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A two-stage method for predicting and scheduling energy in an oxygen/nitrogen system of the steel industry

Zhongyang Han, Jun Zhao*, Wei Wang, Ying Liu

Faculty of Electronics Information and Electrical Engineering, Dalian University of Technology, China

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ABSTRACT

As essential energy resources in steel industry, oxygen and nitrogen are massively utilized in many production procedures, such as iron-making by blast furnaces, steel-making by converters, etc. The trends of the energy generation/consumption flows along with the related scheduling works play a pivotal role on the energy management of steel enterprises. Aiming at an oxygen/nitrogen system of a steel plant in China, a two-stage predictive scheduling method is proposed in this study for resolving the optimal energy decision-making problem. Given the high cost of time consuming on the load change of air separation units (ASU) of the oxygen/nitrogen system, a Granular-Computing (GrC)-based prediction model is firstly established at the stage of prediction, which extends the predicting length to even a day based on data segment rather than generic point-wise mode. At the stage of optimal scheduling, a mixed-integer program model is constructed on the basis of constraining the number of adjustable energy units, which considers not only the actual capacity of the energy devices, but the practical energy conversion procedure as well. The experiments employing the real data coming from this plant also involve two stages, the long-term prediction and the energy scheduling, and the experimental results exhibit both satisfactory accuracy and practicability. Furthermore, the results of system application also indicate the effectiveness of the proposed method.

1. Introduction

Oxygen/nitrogen system in steel industry, which contains a series of energy media such as oxygen, nitrogen, etc., is the one of most fundamental energy resources for a steel enterprise. In daily routine production, the related processes such as steel-making by converters, iron-making by blast furnace and non-ferrous metal smelting always require continuous supplying of oxygen or nitrogen. Therefore, oxygen and nitrogen are widely utilized and on greatly demand in steel industry, and its scheduling works will be significantly beneficial for the production efficiency, energy saving and even be indirectly related to economic profits of steel enterprises.

In literature, the studies in the field of optimal energy decision-making in steel industry had been carried out. For instances, a multiple traveling salesman problem (TSP) was modeled in Tang, Liu, Rong, et al. (2000) to apply to a scheduling of hot rolling process by considering the energy saving constraints. And, an improved differential evolution algorithm was reported in Tang, Zhao and Liu (2014) for a dynamic scheduling in steelmaking-continuous casting production. Besides, as a common measure for energy carriers and materials, the exergy accounting of energy and materials flows were computed in Costa, Schaeffer and Worrell (2001) and a life-cycle inventory (LCI) of steel manufacturing was consequently presented. Although these abovementioned studies were successful for the energy utilization in steel plants, they were mainly concentrated on automatic control of the equipments or generic energy statistic management rather than real time energy scheduling or optimal energy decision-making issues. While a mixed integer linear programming (MILP)-based model was reported in Karlsson (2011) for the industrial energy adjustment based on the aim at achieving a reasonable utilization of byproduct gas along with the energy waste reduction. Then, a balance allocation method of byproduct gas also using MILP was presented in Kim, Yi and Han (2003), whose objective was to minimize the gas diffusion, maintain the stability of gas holders, and maximize the fuel utility. However, the scheduling solutions conducted by Karlsson (2011) and Kim et al. (2003) were static optimization mode and concerned little on the system dynamic characteristics.

Owing to the complicated steel manufacturing process and its complex energy pipeline network, it is practically impossible to establish an effective physical or mechanism based model for describing the oxygen/nitrogen system, one can refer to Proctor, Fehling, Shay, et al. (2000). With the accumulative large quantities of industrial data in practical database, some remarkable researches based on data-driven approaches were consequently proposed for the energy

* Corresponding author.
E-mail address: zhaoj@dlut.edu.cn (J. Zhao).

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prediction issues. Employing an improved least square support vector machine (LSSVM) and a recurrent neural network (RNN), Han, Liu and Zhao (2012) and Zhao, Wang, Liu, et al. (2011) respectively established the prediction models for gas tank levels and the related energy consumers in steel plant. Subsequently, Zhang, Zhao, Wang, et al. (2011) took the predicted gas tank levels as a reference and designed a reasoning method for the byproduct gas scheduling. In addition, for the purpose of prediction and energy adjustment of coke oven gas system in steel industry, a hybrid model was claimed in Zhao, Liu, Wang, et al. (2012) by combining a Gaussian process (GP) model and an echo state network (ESN). However, it is very difficult for the existing approaches to resolve the scheduling problem of oxygen/nitrogen system due to its different structure, the prediction horizons and the dynamic feature comparing to the byproduct gas systems.

Considering a practical oxygen/nitrogen system of a steel plant in China, this study proposes a two-stage predictive scheduling method for the energy scheduling. Given that the scheduling operation (e.g. ASU load change procedure) requires a relative long time period, at the prediction stage a long term prediction model is established by using a granular computing (GrC)-based method for oxygen/nitrogen consumption demand prediction. Based on industrial semantics directly related to energy devices operations, data granulation is performed so that the predictive horizon can be reasonably extended. Then an MILP model, considering the adjusting capacity of the energy network and the energy conversion relationship between gaseous and liquid state, is established at the scheduling stage, where the constraints of the scheduled equipment amount is also taken into account. A series of comparative experiments indicate that the proposed approach gives satisfactory long-term prediction results compared to the other traditional pointwise iterative approaches. The application of the developed scheduling system also demonstrates that the provided solutions become superior to the manual one on both operational time cost and convenience.

The paper is organized as follows. The problem background of the oxygen/nitrogen system is described in Section 2. The proposed two-stage predictive scheduling is elaborated in detail in Section 3. Employing the practical data coming from the plant, Section 4 addresses a series of validation experiments, and some practical on-line application results are also exhibited in this section. Finally, a brief conclusion along with some further works is provided in Section 5.

2. Problem descriptions

Regarded as a significant energy resource system in steel industry, a typical structure of an oxygen/nitrogen system in a plant can be illustrated as Fig. 1, in which eight ASUs, the Liquefying Plant (LP), the Liquid Tanks, the consumption units and the transportation system are involved. Acting as the energy generation units, the ASUs supply oxygen and nitrogen mostly in gaseous state, and then a partition of the generated energy are stored in the tanks with liquid state. These Liquid Tanks are named by its related devices. Take 'LTASU1234(O_2)' as an example, it stores liquidized oxygen coming from #1–#4 ASU. The compressors and the pipeline networks are the energy transportation system delivering the oxygen/nitrogen in various pressure levels to the consumption units such as blast furnaces, converters, cold/hot rolling, etc. Besides, there are a number of redundant compressors available if a compressor falls down. Under such mechanism, the production process and the energy utilization will not be interrupted.

Thus, one can summarize the characteristics of the oxygen/nitrogen system as follows. 1) Due to various load capacity of the ASUs, multiple categories of pressure levels of the energy, and long distributed pipeline networks, it is extremely difficult to establish a physics-based model for describing the oxygen/nitrogen system of this study. 2) The adjustable capacity (the scheduling measures) of the oxygen/nitrogen system is relatively limitative, i.e., only a few of Liquid Tanks with small volume can be used for temporary storage, and the load changing of ASU could also be available for scheduling.

In production practice, it is noticeable that the oxygen/nitrogen utilization process always involves some regular operational modes or phases, which can be reflected by a series of similar data segments. It can be obviously depicted from Fig. 2 that there are generally three categories of operational modes of an oxygen consumption unit. One can use the feature modes of the following semantically different information granules, see Mode #1–#3, to describe the operational characteristics of the equipment. Although there are some similarities between these modes, the amplitude and the duration of each mode are substantially different. As such, the practical features should be reasonably and generally considered in the model establishment.

3. A two-stage predictive scheduling method for oxygen/nitrogen system in steel industry

This section explicitly introduces a two-stage predictive scheduling method for the oxygen/nitrogen system, in which a GrC-based long-term prediction model is firstly established with the practical consideration of industrial-oriented semantics so as to reasonably extend the time horizon of prediction. Then, an MILP based model is constructed which comprehensively involves the real-application concerned constraints.

3.1. GrC-based long-term prediction model

Since the energy scheduling, which primarily refers to formulation of scheduling scheme and procedures of device operation (e.g., load change of ASUs), usually expends a long period of time, a long-term prediction is on highly demand for sufficiently providing helpful guidance on the decision making of the energy system in steel industry. The existing prediction methods mostly focused on the single data points-based one (pointwise), adopting the iteration mechanism for the future values (Cheng, Tan, Gao, et al., 2006; Kayacan, Ulutas, & Kaynak, 2010). In such a way, the predicting error in iteration process could be accumulated, and the accuracy would fall down along with the iteration proceeds. Deeply merging with fuzzy modeling, rough sets and the related theories (Pawlak & Skowron, 2007; Pedrycz, 2009), Granular Computing (GrC) becomes a popular paradigm on the subject of data-driven method (Bargiela & Pedrycz, 2003; Bargiela & Pedrycz, 2008; Pedrycz, Skowron, & Kreinovich, 2008). It takes data granule, i.e. data segments with a series of points, as the analysis unit instead of single data point, which enables to extend the prediction horizon (long-term prediction).

3.1.1. Data granulation

As an essential preparation for GrC modeling, a reasonable data granulation always considers prior knowledge for making the model more human-centric. Literatures in the past mostly granulated the original data by the ascending/descending trend or unsupervised learning, one can refer to the details in Lin (2009). However, given that the energy utilization (data flow) of the studied oxygen/nitrogen system usually corresponds to a specific device operation status, e.g. continuous consumption, short pauses, etc., mentioned as the above illustrative description, it is obviously useful to adopt such practical semantic meaning for data granulation process.

Here, to clarify the granulation process considering the operational feature of industrial data, two examples are illustrated in Fig. 3, where Fig. 3(a) is the oxygen consumption flow of #1 converter and Fig. 3(b) is the nitrogen consumption of #2 blast furnace. It is obviously depicted that the oxygen consumption of