through calculation. The day-ahead scheduling period planned is 24h, and 1h is a scheduling period. Based on the previous results, the power system's rolling schemes are updated every 1h, and some equipment of the thermal system is updated every4h; the real-time scheduling is

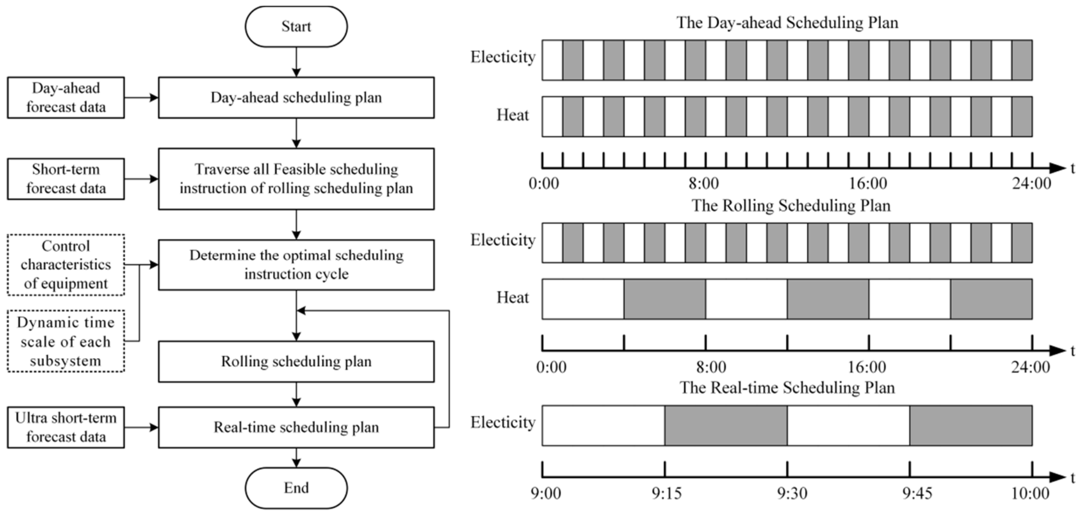

Figure 1. Optimal coordination method of multi-time scale in IES scheduling.

updated every 15 minutes and is responsible for the upcoming next period.

4. Case analysis

In order to verify the feasibility of the proposed optimal matching method of multi-time scale in IES scheduling, a model of small-scale electric-heating EH is constructed in this section, which is solved by the YALMIP Toolbox with Cplex 12.8.0 solver. The scheduling optimization results are shown in Figure 2.

Due to the low electricity price during 01:00-07:00 and 23:00-24:00, the energy station purchases power to meet the electrical load demand and charge the EES; the output of the wind farm is relatively high, and the output of the GT is suppressed to the lowest level. At this time, the thermal load demand of the system is mainly met by GB.

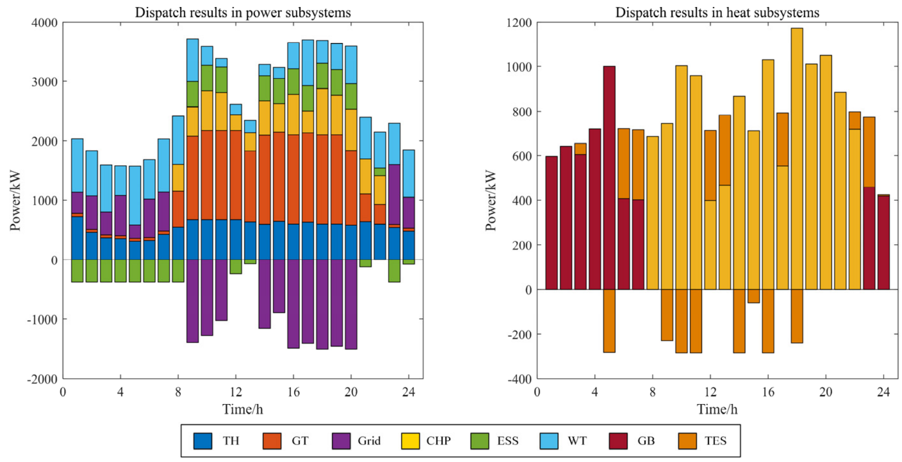

Figure 2. Dispatch results of day-ahead stage in subsystems.

As the level of electrical load increases, the energy hub meets the electrical balance requirements by increasing GT output and releasing ESS electricity. Part of the surplus electricity is stored or sold to the grid. Since the thermal and electrical power of CHP meets a certain proportional relationship, the thermal power of CHP also increases significantly during this period, which causes the thermal power of GB to decrease and become an auxiliary heat source gradually. The thermal load is powered by GB and CHP, and TES is used as a supplement to balance the deviation in thermal power.

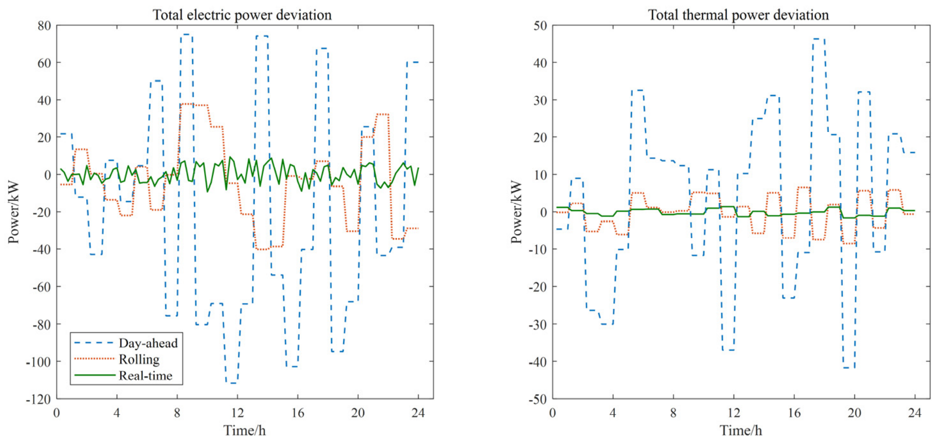

Figure 3. Contrast curves of total power deviation of scheduling schemes in three-time scales.

The contrast curves of the total power deviation of scheduling schemes in three-time scales are shown in Figure 3. It can be seen from Figure 3 that total electrical power and total thermal power in the day-ahead and rolling results deviate significantly from the actual load. In the real-time stage, fast-tracking of load changes by adjusting equipment with good performance can better match the actual load, indicating that the optimization results of the multi-period dispatching model have a small deviation from the reference plan.

5. Conclusion

This paper proposes an optimal matching method of multi-time scale in electricity-heating IES scheduling, considering the characteristics of different energy subsystems and the operating characteristics of multiple equipment types. Compared to the traditional multi-time scale scheduling framework, the deviation between the optimization results with the optimal matching method and the actual load is smaller, verifying the feasibility and effectiveness of the proposed scheduling optimization method.

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