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Special Focus on Optimization for Cyber-Physical Energy Systems

Cyber-physical model for efficient and secured operation of CPES or energy Internet

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Dear editor,

Global energy and environmental crisis is one of the most serious issues on the sustainable development of human society in the 21st century. Making full use of renewable energy sources is one of the most effective ways to resolve the energy and environmental problems. However, we are facing the serious challenges due to the uncertain natures of the renewable energy sources.

Efficient consumption at demand side has magnifying effect on energy savings with regard to the unutilized energy in production and conversion [1]. If the flexible energy demand is controlled to match the uncertain renewable supply, these uncertainties can be accommodated and their impact on the system operation can be reduced. Therefore, optimal coordination of the energy supply and demand are extremely important.

Facilitated by information technology, cyber-physical energy system (CPES) or energy Internet provides a desirable infrastructure for supply-demand coordination in a networked energy system. As shown in Figure 1(a), a typical CPES supports bi-directional flows between the supply side including thermal and hydro power, urban heating systems, natural gas, renewable supply, etc., and demand side including enterprise, commercial and residential buildings, and other typical energy systems with many media such as electrical, thermal, natural gas, and storage devices.

Many efforts have been made to improve the efficiency of energy and power systems. Ilic et al. [2] developed a cyber-physical system (CPS)-based model for distributed sensing and control of energy systems. Guo et al. [3] described a future architecture of the energy interconnection based on CPS. Wei and Li [4] developed a complex network model based on CPS for the modern city water supply networks. Although the above innovative results are reported in the literature, the coupling and conversion among multiple energy media and sources, and the interaction effect between cyber and physical system are not explicitly formulated. As a result, the advantages of information flows to all corners of CPES may not be fully utilized and it is difficult to maximize its efficiency.

CPES is a typical complex networked system that integrates data collection, communication, computation and optimization. Based on the information technology and big data analysis, CPES can collect the accurate information of energy consumption, system status, and environments that are closely related to renewable supply, which is necessary to optimally coordinate the supply and demand to achieve energy savings and emission reduction. Because of the complicated energy conversion and transmission processes and the coupling between cyber and physical system, how to

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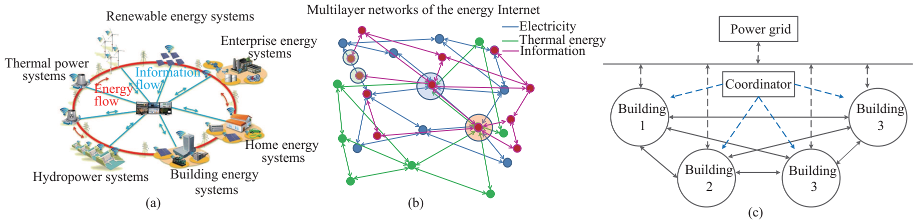

Figure 1 (Color online) (a) A typical CPES; (b) multiple networks in the CPES; (c) a network of building energy systems.

explicitly formulate the CPES remains open in general.

In this study, a cyber-physical model is introduced for efficient and secured operation of CPES or energy Internet. It can capture the intrinsic nature of energy conservation between the supply and demand at all levels and the coupling among multiple energy media and systems. The interaction between the cyber and physical systems, and the topology of various energy networked systems are explicitly formulated to facilitate system optimization, and safety and security analysis.

CPES formulation. As shown in Figure 1(b), a CPES consists of multiple networked systems including that of electricity, thermal energy, natural gas, and information. The models of the individual energy systems are extensively studied in the literature. For example, the scheduling problem of power system is usually formulated as an optimization model with the security constraints of all lines and branches, energy balance at each node, operation constraints of energy production. The model of the natural gas network generally formulates natural gas well, transmission pipelines, compressor, storage devices of natural gas, and loads. The thermal energy network is usually formulated by the steady-state equations of thermodynamics and fluid mechanics. In a CPES, individual energy systems or networks may be coupled due to energy conversions among the different energy media and sources. Therefore, a CPES model needs to capture the coupling and conversion of individual energy systems, and the interaction between cyber and physical systems. It is generally not a simple superposition of the models of the individual energy network.

We develop a steady-state model for a CPES. Consider the CPES consisting of N nodes with discrete-time in K stages. Its topology is represented as a directed graph $G = (\mathcal{V}, \mathcal{E})$, where $\mathcal{V}$ is the vertex set composing of N vertices, i.e., $\mathcal{V} = \{v_1, \ldots, v_N\}$. Note that each v_i in graph G corresponds to the node i in the CPES; and $\mathcal{E} \subseteq \mathcal{V} \times \mathcal{V}$ is the edge set of the directed edges connecting two vertices. The attribute of each vertex v_i is a vector $\boldsymbol{v}_i$ divided into two parts, namely energy vector $\boldsymbol{v}_i^e$ and information vector $\boldsymbol{v}_i^s$, i.e., $\boldsymbol{v}_i = [\boldsymbol{v}_i^e, \boldsymbol{v}_i^s]^{\mathrm{T}}$. The information vector is defined as $\boldsymbol{v}_i^s = [\overrightarrow{\boldsymbol{x}}_i, \overleftarrow{\boldsymbol{x}}_i]^{\mathrm{T}}$, where elements of $\overrightarrow{\boldsymbol{x}}_i$ ($\overleftarrow{\boldsymbol{x}}_i$) are the system states and the information of node i transmitted to (obtained from) its neighbor nodes among the cyber network. Suppose that $\mathcal{N}_i$ is the set of neighbor nodes for node i. The energy vector can be divided into $|\mathcal{N}_i|$ parts, i.e., $\boldsymbol{v}_i^e = [\boldsymbol{e}_{i,1}, \boldsymbol{e}_{i,2}, \ldots, \boldsymbol{e}_{i,|\mathcal{N}_i|}]^{\mathrm{T}}$ with non-negative elements. For any vector $\boldsymbol{e}_{i,j}$, it indicates the energy exchange between node i and j, which can thus be partitioned into two parts, i.e., $\boldsymbol{e}_{i,j} = [\overrightarrow{\boldsymbol{e}}_{i,j}, \overleftarrow{\boldsymbol{e}}_{i,j}]^{\mathrm{T}}$, where $\overrightarrow{\boldsymbol{e}}_{i,j}$ ($\overleftarrow{\boldsymbol{e}}_{i,j}$) is a vector, in which each element is one type of the energy transmitted to (from) the neighbor node j. A weighted adjacency matrix $\boldsymbol{A} = (\boldsymbol{w}_{i,j})_{N \times N \times H}$ with non-negative elements is used to describe the topology of the CPES, where H is the dimension of the $\boldsymbol{v}_i$; and $\boldsymbol{w}_{i,j} = [w_{i,j}^1, w_{i,j}^2, \ldots, w_{i,j}^H]^{\mathrm{T}}$ is a weight vector, in which each element is the connected relation and its weight. For the energy vector in $\boldsymbol{v}_i$, the weight indicates the energy loss in the transmission line, and 0 if there is no connection. For the information vector, the weight is 1 (0) if there is (no) connection.

Based on the above definition, the node model describes the dynamic conversion among multiple energy media and systems, and guarantees the energy balance in each node, which is given by

$$
\begin{aligned}
&\min_{\boldsymbol{u}_i^k} J_i \quad \text{with } J_i = \sum_{k=1}^{K} f_i^k(\boldsymbol{x}_i^k, \boldsymbol{u}_i^k, \overleftarrow{\boldsymbol{x}}_i^k),\\
&\text{s.t. } \boldsymbol{e}_{s,i}^k + \sum_{j \in \mathcal{N}_i} \overleftarrow{\boldsymbol{w}}_{i,j} \overleftarrow{\boldsymbol{e}}_{i,j}^k = \boldsymbol{e}_{d,i}^k + \sum_{j \in \mathcal{N}_i} \overrightarrow{\boldsymbol{e}}_{i,j}^k, \qquad (1)\\
&\qquad \boldsymbol{x}_i^{k+1} = g_{s,i}(k, \boldsymbol{x}_i^k, \boldsymbol{u}_i^k, \overleftarrow{\boldsymbol{x}}_i^k),\\
&\qquad \text{operating constraints of energy devices,}
\end{aligned}
$$

where k is the stage index, with $k = 1, 2, \ldots, K$; $\boldsymbol{x}_i^k$ is the system state of the node i at k; $\boldsymbol{u}_i^k = [\boldsymbol{e}_{s,i}^k, \overleftarrow{\boldsymbol{e}}_{i,j}^k, \boldsymbol{e}_{d,i}^k, \overrightarrow{\boldsymbol{e}}_i^k]^{\mathrm{T}}$ is the decision vectors of the node i at k; $f_i^k(\cdot)$ is the objective function; $\boldsymbol{e}_{s,i}^k$ ($\boldsymbol{e}_{d,i}^k$) is a vector with each element being one type of energy production (demand) and output (input) energy of storage devices in node i at k; $\overleftarrow{\boldsymbol{w}}_{i,j}$ is a part of $\boldsymbol{w}_{i,j}$ corresponding to the energy exchange from the neighbor node j to node i; and

$g_{s,i}(\cdot)$ could be linear or nonlinear. The first constraint in (1) expresses the energy balance in node i and the second one for the system state dynamics and the information updating from neighbor nodes. The detailed operation constraints of energy supply, demand and storage devices can be found in our previous studies [1] in detail.

The above CPES model is applicable to system optimization, and safety and security analysis with various objectives, such as those of minimizing the energy cost for economy dispatch, minimizing the emission reduction for environmental protection, minimizing the operation risk on the safety and security, or having a tradeoff between the three objectives mentioned above. The detailed formulation can be found in our follow-up publications.

The traffic model is used to describe the transmission of information and energy flow and guarantee the energy balance in the transmission lines of the CPES. For the s-th type of energy exchange between node i and j, we have the following constraint for the balance in the transmission line:

$$\overrightarrow{e}^{s,k}_{i,j} - \overleftarrow{w}^{s}_{i,j}\overleftarrow{e}^{s,k}_{i,j} = \overleftarrow{w}^{s}_{j,i}\overleftarrow{e}^{s,k}_{j,i} - \overrightarrow{e}^{s,k}_{j,i}, \tag{2}$$

where $\overrightarrow{e}^{s,k}_{i,j}$ and $\overleftarrow{e}^{s,k}_{i,j}$ are the s-th element of $\overrightarrow{\boldsymbol{e}}_{i,j}$ and $\overleftarrow{\boldsymbol{e}}_{i,j}$ for the node i at k, respectively, $\overleftarrow{w}^{s}_{i,j}$ and $\overleftarrow{w}^{s}_{j,i}$ are the s-th element of $\boldsymbol{w}_{i,j}$ and $\boldsymbol{w}_{j,i}$, respectively, which indicate the energy loss of the transmission line between node i and j.

For the information exchange between node i and j, we have the following equation for node i:

$$\overleftarrow{\boldsymbol{x}}^{k}_{i,j} = Q^k\overleftarrow{\boldsymbol{x}}^{k-1}_{i,j} + (1-Q^k)\overleftarrow{w}^{x}_{i,j}\boldsymbol{D}[\overrightarrow{\boldsymbol{x}}^{k}_{j}, \ldots, \overrightarrow{\boldsymbol{x}}^{k-p}_{j}]^{\mathrm{T}}, \tag{3}$$

$$\Pr(Q^k = 1) = q, \quad \Pr(Q^k = 0) = 1 - q, \tag{4}$$

where $\overleftarrow{\boldsymbol{x}}^{k}_{i,j}$ is the j-th parts of the vector $\overleftarrow{\boldsymbol{x}}_i$ and it indicates the information obtained from node j at k; Q^k is integer variables, $Q^k = 1$ means that data dropout occurs at k, otherwise, $Q^k = 0$; $\overleftarrow{w}^{x}_{i,j}$ is a part of $\boldsymbol{w}_{i,j}$ corresponding to the information exchange from the node j to node i; $\boldsymbol{D}$ is a vector with the dimension $p+1$, representing the communication delay; and q is the probability of data dropout. Note that in $\boldsymbol{D}$, only one element is 1, and others are 0. Eq. (3) describes the information obtained from node j. At each stage, node i receives the information from neighbor nodes according to (3), and uses this information in the calculation of the node model as shown in (1). In this way, the interaction between cyber and physical systems in the CPES is captured.

Examples. As shown in Figure 1(c), a case study of an energy network of four buildings is performed to demonstrate the effectiveness of the above CPES model. The solution for this problem can be obtained by iteratively solving the node and traffic model. The details of the case study and numerical results can be found in the supplementary document. Furthermore, if the node model is formulated by the Markov decision process (MDP), based on the network topology, the CPES model can be converted into the networked MDP and solved by the partially observed MDP framework [5]. Based on our previous work, the event-based optimization is one of the possible ways to solve the partially observed MDP problem, and can improve the computational efficiency by using the structure information of the problem [6]. Therefore, the above CPES model is applicable to many practical CPS optimization problems.

Conclusion and future work. We develop a CPES model to capture the coupling between various energy resources and handle the interaction between the cyber and physical system. The mechanism of information exchange between neighboring nodes is being developed as an efficient distributed optimization method. In addition, another future work is to develop the effective solution methodology for solving the problem of the partially observed MDP form.

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Supporting information The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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