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Energy optimization and analysis modeling based on extreme learning machine integrated index decomposition analysis: Application to complex chemical processes

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ABSTRACT

Energy optimization and analysis of complex chemical processes play a significant role in the sustainable development procedure. In order to deal with the high-dimensional and noise data in complex chemical processes, we present an energy optimization and analysis method based on extreme learning machine integrating the index decomposition analysis. First, index decomposition analysis has been used to decompose the high-dimensional data to three energy performance indexes of the activity effect, the structure effect and the intensity. And then, those indexes and the production/conductivity of the chemical process are defined as inputs and outputs of the extreme learning machine respectively to build energy optimization and analysis model. Finally, the proposed method has been applied to optimizing and analyzing energy status of the ethylene system and the purified terephthalic acid solvent system in complex chemical processes. The experiment results show that the proposed method has the characteristics of fast learning, stable network outputs and high model accuracy in handling with the high-dimensional data. Moreover, it can optimize energy of chemical processes and guide the production operation. In our experiment, the production of ethylene plants can be increased by 5.33%, and the conductivity of purified terephthalic acid plants can be reduced by 0.046%.

1. Introduction

Complex chemical processes make a difference in developing the industry development in China. At the same time, the ethylene production is the main process in chemical industries. However, the energy efficiency level of ethylene production is far lower than the international advanced level in the chemical industry [1,2]. More than 50% of the ethylene plants operating costs are derived from the cost of energy consumption of ethylene [3]. Meanwhile, the demand of PTA (purified terephthalic acid) has increased in recent years and has become a significant row material in chemical industries. Unfortunately, On account of the high cost of adding a new plant, the overall energy efficiency has decreased [4]. In summary, it is an effective way to improve the productivity and energy efficiency of the complex chemical process by building the energy optimization and analysis model.

Although the optimal index method and the mean method are commonly used to analyze the energy efficiency [5], the energy-saving knowledge cannot be applied to guide the analysis of actual situation of energy efficiency. Data fusion method is much better to analyze the energy efficiency of ethylene plants. Geng et al. proposed an extraction method based on data fusion for the ethylene industry [6], and the hierarchical linear optimal fusion algorithm has been used for energy consumption indices acquisition [7]. But they do not take into account the impact factors of energy consumption indicators. Kleemann et al. optimize the recovering method to save the energy in chemical processes [8]. However, it does not take the economic cost of restructuring the industrial plants into consideration. Geng et al. analyzed the performance efficiency of China's ethylene plats by using the Data Envelopment Analysis (DEA) integrated Analytic Hierarchy Process (AHP) [9] and DEA-cross model [10]. Han et al. based on fuzzy DEA cross-model proposed a method to analysis the energy efficiency

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[11]. However, the efficiency discrimination of DEA will be poor when more than a third of efficiency values are set to 1 [12]. Olanrewaju et al. integrated IDA-ANN-DEA to evaluate and optimize energy consumption in industrial sectors [13] and to assess the energy potential in the South African industry [14] while they did not take into account the local minimization problem, convergence rate and the structure of traditional ANN. And this method is used to assess broad industry, but not instance to the specific production process and offer a guidance of that process. The existing energy optimization and analysis methods in the complex chemical processes are insufficient. Therefore, we propose an extreme learning machine (ELM) based on index decomposition analysis (IDA) (IDA-ELM) method to optimize and analyze the energy of the chemical industry. In our experiment, the production of ethylene plants can be increased by 5.33%, and the conductivity of PTA plants can be reduced by 0.046%.

Our remainder study is elaborated as the following manner. Section 2 introduces the current research status of energy analysis and optimizes in chemical processes with ELM and IDA. The ELM and the IDA have been explained in detail and the energy optimization and analysis model based on IDA-ELM in the complex chemical process is also illustrated in Section 3. Section 4 presents the case study about energy optimization and analysis of ethylene production industry and PTA production industry based on IDA-ELM, respectively. Finally, the conclusions are obtained in Section 5.

2. Related work

Generally, in order to build the energy optimization and analysis model of the complex chemical process, we need to consider the following characteristics: easy to be disturbed by external interference, high dimension, noise, and varied. Many artificial intelligence methods can be used to deal with this problem, such as genetic algorithm, bird-mating [15] and artificial neural network (ANN) [16]. Among them the most primary characteristic of the ANN are paralleled distributive processing, continuous time-related nonlinear dynamics, and fast response without considering the internal mechanism, so it is widely used in many fields: Hong et al. use ANN and an improved Particle Swarm Optimization to explain the PV system performance [17]. Certainly, ANN has also been commonly used in modeling complex chemical processes [18]. Geng et al. proposed an energy efficiency predict method based on neural network [19]. Li et al. used artificial network to simulate the gas generation and transport [20], and Barrasso et al. descript the wet granulation process by the artificial network [21]. However, the neural network learning algorithms are easy to fall into local minimum and slow convergence. The ELM is a single hidden layer feed-forward neural network proposed by Huang et al. [22]. The ELM uses Moore-Penrose generalized inverse to calculate the weight in the output layer instead of changing the weight during training, which has been used in the traditional way [23]. Therefore, the ELM avoids the tedious training and a variety of problems produced by the descent learning and the number of hidden nodes is the only parameter that needed to be defined. Meanwhile, the ELM has the characteristics of good performance in generalization and fast convergence speed. Therefore, ELM has been widely used in classification like spectroscopy-based classification with ELM in food industry [24] and classification applications to votes [25], building the batch process model [26], Soft-sensing model development [27], applying bulk polymerization of the styrene batch process and evaluate control actions [28], wind speed forecasting etc. [29]. He et al. proposed a double parallel structure ELM and used the Pearson Correlation Coefficient (PCC) between the output and input to build two independent subnets. This method was proposed to accurately model and develop a data driven soft sensor for complex chemical processes [30]. Suresh et al. presents a real-coded genetic algorithm to select the optimal number of hidden neurons, input weights and bias. This method also presents an alternate and less computationally intensive approach to search the best parameters of ELM, which improve the ELM performance in sparse multi-category classification problems [31]. Salcedo-Sanz., et al. combine the modified Harmony Search optimization algorithm with ELM to select the best set of features for ELM and predict the one-year-ahead energy demand [32]. Liu et al. use four signal decomposing algorithms to combine four different hybrid models and calculate the input of ELM, so that all the hybrid algorithms have better performance in wind speed forecasting [33]. He et al. proposed a data-attribute-space-oriented double parallel structure to enhance the ELM machine and applicate it to the regression datasets [34]. However, the ELM has a problem with the validity of analysis in complex chemical processes. An IDA is exploited to select the main index among input variable to improve the reliability and the analysis accuracy.

During the practical analysis, the production of complex chemical processes is always affected by many parameters. And the parameters are easily disturbed by the outside. Each parameter has a certain amount of information. In addition, there is mutual influence among parameters. Because of the complexity in the complex chemical processes, there are some errors and noises in the parameters during the measurement.

IDA is a promising method for analyzing energy efficiency [35]. IDA methodology has been divided into additive and multiplicative [36], and has been widely used in energy and carbon emission analyses [37]. What's more, various studies have contributed to the use of the IDA [38], for example, Unander et al. use this method to decompose the IEA countries' energy-use [39]. In Brazil, IDA has been used to decompose the energy use [40]. Hatzigeorgiou et al. decomposed the CO_2 emissions in Greece during 1990–2002 into four factors: energy intensity effect, income effect, population effect fuel and share effect by using the IDA, and obtained the result that the main element is the income effect [41]. Hammond et al. uses decomposition analysis to separate the contributions of changes into five parts to the reduction in carbon emissions. And the reduction in energy intensity is the primary reason [42]. The research results mentioned above show the effectiveness and practicality of the IDA. However, the IDA method is only combined with the indicators of each domain for energy efficiency analysis and evaluation, but did not give the corresponding improvement and the specific improvement direction. Therefore, we propose IDA-ELM to analyze the production and energy consumption of ethylene plants and PTA plants.

Ethylene product system and PTA product system are typical examples of complex chemical processes. All of those systems have the characteristics of high-dimension and noise, thus IDA can be used to decompose these variables into several parts so that we can easily utilize accessible operational data to further obtain the crucial parameter and primary cause. Therefore, we can reduce the redundant features to shorten the analysis time and improve the accuracy. Meanwhile, the complex mechanism in those chemical processes can be avoided. The features of complex chemical processes data are extracted based on the IDA, which are set as the input of ELM. And then we let the production/conductivity of each plant to be the output data of ELM. Finally, comparing with the ELM, we use the IDA-ELM model to optimize and analyze energy status of ethylene system and the PTA solvent system to test the feasibility and effectiveness. Furthermore, it can also offer the operation guidance for energy saving.