Research on the Energy Internet Coordinated Scheduling Model Based on a Bi-Level Optimization

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ABSTRACT

As an important measure to cope with the energy crisis, the energy Internet can realize the cascade utilization of energy. In this paper, a standardized system model of the energy Internet is proposed, and the typical energy Internet processes are modeled. And a scheduling model is proposed to realize the decoupling calculation of energy Internet through a bi-level optimization. A simple case shows that the introduction of the energy interconnection and energy storage can improve the energy efficiency of the system and reduce the cost of energy supply.

Keywords: the energy Internet, scheduling model, bi-level optimization, system model

INTRODUCTION

The economic development is inseparable from the support of energy production. Nowadays, the energy demand is rapidly increasing. However, the energy consumption mainly comes from the traditional non-renewable fossil fuels, having uneven distribution over the world. Although the fossil energy has large reserves, resource exhaustion and environmental pollution have been faced under the large-scale exploitation in the past hundreds of years. In the next few decades, an energy crisis has been foreseen. Mitigating the energy crisis and reducing the air pollution have become urgent. Obviously, the traditional high-carbon and centralized energy use mode is no longer in line with the requirements of development of energy. The comprehensive utilization of the traditional energy, the renewable energy, the energy storage and the demand-side resource is an important way to solve the energy crisis in the future.

With the rapid development of Internet information technology, it is proposed that building an energy Internet with the feature of deep integration of the renewable energy and information technology will be the key to achieve the clean and sustainable development of energy. The famous American economist Jeremy Rifkin proposed the idea of the energy

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Internet. It is envisaged that the energy Internet will fundamentally change the way of energy development and utilization and is the core of the third industrial revolution, which will have a profound impact on the mode of economic development and the lifestyle. Five connotations of the energy Internet were described: shifting to renewable energy; buildings as power plants; deploying hydrogen and other storage technologies; using internet technology to transform the power grid; transitioning the transport fleet to electric, plug-in and fuel cell vehicles. The energy Internet concept advocated by Rifkin is the optimal configuration and comprehensive use of the power, storage and demand-side resources with the Internet technology in the wide area. And ultimately the purpose of transforming the use of centralized traditional fossil energy into the use of distributed renewable energy is achieved.

The energy Internet is a market with huge potentials, allowing a variety of resources through the dynamic decision to participate in the market. On the one hand, the energy Internet will stimulate the market activity. On the other hand, the energy Internet will help to solve the energy crisis and provide resources for the production and development of the society. At present, there are a lot of researches on the energy Internet, including the integrated energy system [1], the energy conversion [2], and the architecture of the energy Internet [3] and so on. In the chapter II, the standardized system model is established and several typical models are given. Based on a bi-level optimization, the operation and control model of the energy Internet is established in the chapter III. Verification and analysis are done through data cases in the chapter IV.

**SYSTEM MODEL OF THE ENERGY INTERNET**

**Standardized System Model**

The energy Internet system is an energy flow network that allows the conversion and circulation of many kinds of energy. At the theoretical level, the energy flow of the energy Internet is undifferentiated in the orientation, similar to the single energy network. While on the physical level, the energy Internet can actually be considered as the coupling of multiple single energy networks through the energy conversion nodes, the physical energy level of the energy Internet can actually be viewed as multiple single energy networks coupling through the energy conversion nodes. The energy Internet at the physical level can be expressed as the above schematic diagram in Figure 1, and this standardized model can be extended under the essential technical support. It can be seen that the energy Internet contains three basic components: transmission, conversion and storage. The following chapters are the standardized definitions of the three components, which can be replaced by specific forms of energy in the actual utilization.
TRANSMISSION

The transmission formulation: \( X_{out} = \kappa X_{in} \).

The efficiency function: \( \kappa = f(a_1, a_2, \ldots) \), where \( a \) refers to the variables associated with the transmission network.

The transmission cost: \( C = g(a_1, a_2, \ldots) \). For the electric grid, the cost mainly refers to the cost of network loss. For the gas network, it mainly refers to the pressure cost, and for the heat pipelines, it is the cost of heat loss.

CONVERSION

The transmission formulation: \( Y_i = \kappa_i X, i = 1, 2, \ldots, n \), \( \sum_{i=1}^{n} \kappa_i \leq 1 \).

The efficiency function: \( \kappa_i = f_i(x_1, x_2, \ldots, t_1, t_2, \ldots, y_1, y_2, \ldots) \), \( i = 1, 2, \ldots, n \).

The transmission cost: \( C = g(t_1, t_2, \ldots) \).

STORAGE

In the Figure 2, the energy is stored when the \( X \) is positive, while the reverse means the release of the energy.

The transmission formulation: \( X_i = \kappa X \). The value of \( \kappa \) is less than 1 when the energy is stored, and more than 1 when the energy is released.

The efficiency function: \( \kappa = f(s_1, s_2, \ldots) \), where \( s \) refers to the variables associated with the storage devices.

The transmission cost: \( C = g(s_1, s_2, \ldots) \), such as the economic incentive to call the energy storage process or the operating cost of the energy storage device.

Typical Transmission Process

ELECTRICITY

Line loss refers to the energy loss emitted by heat in the transmission process, including the active power consumed by resistance and conductance. The line loss rate is an important index to assess the economic performance of power system. The average line loss rate in China in recent years is around 6%. The cost of the transmission process includes the construction cost \( C_{\text{construct-P}} = \sum \lambda_{\text{m}} P_{d} \), which is often omitted in the optimal operation. The constraints include the efficiency of transmission, the bound of lines and power flow constraints.
In the transmission process of natural gas in the pipeline, the compressor has a great energy consumption. Generally, 3%~5% of the transmission gas is used as the energy of self-consuming gas. To simplify the calculation, we can account for the compression cost of the compressor in the cost.

The flow of gas within a simple tube can be expressed as
\[ p_1^2 - p_2^2 = cu|u|^\beta, \]
where \( p_1 \) and \( p_2 \) refer to the pressure at both ends of the tube. \( u \) represents the mass flow through the pipe. \( \beta \) is constant, equal to 1 when the tube is horizontal. \( c \) means the pipe resistance, which depends on the physical properties of the pipe and is related to the hydraulic friction coefficient, length and inner diameter of the pipe.

The structure of natural gas pipeline network is generally described by the correlation matrix, and the node-pipe matrix and the circuit-pipe matrix are defined as:
\[
A = \left[ a_{ij} \right]_{N \times M}, B = \left[ b_{ij} \right]_{K \times M}.
\]

Where \( N, M, K \) respectively represents the number of the nodes, pipes and circuits. When \( a_{ij} = 1 \), the node \( j \) is output to \( i \), and when the value is -1, the node \( i \) is output to \( j \), the value of 0 for the non-connection. When \( b_{ij} = 1 \), the direction of pipe \( j \) is in line with circuit \( I \) and the value of -1 represents the opposite direction. The value of 0 indicates that the pipe \( j \) is not on the circuit.

Set \( Q_{v,s} \) as the pipe flow vector, \( F_{v,s} \) as the node flow vector and \( \Delta p_{v,s} \) as the pressure drop vector of the pipe. Then \( AQ = F \) and \( B\Delta p = 0 \) are satisfied.

The node-pressure method is used to analyze the steady state of the network. Initialize the value of the node pressure, modify the pressure by node equation, and solve it iteratively, so as to satisfy the above equations.

The cost of the gas transmission process includes the construction cost which can be omitted and the compression cost.

\[
C_{\text{construct-G}} = \sum \lambda_{\text{line-G}} l, \quad C_{\text{press-G}} = \sum_{x \in M} S_{\text{press-G}} \int 0.03 \lambda_{\text{t}} |Q(t)| dt.
\]

Where \( S \) refers to the state of the compressor, and the compression is opened with the state value of 1 while the value of 0 indicates that the compression is closed.

Except the above network balance constraint, some other constraints are as follows.

Pressure and flow constraints of nodes:
\[ p_{i_{\text{min}}} \leq p_i \leq p_{i_{\text{max}}}, F_{i_{\text{min}}} \leq F_i \leq F_{i_{\text{max}}}, i \in N, \]

where \( p \) and \( F \) refer to the pressure and flow.

The pipe strength constraint:
\[ Q \leq Q_{\text{max}}, i \in M \]

The compressors' feasible domain constraints are complex, which are simplified as a simple capacity limit of the compressor.

HEAT

The steam heating network and gas network belong to the same type of network with similar operation principle. On one hand, the heat network accepts injection to heat the load; on the other hand, it provides power for the flow of steam. The steam flow in the pipe network should meet the flow balance, which is similar to gas pipe network constraints. But the heat pipe does not belong to the kind of pressure pipe, so the compression station does not...
need to be pressurized. Therefore, the compression cost does not need to be charged in the cost.

The heat loss mainly comes from the heat loss of the thermal insulation structure, so the transmission efficiency is mainly influenced by the insulation measures of the pipeline. Generally, the efficiency is 70%.

The constraints of the heat network are as follows.
The pressure and flow constraints of nodes: \( p_{\text{min}} \leq p_i \leq p_{\text{max}}, F_{\text{min}} \leq F_i \leq F_{\text{max}}, i \in N \).

The security constraint of the flow in the pipe: the steam flow in the pipe should be kept in a certain velocity to ensure that the transmission is within the strength range of the pipeline. Set the average velocity is \( \bar{v} \), then \( \bar{v} = \frac{Q}{\rho A} \), where \( Q \) is mass flow, \( \rho \) is the medium density and \( A \) is the section area of the pipe, which needs to satisfy: \( v_{\text{min}} \leq v_i \leq v_{\text{max}}, i \in M \).

The network balance constraint is similar to the one of the gas network.

Typical Conversion Process

TRADITIONAL GENERATION

The cost of a traditional power unit can be expressed in the form of quadratic function:
\[ C_g(P,t) = aP^2(t) + bP(t) + c. \]

The constraints mainly include the output constraint \( P_{\text{min}} \leq P(t) \leq P_{\text{max}} \) and the ramping constraint \( P(t-1) - \Delta P_d \leq P(t) \leq P(t-1) + \Delta P_u \), where \( P_d, P_u \) refer to the bound of the output and \( \Delta P_d, \Delta P_u \) respectively refer to the ramping rate in unit time period.

P2G

At present, the efficiency of P2G ranges from 70% to 95%.

The cost includes:
1. The actual cost of annual operation / maintenance of the P2G plant is about 5% of the fixed cost.
2. Power source cost: \( C_p = \lambda _p \cdot P \), where \( \lambda _p \) is the power price.

The constraints include:

Input power capacity constraints and state constraints: \( s_{P2G, P_{\text{min}}} \leq P \leq s_{P2G, P_{\text{max}}} \), where \( s_{P2G} \) means the state of P2G station.

The energy conversion efficiency of P2G can be expressed as: \( G = \eta _{P2G} \cdot P. \)

CCHP

The CCHP system can not only generate about 40% of the power generation efficiency, but also reduce the line loss of 6% to 7% compared with the traditional long-distance transmission. At the same time, the waste heat can be recycled, and the comprehensive utilization rate of energy is above 80%, realizing the cascade utilization of energy.

The evaluation of the efficiency of CCHP includes the following indicators: primary energy efficiency of power, heating and cooling, and primary energy conversion efficiency, which can be represented by.
The cost of the CCHP includes: 
\[ \eta_{\text{CCHP}} = \eta_{\text{CCHP}-P} + \eta_{\text{CCHP}-C} + \eta_{\text{CCHP}-H} \]

Fuel costs: 
\[ C_g = a + bP + cP^2 + dH + fH^2 + gPH, \]  
where \( a-f \) are coefficients.

Operation costs: 
\[ C_{\text{run-C CHP}} = K (P + H / \rho) \]

The constraints of the CCHP include:

Energy conversion constraints: 
\[ P = \eta_{\text{CCHP}-P} \cdot G, \quad H = \eta_{\text{CCHP}-H} \cdot G \]

Conversion bound constraints: 
\[ P_{\text{min}} \leq P \leq P_{\text{max}}, \quad H_{\text{min}} \leq H \leq H_{\text{max}} \]

Input gas constraint:
\[ k_{\text{CCHP}} G_{\text{CCHP}}^{\text{min}} \leq G \leq k_{\text{CCHP}} G_{\text{CCHP}}^{\text{max}} \]

**Typical Storage Process**

**ELECTRICITY STORAGE**

The efficiency of battery technology is usually between 75% and 95%. The charge state \( \text{SOC} \) reflects the remaining quantity of the battery, and the formula for accumulator storage capacity can be generally expressed as:

\[ \Delta \text{SOC} = S_{\text{bat}} \cdot \eta_{\text{bat}} \cdot \frac{1}{C_{\text{bat}}} \int_{t-1}^{t} (I_{\text{bat}} - I_{\text{loss}}) dt \]

Where \( S_{\text{bat}} \) refers to the battery state and \( \eta_{\text{bat}} \) refers to the efficiency.

The constraint of the energy storage is: 
\[ \text{SOC}_{\text{min}} \leq \text{SOC} \leq \text{SOC}_{\text{max}} \]

**HEAT STORAGE**

The heat storage device usually uses water as a storage medium, which is used for short-term storage of heat. Due to the inevitable heat exchange between the hot and cold medium and between the heat storage system and the outside world, the efficiency of the heat storage tank can be modeled.

The constraint of heat storage:

Heat balance constraint: 
\[ H(t) = \eta_{\text{hr}} H(t-1) + S(t) \]

Constant heat storage capacity of heat storage device: 
\[ \sum_{t=1}^{24} S(t) = 0 \]

Heat absorption and discharge limit: 
\[ H_{\text{max}} \leq H(t) \leq H_{\text{max}}, -h_{\text{max}} \leq S(t) \leq h_{\text{max}} \]

Where \( H(t) \) means the heat storage capacity at the end of \( t \) and \( \eta_{\text{hr}} \) is the efficiency.

**COORDINATED OPTIMAL SCHEDULING MODEL**

For a complete scheduling cycle, minimize the operation cost of energy Internet or maximize the efficiency of energy utilization under all operation constraints. The decision variables of the scheduling model are the energy output and the working state of each process.
Economic Model

\[
\min F = \sum_{i=1}^{24} \sum_{i \in N} \sum_{j \in E} \sum_{k \in O} S_{i,j,k} C_{i,j,k},
\]

\[
S = \begin{cases} 
1 & \text{state is open} \\
0 & \text{state is closed}
\end{cases}
, \quad O = \{\text{purchase, produce, conversion, transmission, storage}\}.
\]

Where \(N\) represents transmission network set, \(E\) represents energy type set, \(O\) represents energy operation set, \(F\) represents the total cost, \(S\) represents the state of each process and \(C\) represents the specific cost functions of each operation.

Constraints:

- Conservation of the energy:
  \[
  \sum_{i \in N} \sum_{j \in E} P^i_{i,j} = \sum_{i \in N} \sum_{j \in E} P^2_{i,j} + \sum_{i \in N} \sum_{j \in E} P_{i,j,\text{storage}} + \sum_{i \in N} \sum_{j \in E} \sum_{k \in O} P^\text{loss}_{i,j,k}.
  \]

- Rationality of series operation state:
  \(S_{il} \geq S_{lb}\), where \(S_{il}\) and \(S_{lb}\) represent the pre and post operation respectively.

- Constraints of the transmission, conversion and storage process.

Efficiency Model

\[
\min Loss = \sum_{i=1}^{24} \sum_{i \in N} \sum_{j \in E} \sum_{k \in O} S_{i,j,k} P^\text{loss}_{i,j,k},
\]

Constraints:

- Conservation of the energy:
  \[
  \sum_{i \in N} \sum_{j \in E} P^1_{i,j} = \sum_{i \in N} \sum_{j \in E} P^2_{i,j} + \sum_{i \in N} \sum_{j \in E} P_{i,j,\text{storage}} + \sum_{i \in N} \sum_{j \in E} \sum_{k \in O} P^\text{loss}_{i,j,k}.
  \]

- Rationality of series operation state:
  \(S_{il} \geq S_{lb}\), where \(S_{il}\) and \(S_{lb}\) represent the pre and post operation respectively.

- Constraints of the transmission, conversion and storage process.

Solution

In the scheduling model of energy Internet various sources are the source and load for each other, so it is difficult to solve the problem. According to the standardized system model of energy Internet, it is easy to think of transforming the problem into a bi-level optimization problem and decouple the solution of every network. Under the condition of the primary energy and demand, the primary energy is divided into several parts to participate in the optimal operation of the sole energy transmission network. The upper level problem optimizes the input energy allocation for each transmission network, and the lower level is the independent optimal scheduling for each energy transmission network. So, the primary energy satisfies

\[
P^1_{i,j} = \alpha_i \cdot P^2_{i,j} \cdot \sum_{i \in N} \alpha_i = 1
\]

The bilevel optimization model decoupled the energy Internet into multiple linear structures. Each linear structure was composed of one set of operations, a simplified schematic diagram as shown in Figure 3.

Figure 3. A Simplified Schematic Diagram of the Decoupling Process.
The linear structure restricts the number of energy conversion, while the actual technical conditions may support more conversion operations. However, the conversion efficiency is often less than 1, too much conversion is unnecessary, causing the decline of energy utilization efficiency. So, the number of energy conversion operations can be limited to a smaller upper limit from two aspects of reality and optimization. Therefore, this bi-level optimization solution is feasible. Each network scheduling model is an independent sub optimization problem. All the interactions of different energy are only embodied in the upper level optimization. In reference to the optimization solution of the traditional single energy systems, mature optimization solvers can be used to solve the problem.

CASE STUDY

In this paper, a simple energy Internet is set up to illustrate the model as shown in Figure 4, considering only the interconnection between electricity and gas, but the model can be extended to other energy forms. The network consists of four nodes, the node 1 is the power node, the node 2 is the gas source node, the node 3 is the electric load node equipped with a battery, and the node 4 is the electric and gas load node. The network also includes an electric gas station and a gas turbine to achieve electrical energy conversion, respectively installed in two source nodes.

![Figure 4. A Simple Energy Internet of the Case Study.](image)

Setup the case according to the grid node 1, 2 and the gas network node 8, 14 of [4]. The price and load forecast consult [5]. Consider the following four scenarios:

- not considering interconnections and storage.
- considering the interconnection.
- considering the storage.
- considering storage and interconnection.

The state variables of each conversion and storage process in four scenarios are shown in Table 1. And the electricity and gas load and actual consumption are shown in the following figure 5.

<table>
<thead>
<tr>
<th>Process</th>
<th>P2G</th>
<th>Battery</th>
<th>Gas Turbine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td>●●●●●●●●●●●●●●●</td>
<td>●●●●●●●●●●●●●●●</td>
<td>●●●●●●●●●●●●●●●</td>
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<tr>
<td>Scenario 2</td>
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<td>●●●●●●●●●●●●●●●</td>
<td>●●●●●●●●●●●●●●●</td>
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<tr>
<td>Scenario 3</td>
<td>●●●●●●●●●●●●●●●</td>
<td>●●●●●●●●●●●●●●●</td>
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<tr>
<td>Scenario 4</td>
<td>●●●●●●●●●●●●●●●</td>
<td>●●●●●●●●●●●●●●●</td>
<td>●●●●●●●●●●●●●●●</td>
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</table>

(●—open state or charging state, ○—closed state, ◎—discharging state)
From the results of optimization, it can be seen that in the presence of the interconnection and energy storage, the system will choose the call of the conversion and storage process. This is due to the peak and valley price of electricity price and gas price, which of different energy are staggered. So, when it is at the peak price of one form of energy, although the conversion and storage process will cause some energy loss, the economy of direct energy supply is not as good as the economy of using the conversion and storage if conversion (storage) cost + energy loss > energy cost. In the actual operation of the energy Internet, there are more scenarios that will benefit the system from the energy interconnection storage. For example, when the renewable energy is abandoned, the energy actually changes into the “anergy” and the utilization rate is 0, while the conversion of energy can change the “anergy” back into energy through the conversion of energy forms and the utilization rate can be moved up to a higher value.

It is also seen in Figure 5(b) that the effect of energy storage varies at different periods, which is guessed to be caused by the charging rate and discharging rate. It is observed that the storage device is full after the 1~6 periods, and the remaining power of the storage device is used for energy supply at the peak period. Then the storage device charges in the next valley period. However, if the operation time of the simulation is limited to 24 periods, the energy storage will not carry out the second round of charging because there's not enough time to use it. All conversion and storage processes in Figure 5(c) are involved in the operation, while the operating states of the processes in other energy Internet depend on the technology and cost.

CONCLUSION

This paper studies the standardized system model of the energy Internet and proposes a coordinated and optimal scheduling model which can be extended and applied to various energy forms. Meeting different energy constraints, this paper optimize the operation of multi energy system. The case study shows that introducing the interconnection and energy storage process help to improve the energy efficiency and reduce the cost of energy supply. This paper has done some preliminary work, and there are still many problems to be studied, such as the effects between different energy prices and the optimal operation with the gas network transient considered.

REFERENCES

