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A Unified Energy Bus Based Multi-energy Flow Modeling Method of Integrated Energy System

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Abstract

With the development of energy technologies, the electricity, cooling, heat, natural gas and other energy sources are tightly linked to improve the overall efficiency of energy system in integrated energy systems (IES). As the basis of optimization and simulation, the standardized modeling method of IES has become a challenge considering the deeply coupling of multi-energy resources. This paper proposes an energy bus structure that could realize the systematic modeling of IES. By adopting energy bus model, the components and the structure of IES can be mathematically presented. Then the matrix-based modeling method is proposed to describe the topology of the IES and the characteristics of energy converters. The equations that describe the energy flow relationship of the entire system can be listed out. Finally, a case study of Northern Customer Service Center (NCSC) of State Grid Corporation of China is conducted to verify the effectiveness of the proposed method.

Keywords: integrated energy system; energy bus; bus-based structure; matrix modeling; energy flow

1. Introduction

With the development of energy technologies, the construction of energy systems have made considerable progress. But there are still many problems of traditional energy supply solutions which is more common, such as its high

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Nomenclature

Indices	
m	indices of buses, from 1 to N_{bus}
n	indices of branches, from 1 to N_{bran}
k	indices of converters, from 1 to N_{conv}
Variables	
W	electric power
R	cooling power
Q	heat power
F	hot water power
W_{grid}	output power of grid
W_{PV}	output power of PV
F_{SWH}	output power of solar water heat system
$W_{\text{EC}}/R_{\text{EC}}$	input/output power of electric cooling system
$W_{\text{IC}}/R_{\text{IC}}$	input/output power of ice storage system
$W_{\text{HP}}/R_{\text{HP}}/Q_{\text{HP}}$	input/output power of heat pump
W_{ES}	input/output power of electric storage
Q_{HS}	input/output power of heat storage
R_{IS}	input/output power of ice storage tank
R_{CS}	input/output power of cooling storage
$R_{\text{HE},1}/R_{\text{HEO},1}$	input/output power of heat exchanger 1
$Q_{\text{HE},2}/Q_{\text{HEO},2}$	input/output power of heat exchanger 2
$Q_{\text{HE},3}/F_{\text{HEO},3}$	input/output power of heat exchanger 3
$F_{\text{HE},4}/F_{\text{HEO},4}$	input/output power of heat exchanger 4
$F_{\text{HWT}}/F_{\text{HWTO}}$	input/output power of hot water tank
W_{EL}	electric load
R_{CL}	cooling load
Q_{HL}	heat load
F_{HWL}	hot water load
Parameters	
η_k	efficiency of converter k
COP_k	coefficient of performance of converter k
α_{mn}	distribution coefficient of branch n on bus m

investment, environment unfriendly and low energy efficiency. Therefore, exploring new energy supply solutions is of great value for scientific and industrial.

Integrated energy systems (IES) that bring together the electricity, cooling, heat, natural gas and other energy sources has become an important method to overcome these shortcomings. IES can effectively coordinate and optimize the production, distribution, storage, and consumption of the involved energies, which is of great significance to improve the overall energy efficiency and increase the penetration of renewable energy sources. Therefore, IES has become the focus point of researchers in recent years all over the world.

As the basis of further optimization and simulation, the modeling method of IES has become a challenge considering the deeply coupling of multi-energy resources. As the topology and energy equipment has become more complex, many scholars have put forward different modeling methods from different scales and complexities. Geidl et al. [1] presented Energy Hub (EH) concept in 2007. An energy hub is considered a unit where multiple energy carriers can be converted, conditioned, and stored [2]. Reference [3] proposes a matrix modeling method based on EH to build the coupling matrix. Moreover, there are a number of papers focus on the modeling of a specific IES. Reference [4] proposed an optimization model of an IES consist of CCHP and wind power. Reference [5] established an optimization method of energy flow considering combined electricity and gas network system. Reference [6] established an energy flow analysis method considering combined electricity, gas and heat system.

This paper proposes an energy bus structure that could realize the systematic modeling of IES. By adopting energy bus model, the components and the structure of IES can be presented clearly. Then the matrix-based modeling method is proposed to describe the topology of the IES and the characteristics of energy converters. On this basis, the equations that describe the energy flow relationship of the entire system can be listed out. Finally, a case study of NCSC of State Grid Corporation of China is conducted to verify the effectiveness of the proposed method.

2. Components of energy bus model

Fig. 1 shows the energy bus model of IES in NCSC, which consists of four types of energy sources, electricity, heat, cooling and hot water. The source equipment includes power grid, photovoltaic system and solar water heat system. The converters include microgrid with power storage, electrical cooling system, ice storage system, ground source heat pump, and electrical boiler with heat storage. This example will be used to illustrate how to formulate an energy bus model and how to use the model to calculate the energy flow of the IES.

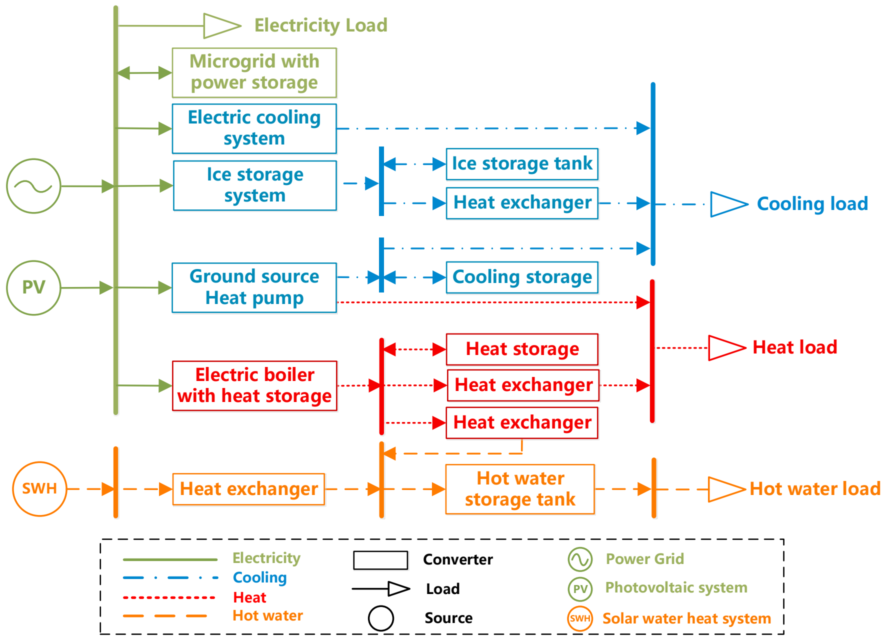


Fig. 1. Energy bus structure of IES in NCSC

Using energy bus structure to model an IES requires modeling the topology and the characteristics of energy converters. The physical equipment could be abstracted into the following components:

- **Energy bus**: The type of energy bus is decided according to the carried energy sources. (e.g. gas bus, heat bus, cooling bus), so there will be only one type of energy on one bus at the same time.
- **Branch**: A branch represents an input or output energy flow of a converter. The topology of IES can be expressed by connecting energy buses and branches.
- **Converter**: A converter represents an energy equipment which could have one or more input and output branch. Source and load are special converters, with only input or output branches.

3. Matrix modeling of energy bus structure

3.1. Energy flow balance equation

The energy flow balance equation on each bus can be clearly listed out by defining the bus-branch connection matrix $\boldsymbol{A}$. The element A_{mn} represents the connection relationship of bus m and branch n, which is defined as follows:

$$A_{mn} = \begin{cases} 1 & \text{if branch } n \text{ is leaving from bus } m \\ -1 & \text{if branch } n \text{ is entering towards bus } m \\ 0 & \text{if branch } n \text{ is not incident to bus } m \end{cases} \tag{1}$$

a) Energy flow balance equation of electric system

Taking the IES in Fig.1 as example, the algebraic sum of energy flows on an energy bus should be zero. The energy flow balance equation is:

$$\boldsymbol{A}_{\mathrm{E}}\boldsymbol{v}_{\mathrm{E}}^{T} = \boldsymbol{0} \tag{2}$$

The bus-branch connection matrix $\boldsymbol{A}_E$ of electric system can be written as:

$$\boldsymbol{A}_{\mathrm{E}} = [-1 \quad -1 \quad 1 \quad 1 \quad 1 \quad 1 \quad 1 \quad 1] \tag{3}$$

$$\boldsymbol{v}_{\mathrm{E}} = [W_{\mathrm{grid}} \quad W_{\mathrm{PV}} \quad W_{\mathrm{ES}} \quad W_{\mathrm{EC}} \quad W_{\mathrm{IC}} \quad W_{\mathrm{HP}} \quad W_{\mathrm{EB}} \quad W_{\mathrm{EL}}] \tag{4}$$

For the same, the bus-branch connection matrix of cooling system, heat system and hot water system could also be listed.

b) Energy flow balance equation of cooling system

$$\boldsymbol{A}_{\mathrm{C}}\boldsymbol{v}_{\mathrm{C}}^{T} = \boldsymbol{0} \tag{5}$$

The bus-branch connection matrix $\boldsymbol{A}_{\mathrm{C}}$ and energy flow vector $\boldsymbol{v}_{\mathrm{C}}$ are:

$$\boldsymbol{A}_{\mathrm{C}} = \begin{bmatrix} -1 & 0 & 0 & 0 & 0 & -1 & 0 & -1 & 1 \\ 0 & -1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 & 1 & 1 & 0 & 0 \end{bmatrix} \tag{6}$$

$$\boldsymbol{v}_{\mathrm{C}} = [R_{\mathrm{EC}} \quad R_{\mathrm{IC}} \quad R_{\mathrm{HP}} \quad R_{\mathrm{IS}} \quad R_{\mathrm{HE,1}} \quad R_{\mathrm{HEO,1}} \quad R_{\mathrm{CS}} \quad R_{\mathrm{HPO}} \quad R_{\mathrm{CL}}] \tag{7}$$

c) Energy flow balance equation of heat system

$$\boldsymbol{A}_{\mathrm{H}}\boldsymbol{v}_{\mathrm{H}}^{T} = \boldsymbol{0} \tag{8}$$

The energy flow vector $\boldsymbol{v}_{H}$ and bus-branch connection matrix $\boldsymbol{A}_{\mathrm{H}}$ are:

$$\boldsymbol{A}_{\mathrm{H}} = \begin{bmatrix} 0 & 0 & 0 & 0 & -1 & -1 & 1 \\ -1 & 1 & 1 & 1 & 0 & 0 & 0 \end{bmatrix} \tag{9}$$

$$\boldsymbol{v}_{\mathrm{H}} = [Q_{\mathrm{EB}} \quad Q_{\mathrm{HS}} \quad Q_{\mathrm{HE,2}} \quad Q_{\mathrm{HE,3}} \quad Q_{\mathrm{HEO,2}} \quad Q_{\mathrm{HP}} \quad Q_{\mathrm{HL}}] \tag{10}$$

d) Energy flow balance equation of hot water system

$$\boldsymbol{A}_{\mathrm{HW}}\boldsymbol{v}_{\mathrm{HW}}^{T} = \boldsymbol{0} \tag{11}$$

The energy flow vector $\boldsymbol{v}_{HW}$ and bus-branch connection matrix $\boldsymbol{A}_{\mathrm{HW}}$ are:

$$\boldsymbol{A}_{\mathrm{HW}} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & -1 & 1 \\ -1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & -1 & 1 & 0 & 0 \end{bmatrix} \tag{12}$$

$$\boldsymbol{v}_{\mathrm{HW}} = [F_{\mathrm{SWH}} \quad F_{\mathrm{HE,4}} \quad F_{\mathrm{HEO,4}} \quad F_{\mathrm{HEO,3}} \quad F_{\mathrm{HWT}} \quad F_{\mathrm{HWTO}} \quad F_{\mathrm{HWL}}] \tag{13}$$

Thus the energy flow balance equations of the entire system could be obtained:

$$\boldsymbol{A}\boldsymbol{v}^{\boldsymbol{T}} = \boldsymbol{0} \tag{14}$$

The bus-branch connection matrix $\boldsymbol{A}$ and energy flow vector $\boldsymbol{v}$ are

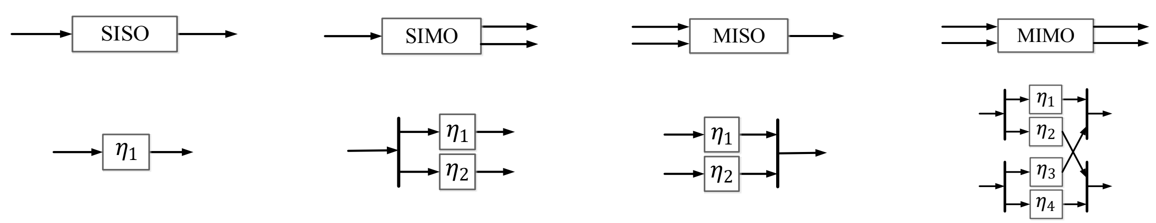
$$\boldsymbol{A} = \mathrm{diag}(\boldsymbol{A}_{\mathrm{E}}, \boldsymbol{A}_{\mathrm{C}}, \boldsymbol{A}_{\mathrm{H}}, \boldsymbol{A}_{\mathrm{HW}}) \tag{15}$$

$$\boldsymbol{v} = [\boldsymbol{v}_{\mathrm{E}} \quad \boldsymbol{v}_{\mathrm{C}} \quad \boldsymbol{v}_{\mathrm{H}} \quad \boldsymbol{v}_{\mathrm{HW}}] \tag{16}$$

3.2. Converter efficiency equation

The converter efficiency equations represent the characteristic of converters in the system. As mentioned above, there are four types of converters: single input single output (SISO), single input multiple outputs (SIMO), multiple inputs single output (MISO), and multiple inputs multiple outputs (MIMO). In the energy bus model, these converters are standardized that each converter will only have one input branch and one output branch. Thus the converter efficiency matrix $\boldsymbol{B}$ could be easily obtained, which is shown in Table 1.

Table 1. Standardization of SISO, SIMO, MISO, and MIMO converters.



SISO	SIMO	MISO	MIMO
$\boldsymbol{B} = [\eta_1 \quad -1]$	$\boldsymbol{B} = \begin{bmatrix} \eta_1 & -1 & 0 \\ \eta_2 & 0 & -1 \end{bmatrix}$	$\boldsymbol{B} = [\eta_1 \quad \eta_2 \quad -1]$	$\boldsymbol{B} = \begin{bmatrix} \eta_1 & \eta_3 & -1 & 0 \\ \eta_2 & \eta_4 & 0 & -1 \end{bmatrix}$

Therefore, the input and output relationship of each converter can be described. The element B_{kn} is defined as follows:

$$B_{kn} = \begin{cases} -1 & \text{if branch n is leaving from converter k} \\ \eta_k & \text{if branch n is entering towards converter k} \\ 0 & \text{if branch n is not incident to converter k} \end{cases} \tag{17}$$

Then the converter efficiency equation of the system is listed out:

$$\boldsymbol{B v^T} = \mathbf{0} \tag{18}$$

3.3. Distribution coefficient equation

In the case shown in Fig.1, for a given cooling load, the production of electric cooling system, ice storage system and ground source heat pump could not be decided. That's because there are more than one available paths between electric bus and cooling bus. The proportion of these converters need to be decided by defining distribution coefficient matrix $\boldsymbol{C}$. The element C_{mn} is defined as follows:

$$C_{mn} = \begin{cases} -1 & \text{if branch n is leaving from bus m} \\ \alpha_{mn} & \text{if branch n is entering towards bus m} \\ 0 & \text{if branch n is not incident to bus m} \end{cases} \tag{19}$$

Then the distribution coefficient equation can be written as:

$$\boldsymbol{C v^T} = \mathbf{0} \tag{20}$$

Combining (16), (18) and (20), the comprehensive energy flow balance equation of this IES is listed as follow:

$$\begin{bmatrix} \boldsymbol{A} \\ \boldsymbol{B} \\ \boldsymbol{C} \end{bmatrix} \boldsymbol{v^T} = \mathbf{0} \tag{21}$$

By solving the matrix equation, the solution of energy flow vector $\boldsymbol{v}$ of the entire system could be obtained.

4. Case study

In this section, the effectiveness of the proposed method is verified through the IES of NCSC shown in Fig.1. The parameters of the energy converters and buses in the system is listed in Table 2, including COP, efficiency and distribution coefficient.

Considering different operation period, two cases of the system are considered:

Case 1: During the cooling period, the heat load is zero and electric boiler is only used for hot water supply. And ground source heat pump produces cooling power.

Case 2: During the heat period, the cooling load is zero, so that electric cooling system and ice storage system stopped working. Electric boiler is used for both heat and hot water supply. Ground source heat pump produces heat power.

The output power of source equipment in the cooling period and heat period is shown in Table 3.

Table 2. Parameters of the energy converters and buses.

Converter	COP	Converter	Efficiency	Bus	Distribution coefficient
Electric cooling system	5.2	Electric boiler	0.95	Heat bus	0.8/0.2
Ice storage system	4.9	Heat exchanger	0.98	Cooling bus	1.0/0/0
Heat pump (heat)	5.4	Hot water storage	0.9		
Heat pump (cooling)	4.2				

Table 3. Output power of source equipment in cooling period and heat period

Equipment	Cooling period/kW	Heat period/kW
Photovoltaics	354.4	19.7
Solar water heat system	43.5	35.7
Microgrid with power storage	11.3	1.2
Hot water storage tank	232.6	477.8
Ice storage	0	0
Cooling storage	1650.3	0
Electricity load	2063.1	1871.2
Cooling load	2679.9	0
Heat load	0	2194.6
Hot water load	243.5	161.7

Fig. 2 shows the energy flow calculation results of cooling period and heat period.

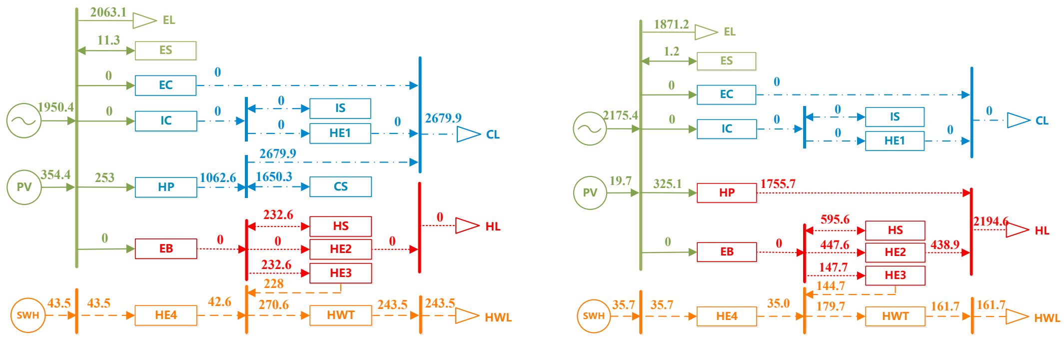


Fig.2 (a) Energy flow of cooling period (b) Energy flow of heat period

5. Conclusion

This paper proposes an energy bus structure that could realize the systematic modeling of IES. The matrix-based modeling method is proposed to describe the topology of the IES and the characteristics of energy converters. On this basis, the equations that describe the energy flow relationship of the entire system can be listed out. Finally, the effectiveness of the proposed method is verified through a case study of NCSC of State Grid Corporation of China considering cooling and heat period.

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