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Soft sensor for real-time cement fineness estimation

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ABSTRACT

This paper describes the design and implementation of soft sensors to estimate cement fineness. Soft sensors are mathematical models that use available data to provide real-time information on process variables when the information, for whatever reason, is not available by direct measurement. In this application, soft sensors are used to provide information on process variable normally provided by off-line laboratory tests performed at large time intervals. Cement fineness is one of the crucial parameters that define the quality of produced cement. Providing real-time information on cement fineness using soft sensors can overcome limitations and problems that originate from a lack of information between two laboratory tests. The model inputs were selected from candidate process variables using an information theoretic approach. Models based on multi-layer perceptrons were developed, and their ability to estimate cement fineness of laboratory samples was analyzed. Models that had the best performance, and capacity to adopt changes in the cement grinding circuit were selected to implement soft sensors. Soft sensors were tested using data from a continuous cement production to demonstrate their use in real-time fineness estimation. Their performance was highly satisfactory, and the sensors proved to be capable of providing valuable information on cement grinding circuit performance. After successful off-line tests, soft sensors were implemented and installed in the control room of a cement factory. Results on the site confirm results obtained by tests conducted during soft sensor development.

1. Introduction

Fineness is one of the most important physical properties of cement. Cement fineness tests are performed in laboratory on samples taken from a grinding circuit. The testing procedure is defined by appropriate standards and is executed at uniform time intervals, typically every two hours [1]. There are numerous limitations due to such important information being available only periodically at extremely long time intervals. Any algorithm that automatically controls a grinding circuit, instead of cement fineness, must be related to another, alternative and easily measurable system parameter, which makes direct control of the most important system parameter impossible. This situation means it is always necessary to guide the system toward operating points that should provide, at a high level of confidence, the desired fineness, usually resulting in fineness far above the limit defined for the product. In this way, much more energy is consumed during the cement grinding process than necessary. The problem of excess energy consumption during the cement grinding process is clear when accounting for the amount of electrical energy consumed in cement production, which is approximately 110 kW h/t, of which, approximately 40% is consumed for cement grinding [2,3]. Since there is no available real-time cement fineness measurement, the focus in energy consumption reduction in cement grinding circuit is directed to improvements in grinding technology [3]. Improved grinding media in traditional ball mills, new grinding mill designs, combined grinding systems [4], clinker pre-crushing [2] and use of high-efficiency separators are energy saving measures commonly undertaken by cement manufacturers. Providing real-time information of cement fineness would offer new, complementary opportunities for reduction of energy consumption.

In addition, other equally important problems originate from the lack of information about cement fineness. Because no information on cement fineness between two samples and related laboratory tests is available, when a laboratory test shows deviation from desired values, it is reasonable to assume that there is a significant amount of poor-quality cement produced between the two samples. That deviation from desired values can be significant and indicate that the process is shifted far away from normal operating conditions; in this situation, it is typically necessary to take radical corrective actions to guide the process to the desired performance. In addition, there is a possibility that even when the cement fineness of two consecutive samples are adequate, in several situations, a large portion of cement produced between the two samples may be of completely different, inadequate, quality. All

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these problems lead to the conclusion that finding a method that provides information on cement fineness in real time can significantly and positively influence the two main indicators of cement grinding circuit performance, energy consumption and quality of cement.

The objective of this paper is to obtain information on cement fineness by determining its correlation with measurable process variables. In this way, reliable real-time estimates of cement fineness can be obtained using a mathematical model to derive the fineness from available data. Such systems are typically called soft sensors or virtual sensors. Soft sensors are used in different types of applications. Soft sensors for measuring acid gases emission in sulfur recovery unit of oil refinery presented in [5] and particle size estimation in wet grinding circuits presented in [6] are applications where soft sensors are used to provide reliable process information when hardware sensors are removed for maintenance. When one hardware sensor is time shared by several parallel processes, soft sensors can be used during time intervals in which hardware sensor is unavailable [7]. Soft sensors working in parallel with hardware sensors can be used for fault detection and can also make it possible for a system in such situations to continue process control using estimated values from a soft sensor to replace measurements from a faulty hardware sensor. In [8] an example of such application in winding machine is presented. Situations when measurements from hardware sensors are not suitable for use in control algorithms because they have a large time delay due to their position in the production process or because of their time-consuming operation, can be solved by soft sensors [9–11]. In [9] this type of solution is used for monitoring of product quality in oil refinery, while in [10,11] chemical process is controlled by controlling the product composition estimated by soft sensor. In a production process where product quality is controlled with only a few sample products and the quality of every product cannot be assured, soft sensors provide a way to obtain information on the quality of each product [12] and assist quality management and process control [13]. Soft sensor applications similar to the cement fineness application address situations where important process variables are available only from off-line laboratory tests and are therefore unavailable for use in control algorithms. This is the case in fermentation process as is presented in [14,15], also this approach can be used for emission prediction and control for a gasoline engine [16]. In [17,18] soft sensors are utilized to provide information of process variables used in steam quality control since online measurement of process variables of interest is not always accurate or reliable and is therefore supplemented by lab analysis taken infrequently in a manual manner.

Results obtained from soft sensors for online estimation of clinker quality [19] show that important information in cement production process can be provided by the use of soft sensors. Soft sensors have already demonstrated their ability to provide solutions in grinding circuits [6,7], where they were used to provide information on the particle size distribution in wet grinding circuits. The problem described in this paper has one significant difference compared with the aforementioned paper on wet grinding circuits. Whereas soft sensors used in the wet grinding circuits were developed using information from a hardware sensor, which in normal operation, provides real-time measurements of particle sizes, a soft sensor for cement fineness must be developed based on information provided from off-line laboratory tests performed every two hours.

Soft sensors are typically developed using first-principle models when they are available and in a suitable form [20]; however, more often, gray or black box models are used. In the case of a cement grinding circuit, due to the complexity of the system, particularly the grinding process, a complete first-principle model suitable for soft sensor development is not available. Attempts to develop gray box model of this process lead to exceptionally complex models whose parameters could only be determined by delicate and extremely time-consuming experiments with relatively large uncertainties associated with several parameters [21]. In addition, though gray box models based on grinding laws agree with laboratory experiments, their transposition to industrial mills gives poor results. However, for purposes of monitoring and system performance analysis, a great amount of historical data for various process variables is collected, which makes black box model parameter identification convenient.

It is necessary to select black box model inputs from large number of candidate process variables. In this paper, selection of model inputs was based on an information theoretic approach. An algorithm called the information theoretic input variable subset selection (ITSS) [22] is used. This algorithm does not depend on any nonlinear function approximation methods; it solely depends on the measured system's input–output data. Information theory is used to analyze interdependency between the process output and inputs to determine, from the entire input data, a subset of input variables that contains most of the information necessary to predict the output. Theoretical knowledge regarding the process that is modeled should also be incorporated when using ITSS to ensure that all important variables to the model are included in the subset [22,23].

In this paper the soft sensor is proposed to estimate cement fineness and provide real-time information on a process variable available only from off-line laboratory tests. The design and implementation of the soft sensor is presented. Data collected during regular production in cement factory Lafarge BFC[1] in Beočin, Serbia is used for soft sensor development. Soft sensor was developed using a black box model based on a multi-layer perceptron neural network. Model is trained using the data obtained by standard off-line laboratory tests conducted every two hours. Their ability to provide real-time fineness estimation on every minute is tested. Soft sensors are implemented and installed in the cement factory Lafarge in Beočin, Serbia.

The remainder of this paper is structured as follows. Section 2 provides a schematic description of the cement grinding circuit. In Section 3, analysis of the collected data is presented together with algorithms and procedures used for models structure selection. In Section 4, experimental results are presented and analyzed, and Section 5 presents the conclusions of this work.

2. Description of the grinding circuit

The cement grinding circuit is the final stage in the cement production process. In this stage of production, clinker produced in the kiln together with additives that are used to attain the desired properties of the produced cement are grinded in the mill into a fine powder (cement). The material is grinded in the rotating ball mill where grinding is performed by steel balls. During grinding, the clinker particles should be reduced in size by a factor between 1000 and 10,000, and it has been proven to be more efficient to apply different grinding forces to different size ranges of the material, which is achieved by constructing mills with several grinding chambers, typically two, with different properties, such as chamber length, size of the ball charge and shape of the liners along the chamber walls.

Fig. 1 shows a simplified scheme of the cement grinding circuit that indicates process variables of interest in this paper. Material flow is indicated with solid lines, whereas dotted lines represent air flow in the circuit. Clinker and additives are transported from

[1] www.lafarge.rs