Comprehensive Optimization Configuration Study for Energy Storage Equipment of Integrated Energy System on User Side

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Abstract. Aiming at the current situation with insufficient study on issue of electric/thermal energy storage comprehensive optimization configuration in the Integrated Energy System on user side under background of smart city, from the perspective of balance between energy supply and demand, the replacement of electric energy and cold/thermal/electric coupling has been taken into consideration to build the model of comprehensive optimization configuration for energy storage equipment in Integrated Energy System. The energy storage takes typical daily system operation optimized dispatching into consideration; the electric/thermal energy storage comprehensive configuration optimization model is built with the goal of lowest annual operating costs of Integrated Energy System; for the constraint conditions, the balance of supply and demand, cold/thermal/electric coupling, replacement of electric energy, energy storage installation and operation and various other factors are taken into consideration; optimization variables are capacity of electric/thermal energy storage equipment and the dispatching value of equipment in typical system scenarios.

1. Introduction

Since the 21st century, the problems including environmental pollution, energy safety and energy efficiency, etc. bring many challenges to the development of field of energy. For the tradition energy system, with the continuous expanding of proportion of new energy and the increasingly diversified demands on energy of users, its basic characteristics are changing. On one hand, the randomness fluctuations on energy supply side are increasing and the controllability is reducing; on the other hand, the kinds of loads on energy demand side are also becoming more and more diversified including household appliances, electric vehicles and electromotors, etc., and the degrees of cold/thermal/electric coupling are deepening which causes the demand fluctuations to be very different. How to stabilize the power fluctuation and guarantee the balance of supply and demand is an urgent issue. The Integrated Energy System for smart city is designed to realize the sustainable development of energy through broadening source and reducing consumption and is becoming a major research hotspot in the world [1-3].

Multiple-energy complementation and multiple-energy flow coordinative optimization are the connotation and architecture of IES. Only taking the electric/thermal/cold coupling into consideration in the IES for study on comprehensive energy storage configuration can meet the demands for future
development of smart city [4-5]. Under the macro-background of our country accelerating the strategy of “replacement of electric energy”, the IES on user side has huge potential for replacement of electric energy. At present, there is no study on the impact of replacement of electric energy on the comprehensive energy storage configuration for IES. In view of the above problems, the optimal configuration methods for energy storage equipment in IES on user side under replacement of electric energy is taken into consideration and studied in this paper aimed at the office buildings in science parks in the smart city and based on the balance of supply and demand as well as cold/thermal/electric coupling.

2. Overall structure of IES
Generally, the IES on user side can be divided into five units, including energy production unit, energy conversion unit, energy storage unit, energy transmission unit and energy use unit. Figure 1 is the brief structure diagram of IES on user side for smart city. The system inputs electric energy through superior grid and obtains renewable energy sources and natural gas from outside at the same time.

![Figure 1. Structure of IES on user side](image)

In the above five units, the energy storage equipment is the important constituent unit of IES which can realize the cross-period transfer of energy, conduct peak-load shifting, and coordinate the unbalance between “source-load” in the network, and is the effective measure for smoothing new energy output and restraining the power fluctuations of renewable energy sources [6-7]. Therefore, the reasonable and effective optimal models are required to conduct energy storage configuration for IES.

3. Objective function
The model takes lowest annual costs on operation of IES as the objective function. The annual costs mainly include investment costs, fuel costs, operation and maintenance costs, electricity purchasing costs and carbon tax costs of energy storage equipment. In addition, there are corresponding subsidies on replacement of electric energy in national policies with the expression of:

$$
\min F(x) = \xi_{Cap} + \xi_{Fuel} + \xi_{Om} + \xi_{Grid} + \xi_{Env} - \xi_{Sub}
$$

(1)

Where, $\xi_{Cap}$, $\xi_{Fuel}$, $\xi_{Om}$, $\xi_{Grid}$ and $\xi_{Env}$ respectively refer to investment costs, fuel costs, operation and maintenance costs, electricity purchasing costs and carbon tax costs, thereinto, when the $\xi_{Grid}$ is minus, it means the incomes of electricity sales; $\xi_{Sub}$ means the policy subsidies for replacement of
electric energy. The waiving of carbon tax costs incurred in purchasing electricity from grid is adopted in this paper as the policy subsidy manner.

(1) Investment costs
The investment costs refer to costs on purchasing and installation of batteries and water storage tanks. The investment is converted into equivalent annual value based on the service life. Considering its installation capacity and costs on unit capacity, such costs shall be:

\[ \xi_{\text{cap}} = \sum s \psi_s C_s \omega^\text{cap}_s \]  

Where, \( \psi_s \) refers to discount rate of equipment; \( C_s \) and \( \omega^\text{cap}_s \) respectively refer to the installation capacity and costs on unit capacity of No. \( s \) equipment in the system.

(2) Fuel costs
The fuel required during operation of IES is natural gas and the costs are:

\[ \xi_{\text{fuel}} = \xi_{F} \sum f_{i,s} \]  

Where, \( \xi_{F} \) refers to price of natural gas; \( f_{i,s} \) refers to the natural gas consumption of the \( s^{\text{th}} \) equipment at moment \( t \).

Operation and maintenance costs
Except for the newly-equipped energy storage equipment, the operation and maintenance costs also include costs of installed equipment. Considering that the operation and maintenance of equipment are related to the working period and output power, the costs are:

\[ \xi_{\text{OM}} = \sum_{i,s} (P^{\text{OM}}_i \omega^{\text{OM}}_i) \]  

Where, \( P^{\text{OM}}_i \) refers to the output power of the \( i^{\text{th}} \) equipment at moment \( t \); \( \omega^{\text{OM}}_i \) refers to the operation and maintenance costs of unit output of such equipment.

(4) Electricity purchasing cost
When the electricity generation of distributed energy system is insufficient for the supply of regional consumption, it’s required to purchase electricity from grid; otherwise, when the electricity generation is sufficient with a surplus, it can sell to the grid to gain profits to reduce system costs; the costs are:

\[ \xi_{\text{Grid}} = \sum_i (p_{i}^{\text{buy}} \omega_i^{\text{buy}} - p_{i}^{\text{sell}} \omega_i^{\text{sell}}) \]  

Where, \( p_{i}^{\text{buy}} \) and \( p_{i}^{\text{sell}} \) respectively refer to the power bought and sold by the system to the grid at moment \( t \); \( \omega_i^{\text{buy}} \) and \( \omega_i^{\text{sell}} \) respectively refers to the unit price of electricity at buying and selling electricity.

(5) Carbon tax costs
Due to global warming, the state formulates policies to levy taxes on the emission of carbon
dioxide in the hope of reducing the carbon emission and protecting environment. The costs are:

$$\frac{e_{\text{env}}}{\text{Env}} = \omega_{\text{Ctax}}(E_{t}V_{\text{LHV}} \sum_{t,s} f_{t,s} + E_{\text{Grid}} \sum p_{t}^{\text{buy}} \frac{\eta_{\text{Grid}}}{\eta_{\text{Grid}}})$$  \hspace{1cm} (6)

Where, $E_{t}$ and $E_{\text{Grid}}$ respectively refer to the carbon emission based on unit capacity of natural gas
and power plant; $\eta_{\text{Grid}}$ refers to the transmission efficiency of grid; $\omega_{\text{Ctax}}$ refers to carbon tax; $V_{\text{LHV}}$
refers to the low heating value of natural gas.

4. Constraint conditions
The energy storage equipment in the IES in science park of smart city is constrained by various factors
in actual planning and operation, which is expressed as a series of constraint conditions in the models
built in this paper.

(1) Constraint on balance of energy supply and demand
The constraint on balance of energy supply and demand needs to consider three energy demands
and three typical scenarios.

$$p_{t} + x_{\text{Seal}}(\Delta p_{t}) = \sum_{m} p_{t,m}^{\text{OUT}} - \sum_{n} p_{t,n}^{\text{IN}} + (p_{t}^{\text{buy}} - p_{t}^{\text{sel}}) + (p_{t}^{\text{dis}} - p_{t}^{\text{ch}})$$  \hspace{1cm} (7)

$$p_{t} = \sum_{m} p_{t,m}^{\text{OUT}} - \sum_{n} p_{t,n}^{\text{IN}} + (p_{t}^{\text{buy}} - p_{t}^{\text{sel}}) + (p_{t}^{\text{dis}} - p_{t}^{\text{ch}})$$  \hspace{1cm} (8)

$$x_{\text{Seal}}(h_{t} - x_{\text{Seal}}(\Delta p_{t})) = x_{\text{Seal}}(\sum_{m} h_{t,m}^{\text{OUT}} - \sum_{n} h_{t,n}^{\text{IN}} + (h_{t}^{\text{dis}} - h_{t}^{\text{ch}}))$$  \hspace{1cm} (9)

$$(1 - x_{\text{Seal}})c_{t} = (1 - x_{\text{Seal}})(\sum_{m} c_{t,m}^{\text{OUT}} + (c_{t}^{\text{dis}} - c_{t}^{\text{ch}}))$$  \hspace{1cm} (10)

Formula (7) refers to the electric energy balance relation under electric replacement of electric
energy on energy use end; formula (8) refers to the electric energy balance relation under replacement
of electric energy on energy supply end.

Where, $x_{\text{Seal}}$ refers to scenario factor and is 0-1 variable; 1 represents the heat supply season; 0
represents cooling season; during non-transition seasons, only the power balance constrain is
accounted; $p_{t}$ refers to the pure electric load on user side; $\Delta p_{t}$ refers to the quantity replaced in the
thermal load on user side at moment $t$; $\mu$ refers to the replacement coefficient between electric and
thermal loads; $p_{t,m}^{\text{OUT}}$ refers to the output power of the $m^{\text{th}}$ power generation unit in the system at
moment $t$; $p_{t,n}^{\text{IN}}$ refers to the input electric power of the $n^{\text{th}}$ energy conversion equipment in the system
at moment $t$. The thermal and cold power are respectively represented by $h$ and $c$. The meanings of
their superscripts and subscripts are similar with that of electric power. $p_{t}^{\text{ch}}, p_{t}^{\text{dis}}, h_{t}^{\text{ch}}, h_{t}^{\text{dis}}, c_{t}^{\text{ch}}$ and
$C_{\text{dis}}$ respectively refer to the charge-discharge power of power storage, heat storage and energy storage equipment.

(2) Constraint on the replacement of electric energy on energy use end

Two kinds of replacement of electric energy are taken into consideration in this paper; the first is at the energy supply end of IES on user side; the second is at the energy use end. The model built in the paper takes the impacts of replacement of electric energy on energy storage configuration of IES, at the energy use end, the constraint on replacement quality is:

$$0 \leq \Delta p_t < h_{\text{Win}}^{\text{th}}$$

Where, $\Delta p_t$ refers to the replacement quality of electric energy in the thermal load on user side at moment $t$; $h_{\text{Win}}^{\text{th}}$ refers to the thermal load on user side in heat supply seasons. The upper limit of replacement of electric energy is related to the regional development status and relies on specific energy demands of users and there is not unified and specific value. The paper temporarily takes the thermal load value of maximum replacement as the upper limit.

(3) Installation and operation constraint of energy storage equipment

For the energy storage units needing configuration, there are various constraints for their equipment installation and operation.

The constraints in installation capacity are:

$$0 \leq C_s \leq C_s^{\text{max}}$$

Where, $C_s^{\text{max}}$ refers to the upper limit of installation capacity of such energy storage equipment.

The constraints in input and output of energy storage equipment are:

$$\begin{align*}
\chi_s^{\text{ch}}(C_s, \delta_s^{\text{min}}) & \leq Q_{s,\text{ch}}^{\text{th}} \leq \chi_s^{\text{ch}}(C_s, \delta_s^{\text{max}}) \\
\chi_s^{\text{dis}}(C_s, \delta_s^{\text{min}}) & \leq Q_{s,\text{dis}}^{\text{th}} \leq \chi_s^{\text{dis}}(C_s, \delta_s^{\text{max}})
\end{align*}$$

Where, $\delta_s^{\text{min}}$ and $\delta_s^{\text{max}}$ respectively refer to the minimum and maximum SOC values of the $s$th energy storage equipment in the system; $\chi_s^{\text{ch}}$ and $\chi_s^{\text{dis}}$ respectively refer to the charge-discharge factors of energy storage equipment and are 0-1 variables; 0 represents no charging or discharging for equipment; 1 represents that the equipment is under charging or discharging; $Q_{s,\text{ch}}^{\text{th}}$ and $Q_{s,\text{dis}}^{\text{th}}$ respectively refer to the input and output power of energy storage equipment.

In addition, the charging and discharging of energy storage unit cannot be made at the same time; therefore, the following constraint exists:

$$\chi_s^{\text{dis}} + \chi_s^{\text{ch}} \leq 1$$

5. Prospect on solution algorithm

The issue of energy storage equipment optimization configuration studied in this paper is a 0-1 mixed integer linear programming issue; the standard form of the model of such linear programming is:
\[
\begin{align*}
\min & \quad F(x) \\
\text{s. t.} & \quad h_i(x) = 0, i = 1, \ldots, m \\
& \quad g_j(x) \leq 0, j = 1, \ldots, n \\
& \quad x_{\text{min}} \leq x \leq x_{\text{max}} \\
& \quad x_k \in \{0, 1\}
\end{align*}
\] (15)

Where, \( x \) refers to the variable to be optimized; \( \min F(x) \) refers to the objective function; \( h_i(x) = 0 \) refers to the equality constraint; \( g_j(x) \leq 0 \) refers to the inequality constraint; \( x_{\text{min}} \) and \( x_{\text{max}} \) respectively refer to the lower and upper limits of variables; \( x_k \in \{0, 1\} \) indicates that some variables are 0-1 variables.

Currently, for the mixed integer linear programming model, there are various softwares that may be used for solution, such as Cplex, GLPK, LPSolve and Yalmip.

6. Conclusion

From the perspective of balance of energy supply and demand, this paper considers replacement of electric energy and establishes the comprehensive optimization configuration models for electric/thermal storage based on cold/thermal/electric coupling. From a new perspective, this paper proposes the energy storage configuration methods in the IES on user side for smart city. This paper also conducts detailed analysis on objective function, constraints and solution algorithm. However, due to limited space, the examples are not taken in this paper to validate the methods stated which needs to be optimized in future studies.

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