Coordinated Energy Management Systems for Multi-Energy Negotiated Transaction with Marginal Cost Information and Its Properties from the Viewpoint of Graph Complexity

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Abstract: Multi-energy networks, which include electricity, heat, and fuel energies, have attracted attention in recent times. These energies should be traded in market dynamics to maximize total economic benefits. However, energy transmission constraints caused by heat and/or fuel network structure restrict trading with market transactions. Therefore, in this paper, a coordinated energy management system based on negotiated transaction mechanism is considered. Then, a transaction protocol based on marginal cost of energy accommodation is proposed. Some properties of a general multi-energy network of negotiated transactions are also discussed. Then, the spatiotemporal multi-energy network is proposed as a generalized energy transformation model, along with an investigation of its properties from the viewpoint of graph complexity with a simulation example.

Key Words: energy management system, multi-energy, negotiated transaction.

1. Introduction

A market mechanism and/or community energy management system (EMS) for multi-energies that include electricity, heat, and fuel, such as gas, oil, or hydrogen, has attracted attention in recent times [1],[2]. The optimization of EMS with higher degrees of freedom for multi-energy trading should realize higher cost performance and social welfare.

Nevertheless, the trading of heat and/or fuel is based on pipelines, which causes geometric restrictions on available energy networks. Therefore, in general, heat and fuel trading and accommodation are localized, which is not optimal compared to global market trading and/or hierarchical EMS-based [3],[4] power network optimization. Localized EMS methodologies with multi-energy negotiated transactions are then required.

Most of all, past research activities into smart grids and many kinds of EMS are concerned with smart grids and market mechanism. In general, power grid networks can realize widespread and real-time energy exchange or accommodation. Also, economical optimization is achieved by virtual energy accommodation and trading with the market mechanism. On the other hand, the pipeline network that deals with heat and fuel energy is localized with economical restrictions, such as construction cost, while heat and fuel energy can be easily stored in thermal storage and fuel tanks. As such, heat and fuel energy is suitable for local and long-range energy network optimization.

From these considerations, the localized multi-energy network and its optimization problem is expected to be one of the new research areas in the smart grid.

Initially, the requirements of EMS for multi-energy accommodation are discussed in this paper. Second, the EMS scheme for multi-energy negotiated transactions with the condition of localization is considered. Then, a new multi-energy negotiated transaction protocol is proposed, which is based on marginal cost [5],[6] obtained from each energy cost and its transformation cost. In addition, the general multi-energy negotiated transaction system as the energy accommodation network is considered and its theoretical characteristics are discussed [7]. Lastly, we extend the discussion to the generalized structure of the energy network system, and the generalized spatiotemporal multi-energy (STME) network is proposed. Then we focus on the structure of the network from the viewpoint of graph complexity [8],[9], and investigated the relationship between the degrees of freedom of the energy system and the graph complexity. These properties are shown with a simulation example.

2. Negotiated Transaction Protocol Based on Marginal Cost

2.1 Problem Description

In this paper, many kinds of energy devices, such as heat resources with a heat pump and absorption chiller, electricity resources with a generator and cogeneration system, an energy storage system with a battery, thermal storage, and a fuel tank are considered. The unit prices of electricity and heat generated from these energy devices are determined by the prices of input factors, such as fuel price, commercial electricity and heat price, each energy device’s capacity and efficiency, heat recycle rate in a cogeneration system, time and seasonal factors, and weather factors related to the performance of some energy devices. These unit prices are expressed as the energy marginal cost. An example of a marginal cost function is shown in Fig. 1, which is the relation between energy amount and energy unit cost. Generally speaking, energy resources with cheaper prices are consumed in advance, so the total energy marginal cost curve is a stepwise function, as shown in Fig. 1, where the step change of marginal cost corresponds to a new energy device selection.

As a most simple case, two energy consumers are supposed
to use heat energy accommodation. The supposed energy devices of the two energy consumers are shown in Fig. 2.

Each consumer can buy commercial electricity, commercial heat, such as steam, hot or cool water, and commercial fuel, such as gas, oil, and hydrogen. Then, heat energy is exchanged between the two consumers via a pipeline network, as shown in Fig. 2.

Suppose that User A has \( M \) kinds of heat resource devices, and their output levels are \( \{x_1, x_2, \ldots, x_M\} \) and corresponding marginal costs are \( \{MC_{x_1}, MC_{x_2}, \ldots, MC_{x_M}\} \). Similarly, suppose that User B has \( N \) kinds of heat resource devices, and their output levels are \( \{y_1, y_2, \ldots, y_N\} \) and corresponding marginal costs are \( \{MC_{y_1}, MC_{y_2}, \ldots, MC_{y_N}\} \). Here we suppose \( MC_{x_1} < MC_{x_2} < \cdots < MC_{x_M} \) and \( MC_{y_1} < MC_{y_2} < \cdots < MC_{y_N} \). If the heat demand in User A is determined as \( H_A \), then cheaper heat resource is used in advance and each heat device output is as follows as an optimal strategy for User A:

\[
H_A = x_1 + x_2 + \ldots + x_M. \tag{1}
\]

Then the economic cost of heat energy supply is

\[
H_{Acost} = MC_{x_1} \cdot x_1 + MC_{x_2} \cdot x_2 + \cdots + MC_{x_M} \cdot x_M, \tag{2}
\]

where \( x_1 = x_{1\text{max}}, x_2 = x_{2\text{max}}, \ldots, x_{m-1} = x_{m-1\text{max}} \).

That means the outputs of heat devices from no.1 to no. \( m-1 \) are maximum load level and only the last heat device no. \( m \) is partial load, while the heat load no. \( m+1 \) to no. \( M \) are stopped. Similarly, if the heat demand in User B is determined as \( H_B \), then each heat device output is as follows as an optimal strategy for User B:

\[
H_B = y_1 + y_2 + \cdots + y_N. \tag{3}
\]

Then the economic cost of heat energy supply is represented as follows:

\[
H_{Bcost} = MC_{y_1} \cdot y_1 + MC_{y_2} \cdot y_2 + \cdots + MC_{y_N} \cdot y_N. \tag{4}
\]

These energy balance equations are results of each individual optimization.

Then if heat energy accommodation is considered, the total optimal strategy is as follows.

\[
H_A = x_1' + x_2' + \cdots + x_M' + y_N' + \cdots + y_{N'}', \tag{5}
\]

\[
H_B = y_1' + y_2' + \cdots + y_{M'}' + x_M' + \cdots + x_{M'}'. \tag{6}
\]

Then the total economic cost of heat energy supply is

\[
H_{Acost}' = MC_{x_1} \cdot x_1' + \cdots + MC_{x_M'} \cdot x_M' + MC_{y_{N'}} \cdot y_{N'}, \tag{7}
\]

and

\[
H_{Bcost}' = MC_{y_1} \cdot y_1' + \cdots + MC_{y_{M'}} \cdot y_{M'}, \tag{8}
\]

Then the decrease of the cost

\[
(H_{Acost} + H_{Bcost}) - (H_{Acost}' + H_{Bcost}') \tag{9}
\]

is the economic benefit obtained by the heat energy accommodation.

In the case of market trading, in which all energy customer can trade directly with the market without any agency, social welfare is defined as

\[
\text{social welfare} = \text{total consumer benefit} - \text{total supplier cost}.
\]

However, in this case, where there are only two players within the negotiated transaction, social welfare is simply defined as the total economic benefit defined in (9).

Next, a procedure for realizing energy accommodation between the two consumers, with negotiation between each EMS of the two energy consumers, is proposed as follows.

Step 0: Each player’s EMS calculates the marginal cost of each device and marginal cost curves.

Step 1: As the initial solution for iteration, each EMS predicts corresponding demand and calculates the individual optimal operation and energy usage plan with the general optimization method for EMS [4],[5]. Set \( N = 1 \).

Step 2: Each EMS exchanges marginal cost curve information with the others, which includes surplus energy from each player’s device.

Step 3: Each EMS recalculate the individual optimal operation, considering the other players’ surplus energy. Increment \( N = N + 1 \). Then, the economic cost of energy supply is calculated from the individual marginal cost curve and those of the other players.

Step 4: The total cost of each EMS of stage \( N \) is compared with that of stage \( N - 1 \).

If an EMS detected its cost decrease, then it negotiates with other players’ EMS to utilize their surplus energy as energy accommodation.

Otherwise, the negotiation iteration ends.
Fig. 3 Energy accommodation procedures.

Attritionary, if $N = N_{\max}$ then the negotiation iteration is enforced to end.  

Step 5: All players’ negotiation iterations end, and each EMS calculates the economic benefit of energy accommodation, namely the difference between the cost of Step 1 and the cost of the final step, and its portion of the predetermined sharing rate of the total economic benefit obtained with energy accommodation gained by the other players.

The procedure is illustrated in Fig. 3.

Hereafter, we restrict the discussion in this paper under the following conditions.

1) All energy devices are supposed to have linear cost properties, so the marginal cost curve is a perfect flat stepwise function as shown in Fig. 1.
2) Each player does not have any strategic will during negotiation procedure. So, they are supposed to disclose the true marginal cost information to other players.

1 The negotiation iteration in Fig. 3 has a possibility of infinite loop. So, in Step 4, the upper bound of iteration number $N_{\max}$ is introduced as the safe guard. The infinite loop may be caused if some of energy devices have strong nonlinearity, which causes non-flat marginal cost in Fig. 1 and it may lead to a kind of limit cycle in a nonlinear feedback system. Another possible case is that if each player had a strategic will like a game, they might change the marginal cost information during every negotiation iteration procedure. Then selection of optimal energy devices may change every iteration that causes infinite negotiation iteration.

2 With the optimization procedure, economic benefit can be obtained as the difference between optimal energy accommodation and separated individual optimization. Then, the economic benefit should be shared with both users. “Sharing rate” means the ratio of the division of the economic benefit between two users. Generally speaking, the sharing rate shall be even, namely 50% and 50%.

With these conditions, the optimal selection of cheaper energy devices must be unique, so the negotiation iteration should be finite.

The nonlinear cost properties of energy devices and/or the game theoretical behavior of players are future research work.

An example of the marginal cost curve in the case of the two consumers’ negotiation procedures mentioned above is illustrated in Fig. 4. In Case 1, the left part of the marginal cost curve shows that consumer A can obtain economic benefit by procuring energy from consumer B, compared to standalone energy usage. Similarly, in Case 2, the right part of the marginal cost curve shows that consumer A can obtain economic benefit by selling the surplus energy to consumer B, compared to standalone energy usage.

These procedures are the proposed protocols of a negotiated transaction for multi-energy accommodation.

2.2 Numerical Example

A typical numerical simulation example is shown here. The EMS plant configuration is illustrated in Fig. 5.

Each commercial power price and capacity, energy device properties (COP, Capacity) is summarized in Table 1.
Table 1: Properties of energy device specifications.

| Device name ID | Price, COP | Capacity |
|----------------|------------|----------|
| Commercial Elec. | 10,15,20yen/kW (base/mid/peak) | 1000kW |
| Gas ABR* | 1.0 | 300kW |
| Heat recovery ABR* | 1.0 | 100kW |
| Turbo Refrigerator | 1.8 ~ 2.5 (peak/mid/load) | 300kW |
| Thermal storage | 1.0 | $\infty$ |

*ABR: Absorption refrigerator
** HP: Heat pump

Fig. 6: Load curve of electricity and cool water of each player.

The electricity and cool water load curve of each player in a day in summer is considered to be as shown in Fig. 6.

The result of the simulation result is shown in Fig. 7. Figures 7(a) and (b) show the accumulated curve of marginal cost for each heat source arranged from the cheapest to the highest cost. The vertical line represents current demand for heat energy; that is, cool thermal for an air conditioner. Figure 7(c) shows the energy transfer from player #1 to player #2 because the surplus and cheap heat energy of player #1, marked with a solid line circle, is transferred to player #2 instead of the higher cost heat energy of player #2, marked with a dotted line circle.

To illustrate the mechanism of energy accommodation procedure, this example is quite a simple one where the linear cost
model, namely the marginal cost, is constant in spite of a partial load for each energy resource device. In addition, the demands of energy consumers are supposed to be constant.

From the simulation result, the negotiation procedure works to prioritize the utilization of the other player’s cheaper energy resource instead of the player’s own energy resource with a higher cost.

3. General Negotiated Transaction Network of Multi-Energy

In this section, the energy accommodation procedure is generalized as the energy transformation network model.

3.1 Case Study of Various Energy Negotiated Transactions

In this section, the heat energy negotiated transaction model with two energy consumers, as mentioned in former section, is extended to general cases. The energy to be accommodated can be extended to multi-energy, while the 1:1 energy accommodation between the two energy consumers can be extended to 1:n. Some examples of these extended energy negotiated transaction models are shown in Fig. 8.

Here, the social welfare function $SW(\cdot)$ is defined as the summation of the economic benefits obtained by all energy consumers as follows:

$$SW(\text{condition}) = \sum \text{Energy consumers benefit (condition)} - \sum \text{Energy supplier cost (condition)}.$$  \hspace{1cm} (10)

Here the summation is taken over all players, and the condition is the assumption of energy trading and/or energy accommodation. If it is supposed that the energy demand of consumers is always satisfied, then the former term of (10) becomes constant. Therefore, (10) is also denoted as (11).

$$SW(\text{condition}) = \text{const.} - \sum \text{Energy supplier cost (condition)}. \hspace{1cm} (11)$$

Then the following results are obtained.

**Theorem 1** The social welfare function $SW(\text{Multi-Energy})$, optimized in the multi-energy network, is not less than that optimized in a single energy network:

$$SW(\text{Multi-Energy}) \geq SW(\text{Single-Energy}). \hspace{1cm} (12)$$

**Proof** The degree of freedom of the energy network optimization problem with accommodation of multi-energy is higher than that of single energy. Thus, the optimal solution of a multi-energy network should be better than that of a single energy network.

**Theorem 2** The social welfare $SW(\text{Market})$ obtained in the model of market mechanism which all energy consumers can join is not less than the social welfare $SW(\text{Accommodation})$ obtained in the model of energy negotiated transaction mechanism:

$$SW(\text{Market}) \geq SW(\text{Accommodation}). \hspace{1cm} (13)$$

**Proof** As the discussion in Section 2.1, we defined the market as a mechanism in which all energy customers can trade energy directly with the market without any agency. While we defined the accommodation as a negotiated transaction between two restricted energy customers. The degree of freedom of the energy network optimization problem with market mechanism that allows all energy consumers to join should be higher than that with an energy negotiated transaction mechanism. Thus, the optimal solution of energy network based on the market mechanism should be better than that based on an energy negotiated transaction mechanism.

**Remark** These two theorems are quite trivial, but they suggest the relationship between economic cost optimality and degrees of freedom in EMS problems. Therefore, these results are shown as hints of further discussions.

3.2 Generalized Energy Transformation Network

The functions of energy systems are energy generation, energy transformation and transportation, and energy consumption as energy load. The key rule of an energy network is the matching of demand and supply of each kind of energy, namely electricity, heat and cool thermal energy, and fuel energy. Each kind of energy can be transformed to another kind of energy with transformation devices, as illustrated in Table 2 and Fig. 9.

In addition, some energy storage devices, such as battery storage, thermal storage, and fuel tank, are also denoted in the figure. It is worth noting that some device groups cannot transform each layer energy network to another layer energy network, which means partially irreversible energy transformation.

Then, the generalized energy transformation network is considered below. Allow us to note three viewpoints of the energy transformations.

(1) Spatial energy transfer

Between players #1 and #2, electricity can be transferred with their own power line, and thermal energy can be transferred with their own heat pipeline.

| device          | transformation function         |
|-----------------|--------------------------------|
| boiler          | fuel $\rightarrow$ heat thermal |
| generator       | fuel $\rightarrow$ electricity  |
| co-generation sys. | fuel $\rightarrow$ electricity & heat thermal |
| adsorption      | fuel & heat $\rightarrow$ cool thermal |
| refrigerator    | heat pump chiller $\rightarrow$ electricity & heat thermal |
| binary generation | heat thermal $\rightarrow$ electricity |
| fuel cell       | fuel $\rightarrow$ electricity & heat thermal |
(2) Temporal energy transfer

Between different time zones, we can store and consume energy using energy storage devices, such as battery storage, thermal storage, and fuel tanks. Such devices can transfer energy between different time zones.

(3) Multi-energy transformation

Electricity, cool and heat thermal, and fuel energy can be transformed into each other through many kinds of energy devices, shown in Table 2.

These three kinds of energy transfer/transformation are denoted as the spatiotemporal multi-energy network (STME network). As a simple STME network, we shall consider the restricted case of two players, a night and day time zone, and multi-energy with electricity and heat energy. The simple STME network is illustrated in Fig. 10.

The STME network shown in Fig. 10 is a kind of graph. The node that is the vertex of the graph corresponds to energy resource and energy load. The branch that is the edge of the graph corresponds to energy transfer and transformation devices. At each node, energy supply and energy demand must coincide, while at each energy transfer and transformation, an energy loss factor exists.

Table 3  Simulation model variables & parameters.

| (1) Spatial energy accommodation factor | Player #1 | Player #2 |
|----------------------------------------|----------|----------|
| Power line energy efficiency energy capacity | $E_{TR1}^N, E_{TR1}^D$ | $E_{TR2}^N, E_{TR2}^D$ |
| Heat pipeline energy efficiency energy capacity | $E_{TR2}^N, H_{TR2}$ | $E_{TR1}^N, H_{TR1}$ |
| Efficiency | $\gamma_N = 90\%$ (night) | $\gamma_D = 95\%$ (day) |
| Energy capacity | $H_{TR2}^{max} = 200kW$ |

(2) Temporal energy accommodation factor

| Battery storage energy efficiency energy capacity | $E_{BAT1}^N, E_{BAT1}^D$ | $E_{BAT2}^N, E_{BAT2}^D$ |
|-------------------------------------------------|--------------------------|--------------------------|
| Efficiency | $\varepsilon_1 = 90\%$ | $\varepsilon_2 = 80\%$ |
| Energy capacity | $E_{BAT}^{max} = 100kWh$ | $E_{BAT}^{max} = 200kWh$ |

(3) Multi-energy transformation factor

(transformer from elec. to heat energy)

| Heat pump (elec. to heat) | $E_{HP1}^N, E_{HP1}^D$ | $E_{HP2}^N, E_{HP2}^D$ |
|---------------------------|--------------------------|--------------------------|
| COP | $\phi_1^N = 3.5$ (night) | $\phi_2^N = 3.6$ (night) |
| Energy efficiency | $\phi_1^D = 4.0$ (day) | $\phi_2^D = 3.9$ (day) |
| Energy capacity | $E_{HP}^{max} = 500kW$ | $E_{HP}^{max} = 300kW$ |

(4) Other energy resources (commercial energy)

| Boiler (Gas to heat) | $G_1^N, G_1^D$ | $G_2^N, G_2^D$ |
|----------------------|----------------|----------------|
| Energy efficiency | $\beta_1^N = 90\%$ (night) | $\beta_2^N = 91\%$ (night) |
| Energy efficiency | $\beta_1^D = 95\%$ (day) | $\beta_2^D = 94\%$ (day) |
| Energy capacity | $\infty$ | $\infty$ |
| Commercial power capacity | $E_{max} = 1000kW$ | $E_{max} = 1000kW$ |

| Price of electricity | $P_e = 10yen/kWh$ (night) |
|----------------------|--------------------------|
| Price of gas | $P_g = 2yen/kWh$ (day) |

(5) Energy demands

| Demand of elec. | $D_1^N = 300kW$ (night) | $D_1^D = 200kW$ (night) |
|----------------|--------------------------|--------------------------|
| Demand of heat | $H_1^N = 100kW$ (night) | $H_2^D = 200kW$ (night) |
|----------------|--------------------------|--------------------------|
| Demand of heat | $H_1^D = 500kW$ (day) | $H_2^D = 400kW$ (day) |

| Demand of heat | $H_1^D = 700kW$ (day) | $H_2^D = 600kW$ (day) |

*The reason that energy efficiency changes between night and day is because of different heat loss factors taking account of out-air temperature between night and day.

3.3 Property of STME Network

Here we will consider the properties of the STME network. Some properties of the STME network as a graph are intro-
Table 4 Simulation conditions and corresponding branch numbers.

| Simulation condition       | Branch number in Fig.10 |
|---------------------------|-------------------------|
| Elec. accommodation(night)| b1                      |
| Elec. accommodation(day)  | b2                      |
| Heat accommodation(night) | b3                      |
| Heat accommodation(day)   | b4                      |
| Heat pump (Player#1/night)| b9                      |
| Heat pump (Player#1/day)  | b11                     |
| Heat pump (Player#2/night)| b10                     |
| Heat pump (Player#2/day)  | b12                     |
| Battery storage (Player#1)| b5                      |
| Battery storage (Player#2)| b6                      |
| Heat storage (Player#1)   | b7                      |
| Heat storage (Player#2)   | b8                      |

Produced as follows.

**Average distance:** The minimum number of branches between two nodes is defined as the shortest distance. The average of the shortest distances of all the couples of nodes is defined as the average distance.

**Average degree:** Each node is connected to other nodes with branches. The average of the branch numbers connected to a node is defined as the average degree.

**Average connection:** A node is connected to other nodes with branches. Sometimes, the graph, as a tree, is divided into co-trees caused by a disconnection between the two nodes. Thus, a node can count the number of all connected nodes to the node, which is the node number included in the co-tree. The average of the connected node number for all the nodes is defined as the average connection.

These indices reveal the complexity of the graph. To investigate the property of the STME network, we consider the relationship between STME network complexity and optimization performance of EMS with energy accommodation.

As a numerical example corresponding to Fig. 10, STME network is shown here. The property parameters of energy devices supposed here are summarized in Table 3.

**Simulation conditions:**

Next, the EMS simulation was evaluated for each case, as follows. The structure of the STME network model in Fig. 10 was changed depending on the existence of 12 branches. Then, \(2^{12} = 4,096\) cases of simulation scenarios were generated. The scenario conditions corresponding to the branch number, from b1 to b12, are summarized in Table 4. For each scenario, the EMS optimization solutions were calculated and the total energy costs per day were obtained. The details of the calculation formulation are denoted in the Appendix, where the best solution of EMS optimization is solved as a linear programming optimization problem.

**Metrics of graph complexity:**

Three types of indices of the graph structure complexity of the STME network are introduced and evaluated through all case simulations. The indices are the average distance, the average degree, and the average connection. These are supposed...
to be metrics corresponding to the degree of freedom of energy network optimization.

The simulation results are shown in Fig. 11. Each plot shows the total energy cost as EMS performance versus the STME network complexity indices, average distance, average degree, and average connection.

From the results of the simulation in Fig. 11, the following properties are observed.

(a) The relationship between total energy cost and average distance is not clear. The reason is that average distance does not always reveal the connection condition of each of the nodes in the STME network.

(b) The relationship between total energy cost and average degree seems to be correlated. This is understandable because the increase of degree, namely branch number, means an increase in the degrees of freedom of EMS optimization that leads to total energy cost reduction.

(c) The relationship between total energy cost and average connection also seems to be correlated. This is also understandable because the increase of connection, namely node number, means an increase in the degrees of freedom of EMS optimization that leads to total energy cost reduction.

These results show that the graph metrics, the average degree and the average connection, are candidates for effective metrics that reveal the energy optimization degree of freedom. Thus, these graph metrics have the possibility of being useful indices for designing the ideal energy network.

4. Conclusion

In this paper, a multi-energy based energy accommodation procedure between two energy consumers is discussed. Then, a negotiation protocol for energy accommodation is proposed, which is based on the sharing of marginal cost information determined from each energy device performance and each energy resource price. Next, the energy network model is extended to that of multi-energy and multi-consumer, and some theoretical results are shown and discussed. In addition, the generalized STME network is proposed, and its properties with three types of graph complexity metrics, from the viewpoint of energy optimization degree of freedom, are investigated using 4,096 cases of simulation examples. As a result, the average degree and the average connection are effective metrics for revealing the optimization degree of freedom. This fact suggests a guideline for the design of an ideal energy network with graph complexity metrics.

The multi-energy, multi-agents, and spatiotemporal networks of generalized energy accommodation model with a negotiated transaction mechanism discussed in this paper should be the focus of new research on smart grid or smart energy networks, and future theoretical research is anticipated.

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Appendix

The optimization problem introduced as a numerical example in Section 3.3 is a simple EMS problem with only two players, two time instances of night and day, and two kinds of energy, namely electricity and heat. So the optimized solutions of energy accommodation with negotiation transaction procedures are, on best case, equal to that of linear programming solution formulated below.

The notation of each variable is denoted in Table 3 in each corresponding term. Then the theoretical best optimal solution in each case of EMS problem is obtained as an LP solution (A. 1)–(A. 15):

\[
\begin{align*}
x &= [E_N^1, E_D^1, E_N^2, E_D^2, E_{BAT}^1, E_{BAT}^2, E_{TRI}^1, E_{TRI}^2, E_{TRI}^3, E_{TRI}^4, E_{TRI}^5, E_{TRI}^6] \\
b &= [D_{BAT}^1, D_{BAT}^2, D_{BAT}^3, D_{BAT}^4, D_{BAT}^5, D_{BAT}^6, H_{TRI}^1, H_{TRI}^2, H_{TRI}^3, H_{TRI}^4, H_{TRI}^5, H_{TRI}^6] \\
F &= \begin{bmatrix} I_{4 \times 4} & E & A & -I_{4 \times 4} & Z_{4 \times 10} \end{bmatrix} \\
I_{4 \times 4} &= \begin{bmatrix} 1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 \end{bmatrix}, \\
E &= \begin{bmatrix} -1 & 0 \\
\varepsilon_1 & 0 \\
0 & -1 \end{bmatrix}, \\
A &= \begin{bmatrix} \alpha & 0 & -1 & 0 \\
0 & \alpha & 0 & -1 \\
-1 & 0 & \alpha & 0 \\
0 & -1 & 0 & \alpha \end{bmatrix}, \\
Z_{4 \times 10} &= \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}.
\end{align*}
\]
\[ P = \begin{bmatrix} \varphi_1^N & 0 & 0 & 0 \\ 0 & \varphi_1^D & 0 & 0 \\ 0 & 0 & \varphi_2^N & 0 \\ 0 & 0 & 0 & \varphi_2^D \end{bmatrix}, \quad (A.8) \]

\[ B = \begin{bmatrix} \beta_1^N & 0 & 0 & 0 \\ 0 & \beta_1^D & 0 & 0 \\ 0 & 0 & \beta_2^N & 0 \\ 0 & 0 & 0 & \beta_2^D \end{bmatrix}, \quad (A.9) \]

\[ S = \begin{bmatrix} -1 & 0 \\ \sigma_1 & 0 \\ 0 & -1 \\ \sigma_2 \end{bmatrix}, \quad (A.10) \]

\[ G = \begin{bmatrix} \gamma_N & 0 & -1 & 0 \\ 0 & \gamma_D & 0 & -1 \\ -1 & 0 & \gamma_N & 0 \\ 0 & -1 & 0 & \gamma_D \end{bmatrix}, \quad (A.11) \]

\[ C = \begin{bmatrix} P_{E_1}^N, P_{E_1}^D, P_{E_2}^N, P_{E_2}^D, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0 \end{bmatrix}^T, \quad (A.12) \]

\[ x_{\text{max}} = \begin{bmatrix} E_{\text{max}}, E_{\text{max}}, E_{\text{max}}, E_{\text{max}}, E_{\text{max}}, E_{\text{max}}, E_{\text{max}}, E_{\text{max}}, E_{\text{max}}, E_{\text{max}} \end{bmatrix}, \quad (A.13) \]

\[ x_{\text{min}} = \begin{bmatrix} 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0 \end{bmatrix}^T, \quad (A.14) \]

\[ \text{min} \quad J = C^T x \]

\[ \text{s. t.} \quad F x = b, \]

\[ x_{\text{min}} \leq x \leq x_{\text{max}}. \quad (A.15) \]

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