Energy 132 (2017) 269–279

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Intelligent management of coal stockpiles using improved grey spontaneous combustion forecasting models

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ARTICLE INFO

Article history:
Received 22 November 2016
Received in revised form
13 April 2017
Accepted 11 May 2017
Available online 21 May 2017

Keywords:
Coal management
Spontaneous combustion prevention
Grey model
Optimization algorithm

ABSTRACT

Intelligent coal stockpiles management system is significant for the next-generation cleaner power plants. Prevention of spontaneous combustion is a key issue for such a system, both in economic and environmental terms. As many factors can influence the self heating process of coal such as moisture and ash in coal, temperature distribution and stockpiles' shapes, the remaining ignition time is developed as an aggregative indicator to measure the tendencies of spontaneous coal combustion. Using this value, the grey models have been applied to forecast spontaneous combustion and their performances are good for systems with insufficient information. However, the forecasting accuracy of these models still needs to be improved. Therefore, the ABC-RGM(1,1) model is proposed in this work based on the rolling-GM(1,1) and the Artificial Bee Colony (ABC) optimization algorithm, which has been applied to the management system of a 4 × 600 MW power plant. The computational experiments show that the ABC-RGM(1,1) model achieves better performance than the other popular grey models and accuracy of forecast is greatly improved especially for short-term forecasts. Such an accurate model is highly important and useful for intelligent coal management systems which can improve decision making and reduce risk.

1. Introduction

More than 85% of the world's commercial energy is supplied by fossil fuels, among which coal occupies a large proportion in current thermal power plants [1]. In order to avoid the interruption to power generation caused by fuel shortage, power plants must keep large quantities of coal in storage. Spontaneous combustion of coal in storage is a common concern of thermal power plants due to potentially huge economic loss as well as serious environmental pollution [2]. Thus, intelligent coal management is significant for the next-generation cleaner power plants in both economic and environmental terms. This has raised the need of developing real-time coal management system to monitor coal stockpiles status and predict spontaneous combustion tendency.

In practice, engineers often rely on instruments to detect the location where a pile of coal can potentially undergo a self heating process [3]. Temperature and gases such as carbon monoxide, hydrogen and ethylene are the most commonly used indexed to assess combustion development [4]. Different kinds of detection instruments have been placed in coal piles to monitor the indexes of certain sample points. Nevertheless, apart from being time-consuming and strenuous, the detection method also has a limitation in that the measurement process lacks of accuracy as coals vary a lot in spontaneous combustion points. Moreover, the spontaneous combustion process may have passed its early stage when the indexes are detected, meaning the best chance of controlling hazard has been missed. To overcome this limitation, a three-dimensional model is developed to measure the temperature distribution based on the Wireless Sensor Network (WSN) and a laser scanner. The temperature distribution of stockpiled coals is continuously monitored with real-time updates, preparing time series data for the prediction of spontaneous combustion.

To predict self-heating of coal stockpiles, several mathematic models have been developed to study the mechanism of the spontaneous combustion process based on first principles such as

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http://dx.doi.org/10.1016/j.energy.2017.05.067
0360-5442/

Nomenclature

δ	Longitudinal deflection angle of the laser ranging head, °
φ	Scanning angle of the laser beam, °
s	Distance between the laser head and the reflection point of the stock pile surface, m
h	Vertical height of stockpile, m
d	Distance from stockpile to the center, m
θ	Angle of repose, °
α	Angle at the circumference, °
ρ	Density of coal stockpile, kg/m^3
Cad	Carbon content, %
Vad	Volatile content, %

heat and mass balances [5–11]. Analysis of test data has shown that, besides temperature distribution, spontaneous combustion is affected by many factors such as coal pile shape, moisture content and ash in coal, etc. Remaining ignition time (RIT) is designed as an integrated index for predicting spontaneous combustion by taking into consideration the influences of various factors in this paper.

Due to the complex interactions between oxygen transport and energy transport, the existing forecasting models based on sequential temperature data could not satisfactorily meet the prediction requirements. Some intelligent forecasting models have been proposed to represent this kind of nonlinear relationships, such as artificial neural networks [12], support vector machine (SVM) [13], and so on [14–17]. However, these methods rely on large historical data and in this sense limit their applicability to the situations in which temperature may change rapidly during the self heating process. To overcome this limitation of conventional methods, the grey model is developed for small data sets and has been widely applied to the field of forecasting such as those in industry production, energy consumption and natural phenomenon [18–23]. Furthermore, the rolling mechanism is applied to improve the forecasting accuracy of original grey model by updating the input data and the optimization algorithm is used to optimize the generating coefficients of grey models during the rolling process [24].

In this work, an improved rolling-GM(1,1) model based on an integrated index, which employs the ABC algorithm to optimize the grey development coefficients, is proposed and evaluated through a comparison with other traditional grey models.

2. Literature review

Much research has been done on the mechanism of spontaneous combustion and the influencing factors contributing to this complicated physical-chemical process, leading to the development of some theoretical models for rigorously characterizing the self heating process [5–11]. Brooks used three equations to describe the variations in temperature, pressure and oxygen concentration occurring in a coal dump [5,6]. Through experiments in a static isothermal apparatus, Smith found the rate of the low-temperature oxidation reaction significant in determining the tendency of carbonaceous materials to self heating [10]. Nevertheless, the findings of previous studies are quite restricted to theoretical guidance while there is a lack of real-time support as well as an accuracy necessary for practical applications. A logic fault tree composed of 17 key contributory factors was built to estimate the fire risk of mine field [14]. Zhang et al. established a BP Artificial Neural Network (ANN) with 150 training samples to predict the temperature of coal column, which selected heating time, relative position, the ratio of fine coal thickness, artificial density, voidage and activation energy as the input variables [15]. Jin used Support Vector Machine (SVM) to analyze the correlation between coal temperature and its gaseous products [16]. However, these models generally have poor performance when the data set is insufficient or the influencing factors are quite complicated [19].

To overcome this limitation, the grey theory was utilized to forecast in systems with uncertain models and insufficient information [20–33]. Even though the GM(1,1) model has been widely accepted and applied, the original form of this model has a basic differential equation and constant background parameters, leading to a improvable prediction accuracy. As a result, researchers have proposed improved models mainly from the aspects of improvement of the differential equation, optimization of model parameters and integration with other intelligent methods. Dynamic regulation of the grey development coefficient and the background value [22] has been proved effective in improving accuracy. Lin et al. constructed the FEFGM(1,1) model for inflow forecasting by altering the Fourier series to handle extreme values and applying the fuzzy membership function to solve significant changes in inflow [23]. Zhao et al. developed a Grey model optimized by a Differential Evolution algorithm to forecast the per capita annual net income of rural households in China [32]. In this research, a rolling mechanism is introduced to modify the input series along with an optimization algorithm for finding the optimal generating coefficient values to forecast the heat loss value of coal stockpiles.

Due to the implicit parallelism and intelligence, the genetic algorithm (GA) and the particle swarm optimization (PSO) have been widely applied to solve parameter optimization problems, and have proved to achieve good results. For example, Hsu applied GA to search global optimum solution to construct two improved multivariable grey forecasting models which are used to forecast Taiwanese integrated circuit output [27]. Wang et al. proposed an improved GM(1, 1) model in financial revenue forecasting, which used the chaotic PSO algorithm to optimize the GM model parameters and search the optimal input subset. Motivated by biological and sociological processes, the ABC algorithm is a new stochastic technique based on evolutionary computation and has been proved to possess a better performance in function optimization problem, compared with GA, Differential Evolution (DE) and PSO [34–37].

The main contributions of this work include:

1) An intelligent system for coal management and prevention of spontaneous combustion is developed to streamline data collection, model construction and self heating prediction based on the wireless sensor network and a cyber-model.
2) This article brings forward a mathematic model which combines the grey model with RIT index to forecast the spontaneous combustion process in large thermal power plants.
3) The rolling mechanism and the optimization of coefficients using the ABC algorithm are applied to improve the forecasting accuracy of original grey model, which predicts the spontaneous combustion of coal pile in its early stage.

3. Data preprocessing and model construction

3.1. System architecture

As shown in Fig. 1, the framework for a coal management system that can prevent spontaneous combustion of stockpiled coals is developed, which consists of three layers, namely the hardware layer, the model layer and the computation layer. The discrete