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Neural network-based software sensor: training set design and application to a continuous pulp digester

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Abstract

A neural network-based strategy for detection of feedstock variations in a continuous pulp digester is presented. A feedforward two-layer perceptron network is trained to detect and isolate unmeasured variations in the feedstock. Training and validation data sets are generated using a rigorous first principles model. The most important issue discussed here is the design of the data set required to train the artificial neural network. Efficiency and limitation of such an approach are demonstrated using simulations.

Keywords: Artificial neural network; Fault detection; Soft-sensing; Pulp digester; Fundamental model

1. Introduction

The pulp and paper industry forms a large and important sector of the chemical process industry. During the period 1996–1998 alone, planned capital investments including expansion of existing facilities exceeded US$10 billion. This highlights the capital-intensive nature of this industry and the corresponding demand for higher safety and reliability (Leung, Romagnoli, & Bigaran, 2001). In the meantime, practical implementation of advanced industrial control systems, like model predictive control, requires a watchdog to diagnose the cause of performance degradation. Therefore, early detection of such problems enables the engineer to undertake remedial action including retuning the controller if necessary.

Over the past two decades, a number of approaches for fault detection and diagnosis have been proposed. These myriad techniques (Dash & Venkatasubramanian, 2000) have been classified and summarized in several reviews and publications. Notable reviews include: observer-based methods (Garcia & Frank, 1997), parameter estimation and knowledge-based systems (Patton, Chen, & Nielsen, 1995); knowledge-based systems (Sharif & Grosvenor, 1998); and fuzzy logic methods (Isermann, 1998). More recently, Venkatasubramanian (Venkatasubramanian, 2001; Venkatasubramanian, Rengaswamy, & Kavuri, 2003; Venkatasubramanian, Rengaswamy, Kewen, & Kavuri, 2003a,b) presented a global perspective on these disparate methods. Among these methods, neural networks have very useful properties including the ability to handle nonlinear behavior and tolerance to noise.

In this work, preliminary results for a neural network-based software sensor to infer unmeasured variations (referred to as faults) in the feedstock of an industrial pulp digester are presented. This software sensor is developed to predict time-varying model parameters (Qi, Zhou, Liu, & Yuan, 1999; Molga & Cherbaski, 1999; Porru, Aragonese, Baratti, & Servida, 2000) that affect model-based control performance. The data set required for the neural network creation is usually obtained from plant data experiments. However, in this work, the use of a fundamental model to generate data for unmeasured variables is advocated. A related study is described in Adal, Bakal, Sönmez, Fakory, and Tsaoi (1997) where a fundamental model was used to create training data for a neural network. Additional motivation for the use of this approach is that it represents a non-parametric approach.

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Various methods exist for the design of the data set considered in this paper:

- Random selection where no clear criterion is applied. This is the most common method in the literature.
- Kohonen self-organizing map (Oja & Kohonen, 1999) is a clustering method mapping high-dimensional data sets into a space of lower dimension, while preserving the topology (i.e. the spatial relationships) of the data set as best as possible.
- Kennard and Stone design (Kennard & Stone, 1969) is based on uniform spaced objects over the space. Such an algorithm starts with two most distant objects as members of the data set. Next, all other objects' distances to the first two objects are calculated. The object, which is selected as the next one to join the data set, is the one that has the largest minimal distance to all previously selected objects. The algorithm repeats the selection by comparing all distances of candidates to the already selected objects until a certain predefined number of objects have been found.
- D-optimal design (Carlson, 1992) aims to minimize the generalized variance of the parameter estimates.
- Full or fractional factorial design (Montgomery, 1997) where combinations between discrete levels are accounted for. Full factorial design contains all the possible combinations of the selected settings of the experimental factors, so that a two-level full factorial design requires 2^n experiments (n being the number of factors). One way to accomplish a smaller number of experiments, when treating the same number of factors, is the use of fractional factorial design. This operation leads to a partial loss of information, since it might be impossible to discriminate between the effects or the interactions of the effects.

In (Wu et al., 1996), a case study provides a detailed comparison of random selection, Kohonen self-organizing map, Kennard and Stone design and D-optimal design. None of these methods has a distinct advantage over the other methods. Therefore, given the large size of the problem and the simplicity of the approaches, a fractional factorial design method (Zhang & Subbarayan, 2002; Briceno, El-Mounayri, & Mukhopadhyay, 2002) combined with random selection is applied here for the data set generation.

The main focus of this paper deals with a method to construct, from the digester model, the data set required for the training phase. This paper is organized as follows: first, the problem is described and the fundamental model is briefly introduced. Next, three designs of the training subset of the neural network are discussed. Finally, efficiency, limitations and robustness for the use of each neural network, resulting from the different training subsets, are described.

2. Fault set definition

A continuous digester is a large vertical tubular reactor in which wood chips are converted to wood pulp for papermaking (see schematic in Fig. 1). White liquor (aqueous solution of effective alkali (EA) and hydrosulfide (HS)) strips the presteamed porous wood chips of lignin, freeing the wood fibers. The delignification reaction takes place in the digester section referred to as the cook zone. In this section, both the chips and liquor flow cocurrently. At the end of the cook zone, spent liquor is extracted for chemical recovery. The chips, however, continue their downward flow in the wash zone, composed by modified continuous cooking zone and extended modified continuous cooking (EMCC) zone, where they encounter weak liquor flowing countercurrently. The wood pulp is finally extracted at the outlet of the EMCC. Control of the pulp quality, characterized by Kappa number, is the key control objective. Faults addressed in this work were identified through discussions with a mill partner. They mainly deal with variations of the naturally occurring feedstock properties and are summarized below:

- variation in moisture content of the wood chips fed to the chip bin,
- unmeasured density of each of the five wood chip components: (a) high reactivity lignin; (b) low reactivity lignin; (c) cellulose; (d) galactoglucomman; and (e) araboxylan, and
- unmeasured density of each of the two white liquor species: (a) EA; and (b) HS.

Moisture content is measured infrequently (in some cases, once per day). No known measurements exist for the five wood components. However, these are

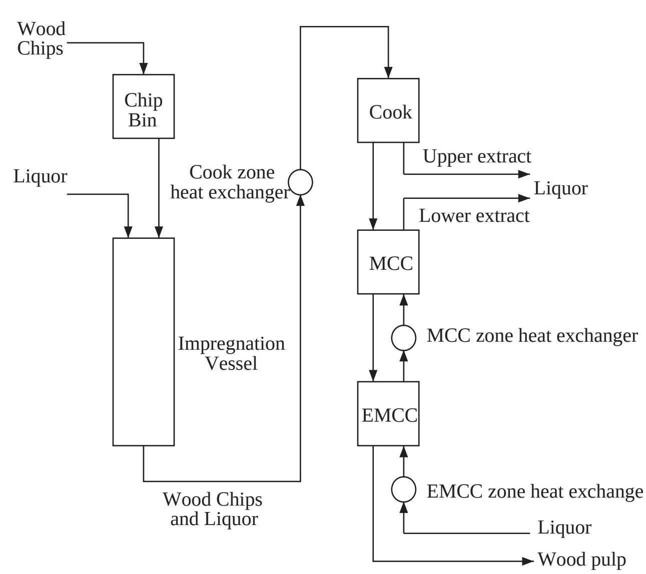

Fig. 1. Schematic of a chemical pulp digester.