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Profit-seeking energy-intensive enterprises participating in power system scheduling: Model and mechanism

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HIGHLIGHTS

- A general strategy of modeling energy-intensive enterprises (EIEs) is given.
- A system-EIE coordination mechanism concerning EIE's privacy is designed.
- The formulation and algorithm of the decentralized coordination problem are given.
- Cases that demonstrate the effectiveness of the proposed approach are included.

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ABSTRACT

Energy-intensive enterprises (EIEs) are typical kinds of industrial loads. They consume large amounts of electricity, and are very sensitive to electricity prices. Moreover, they have very good schedulability: they own various adjustable devices and dispatchable self-owned generation units, and have great flexibility in making production decisions. The characteristics of EIEs make them potentially ideal for coordinating with power systems and gaining a win–win situation, especially when the renewable energy penetration rate is high. However, problems still remain as to how to organize this coordination. In this paper, we design a decomposed coordinative scheduling (DCS) approach in which independent EIEs and the system exchange information iteratively to achieve final settlements. Based on a general modeling of EIEs, we introduce a mathematical formulation for DCS. The corresponding algorithm is also provided. We compare DCS to other scheduling approaches in case studies. It shows that DCS can significantly improve the benefits of the two sides without harming the privacy of EIEs.

1. Introduction

1.1. Introduction to energy intensive enterprises

Energy-intensive enterprises (EIEs) are a typical group of energy consumers. They usually have high energy intensity in per unit production, and the costs of energy account for a large portion of overall production value (30–40% or even higher). As a result, they are usually very sensitive to energy prices. At the same time, EIEs' energy demands are well adjustable even after its technological constraints are considered. This is accomplished by regulating the production facilities and devices, or changing its production plans. Considering the fluctuating prices of external energy supplies (i.e. electricity, gas, heat, etc.), these properties are very valuable, because well-functioning load management based upon these properties can help EIEs gain better economic position. Moreover, EIEs usually have fairly large energy consumption capacity, making them able to impact the whole system. Namely, they are sometimes capable of re-shaping the system demand curves, thus changing the overall system energy costs. We believe that good interactions between the two sides can contribute to increasing overall social welfare. Among different types of energies, electricity is very typical. It is the most common energy used by EIEs and is usually fully or partially supplied by external sources. Additionally, electricity prices can vary significantly during a normal day and change in short-time scale. Therefore, we would like to take electricity as an example and explore the possibility and method of interacting EIEs and systems.

1.2. Literature review

Load management of EIEs have been addressed by many researches, which mainly aims at minimizing EIEs' energy costs.

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Nomenclature

Indices and Parameters

CAIL	continuously adjustable and interruptible load
DAL	discretely adjustable load
$\alpha,\ \gamma,\ \rho,\ \varepsilon$	parameters in the solution algorithm of decomposed coordinative scheduling
$\eta^C,\ \eta^D$	electricity consumption per unit product of CAILs and DALs
$\pi^C,\ \pi^D$	product prices of CAILs and DALs
$\mathbf{a}_l$	network, shift factor vector for line l
$\mathbf{B}^g,\ \mathbf{B}^w,\ \mathbf{B}^{EIE},\ \mathbf{B}^d$	network incidence matrices for generators, wind farms, EIEs and load
$Cap^{tie}_{\max}$	flow limit on the tie-lines
$Cap_{l,\max}$	flow limit on the transmission lines in systems
$c^C_{order},\ c^D_{order}$	order on products of CAILs and DALs
$c^C_{\max},\ c^D_{\max}$	maximum products of CAILs and DALs
M	a number that is sufficiently large
N_{EIE}	number of EIEs
$N_C,\ N_D,\ N_{sog},\ N_{sod}$	Number of CAILs, DALs, self-owned units and fixed loads
$N^C_{MaxItrpt}$	maximum number of times of interruption
$N^{D,fur}$	number of furnaces in a DAL
$P^C_{\min},\ P^C_{\max}$	minimum and maximum active power consumption of CAILs
P^D_{fur}	active power consumption of a furnace in DALs
$P^{sod},\ p^d$	power consumption of fixed loads in EIE and system
$P^{sog}_{\min},\ P^{sog}_{\max}$	minimum and Maximum active power generation of self-owned units
$P^w_{\max}$	maximum available wind power of wind farms
$R^u,\ R^d$	required upward and downward reserve of the system
$ramp^C$	maximum ramping rate of CAILs
$ramp^{sog}$	maximum ramping rate of self-owned units
$SU^C,\ SU^D$	start-up cost of CAILs and DALs
$SD^C,\ SD^D$	shut-down cost of CAILs and DALs
$T^C_{MinOn},\ T^C_{MinOff}$	minimum on- and off- times of CAILs
$T^D_{MinOn},\ T^D_{MinOff}$	minimum on- and off- times of DALs
$T^{sog}_{MinOn},\ T^{sog}_{MinOff}$	minimum on- and off- times of self-owned units
$T^C_{MaxItrpt}$	longest time allowed for a single interruption

Variables

$c^C,\ c^D$	products produced by CAILs and DALs
$p^C,\ p^D$	active power consumed by CAILs and DALs
$p^{EIE},\ \mathbf{p}^{eie}$	active power sold from systems to EIEs
$p^{sog},\ \mathbf{p}^g,\ \mathbf{p}^w$	active power generated by self-owned units, system units and wind farms
$r^{u,C} \in r^{d,C}$	upward and downward reserve offered by CAILs
$r^{u,sog} \in r^{d,sog}$	upward and downward reserve offered by self-owned units
$r^{u,g} \in r^{d,g}$	upward and downward reserve offered by system units
$r^{u,EIE},\ r^{u,eie}$	upward reserve provided by EIEs to systems
$r^{d,EIE},\ r^{d,eie}$	downward reserve provided by EIEs to system
$u^C \in \{0,1\}$	start-up state variables of CAILs
$u^D \in \{0,1\}$	start-up state variables of furnaces in DALs
$u^{sog} \in \{0,1\}$	start-up state variables of self-owned units
$u^g \in \{0,1\}$	start-up state variables of system units
$v^C \in \{0,1\}$	shut-down state variables of CAILs
$v^D \in \{0,1\}$	shut-down state variables of a furnace in DALs
$v^{sog} \in \{0,1\}$	shut-down state variables of self-owned units
$v^g \in \{0,1\}$	shut-down state variables of system units
$w^C \in \{0,1\}$	interruption state variables of CAILs
$x^C \in \{0,1\}$	on/off state variables of CAILs
$x^D \in \{0,1\}$	on/off state variables of a furnace in DALs
$x^{sog} \in \{0,1\}$	on/off state variables of self-owned units

Optimization tools have been developed in [1–3] considering various production constraints. And such approaches have been applied in industries like glass production [4], oil refineries [5], collieries [6], and electric smelting process [7]. Some approaches also include self-owned generation units in EIEs [8,9]. A combined heat and electricity load management approach is proposed in [10] for enterprises those have on-site CHP plant. As discussed in [11,12], strategic load shifting can benefit EIEs themselves and the systems at the same time. However, most researches on load management regard electricity prices as boundary conditions and do not include any interaction between the two sides. According to the researches, sometimes electricity prices have to be forecasted for load management, which might not be accurate enough and could lead to bad results [13].

Power system operators, who are in charge of system scheduling but have no control over EIEs, are very concerned about the energy consumption behavior of those giant participants. Sometimes, prediction and identification tools for industrial load, as presented in [14–17], are needed to assist the system operators in decision-making. However, the complex bodies cannot be well represented by simple static models derived from predictions or estimations. Additionally, it is shown that the responsive behavior of EIEs can be utilized to enhance system performance [18], and a good case study in Germany is presented in [19]. To take advantage of this, time-of-use electricity pricing methods are widely used [20]. Moreover, a recent research proposed a mechanism to include industrial loads in day-ahead system scheduling [21]. However, the proposed method requires load models and parameters to be totally explicit to system operators, which is not realistic in practice.

In recent years, demand response technology has brought remarkable changes to power systems. The fundamental idea of demand response is to use price signals to encourage energy consumers to take an active part in system operation. Certainly, this technology has already been applied to industrial sectors [22–24]. However, load models in these studies are relatively simple and cannot be applied to EIEs. In addition, when the load capacity of an EIE is large enough, it might not be the best choice that the EIE passively act in response to the prices. Instead, a closer interaction between the two sides could be more effective.

Additionally, the integration of renewable energy has brought new challenges to the energy markets and system operation, bringing even stronger needs for coordination between EIEs and systems. In the face of renewable energy's intermittency and volatility, adequate flexibility is required to keep systems safe and reliable. To gain flexibility, lots of coordination schemes have been proposed, such as wind-EV [25], wind-hydro (or wind-pump) [26,27], and wind-gas coordination [28,29]. In [30,31], the coordination of wind power and responsive demands is discussed, and similar idea is developed for industrial loads in [24]. It is reasonable to expect that, by adjusting their energy-consumption behavior according to the availability of renewable energy, EIEs can help reduce the curtailment of surplus clean energy, and help achieve reasonable load levels during shortage of wind and solar power, thus improving the utilization of renewable energies and reducing systems' reliance upon conventional power sources.