Advanced Identification Methods for Industrial Processes with Big Time Delays

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Abstract: This paper presents an advanced method for system identification of industrial processes with big time delays. Identification methods based on neural networks, tree partitioning and wavelet networks are presented and analyzed. The obtained results are compared and the tree partitioning method is selected as most appropriate identification method for the water treatment process. The decision was made based on a thorough analysis on the overall fit between the measured data and the results of the simulated model. At the end, we propose possibilities for further research in this area.

Key words: System identification, systems with time delay, nonlinear system identification, water treatment plants.

1. Introduction

System identification with linear models is well established. Linear models are convenient from a computational perspective, and furthermore, their analysis and use for control design is much simpler than in the case of nonlinear models. There are cases when linear models are not good enough:

- The system is highly nonlinear;
- The system is nonlinear and it operates over a wide range of operation.

In these cases, a nonlinear identification has to be done. There exist several techniques for nonlinear identification that have been widely used in control engineering. Nevertheless in this paper we will focus on an identification based on one of the following methods:

- Neural network method;
- Tree partition method;
- Wavelet method.

These methods are not guaranteed better than the standard control techniques for nonlinear identification, but are being widely used in the recent years [1-2].

This paper is organized as follows: In the second section, we will present a detailed description of the decarbonisation plant placed in the KEK—Kosovo power plant. In the third section, we will present several nouvelle techniques for nonlinear identification of complex process using only the process data. In the fourth section, we will present the results from the conducted experiments of identification and we will compare all used methods. At the end, we will propose the best identification method and research possibilities for the future.

2. Decarbonization Plant

The decarbonization plant consists of 2 reactors...
(decarbonators), 11 sand filter and dosing systems for flocculant (ferrosulphate), lime and polyelectrolyte. Additional equipment for waste water reuse, pumps and blowers, etc. were also needed for proper function of the whole plant. The filtered water after decarbonator and sand filter is stored in a 2 filtered water basins. From this basins several pumps feeds the consumers, like cooling tower and demineralization plant.

The raw water coming via a channel from a lake will be preheated and led to the reactor (decarbonization plant). The treatment of the raw water is done by a slow lime decarborization plant and open sand filter. Flocculants (Ferrosulphate) is dosed into the raw water line to create flocks’ which include colloids and other suspended solids. Adding of lime slurry is necessary to reduce the carbonate hardness. Finally polyelectrolyte is dosed to form larger floccs for better sedimentation. The produced sludge will be drained with the mud pumps outside the plant (sewage or drying bed or similar).

In the decarbonator, the carbonate hardness is reduced by adding lime and the suspended solids will be removed by adding flocculant and polyelectrolyte.

The flocculant will be added into the raw water line in relation of the raw water flow. High turbulence ensures good mixing this ferrosulphate with the raw water. In the inner cylinder of the decarbonator the lime for decarbonisation will be added in accordance of the flow and the pH value. After the reaction of both chemicals the polyelectrolyte will be added in a non-turbulence zone to form bigger floccs for better sedimentation.

The created sludge (mud) is transported by the scraper to the center of the reactor and will be pumped out. The water decarbonator is presented in Fig. 1. For further reading on Decarbonization please refer to the functional description of the process [3].

3. Advanced Nonlinear Identification Methods

The problem of nonlinear identification has been addressed a lot lately, mainly because of the increased computer power and the possibility for computer algorithms to perform prediction or on-line optimization on complex models.

In respect of nonlinear identification methods, generally there are two models used: the nonlinear ARX model and the Hammerstein-Wiener model. The latter is often used in cases when there is a strict distinction between the input and output nonlinearities and the linear block between them. The nonlinear ARX model extends the linear ARX structure which implies that the current output $y(t)$ is predicted as a weighted sum of past output values and current and past input values. When working with chemical processes, which tend to be highly nonlinear, it is recommended that one works with the NARX model. A general block diagram of the NARX model is presented in Fig. 2.

The Matlab® System Identification Toolbox offers six methods for NARX model identification. The nonlinearity estimator block can include linear and nonlinear blocks in parallel. For example:

In comparison with conventional circular correlation algorithm, the computational burden can be downsized to two thirds in the improved circular correlation algorithm. The equation is as follows:

$$F(x) = L'(x - r) + d + g(Q(x - r))$$

where the first part is the output from the linear block, and the $g(x)$ function is the nonlinear estimator output. In this paper, we will take a look at the following three nonlinear estimators.

3.1 Neural Network Method

This method works with a neural network nonlinearity estimator. With a number of parameters that can be adjusted, one can set the type of neural network used, the number of hidden layers, the nonlinearity type in each of the layers, etc. The network is usually trained with the estimation data set and then
tested and verified with the verification data set. It is easily adjustable to any input/output size.

3.2 Tree Partition Method

The tree partition method is based on a binary tree nonlinear estimator, based on the CART (Classification and Regression Trees) principle. Parameters concerning tree pruning and tolerance threshold can be adjusted. The output data is classified into leaves, each of them representing one “class” or one range of measured outputs. Setting parameters influences the pruning of the tree.

3.3 Wavelet Network Method

It is considered to be the most speed-optimized method, since it is using wavelets as estimators. They enable quick iteration calculations, and hence quicker identification. Wavelet networks are constructed as follows:

\[ g(x, \theta) = \sum_{i=1}^{N} w_i \psi(\beta(x - \gamma_i)) \]  

where \( \psi \) is a “mother wavelet”, which is a function satisfying special conditions [4].

After deriving a model with one of the before mentioned three methods, we have to validate the model to see if has appropriate behavior. The validation of the model is performed using the second half of the data set (the first half is used for identification). In the following part, we will discuss some of the results we got using each of the methods.

4. Nonlinear System Identification from the Water Treatment Plant Data

We were provided with 23 days of measured input and output data for the decarbonization plant. Since it varies a lot throughout this period, and it is an extremely long period for use in process identification, we chose to work with smaller data subsets of around 7 hours (400 samples). Knowing the chemical background of the process, for the output pH value of the water, we took two input values: Ferrous sulphate, Lime and one measured disturbance: the input pH value of the water. It can easily be seen from the input data plots that we are working with a highly nonlinear process.

One important aspect of identification of nonlinear systems is choosing the right time delays for each of the input variables and choosing the number of regressors, i.e., the number of previous samples of each variable that will be considered in the system model at a given moment. These values are presented in three matrices: Na, Nb and Nk. Na is consisted of elements representing the number of regressors for each of the output variables, Nb has the same purpose for the input variables, and Nk contains the time delays for the inputs. In our case, we choose

\[ N_a = [10], N_b = [3; 2; 15], N_k = [4; 15; 5] \]  

Getting the time delays is a relatively intuitive process, since Matlab® has provided a useful tool for determining the time it takes for the changes in the input data to reflect the changes in the output data. However, the Na and Nb vectors need some trial-and-error. The initial values usually come intuitively, depending on how well one knows the chemical nature of the process. In this case we used the Wavelet Network method for the iterations (since it proved to be the quickest out of the three) to determine the optimal values for the coefficients.

It is important to mention that our focus in this case is not the simulated data to closely follow the measured data, since we are working with the pH of the water at the output of the reservoir and frequent minor variations are expected. What we need to accomplish is an overall fit of more than 35% paying attention to the dynamics of the process and successfully following all the peaks and trends of the measured data. We should also not neglect the amount of inconsistencies in the
working data (sensor failures, changes in system dynamics, etc.). In order to simplify the calculations and improve the overall performance of the estimator, we round the values of the output data set with a precision of 0.25.

A neural network suggested by Matlab® in the Matlab® 2011a Documentation for estimation of nonlinear models is presented in Fig. 3. We have used this kind of neural network structure with three hidden layers in our first experiment. We are using a feed-forward neural network with three hidden layers, transfer functions of types “logsig”, “radbas”, and “purelin” and unknown input and output sizes. We train it against a given input data set and it shows good results, even though the calculations are too slow, and the output data has to be discretized in order for the neural network to function properly. The results obtained with this method are presented in Fig. 4.

The tree partition method creates piecewise linear function over partitions of the regressor space defined by a binary tree. According to the system identification toolbox manual “The estimation algorithm determines the number of units automatically. Try using tree partitions for modelling data collected over a range of operating conditions” [5]. This method has proved to be more successful in capturing measured data values than the neural network method. It only makes slight errors at some peak points. The measured and simulated systems output are presented in Fig. 5.

Both models work good when it comes to small amount of data and produce up to 70% fit with the actual measured output. However, when we need fast calculations, for example in online identification, both, neural network and tree partitioning methods, have been proven to be too slow in building models, but also in simulating outputs. When we deal with large amount of data, measured over a big time interval, the neural network method is inefficient, and in some special cases the fit has negative values.

A significantly faster method is the Wavelet Network with a linear block, which has produced best results for time limited identification. It produces results of 30-60% fit when it comes to individual data sets and 35% overall fit, which is more than good, since we are working with the actual data set. The low fit is a result of inequalities between the measured and the simulated output when it comes to minor oscillations, most often due to changes in water turbidity. The comparison between the measured and simulated output of the wastewater treatment plant are depicted in Fig. 6.
From the graphs and the values obtained, we can conclude that the wavelet network method resulted with best performance in simulating the plant using smaller data sets. On the other hand the wavelet network identification method resulted with an overall best performance, and the neural network method has proven to have biggest mismatch of the simulated and measured results when dealing with big amount of noisy data sets.

In Table 1, we present how each of the proposed models behaved for overall fit with the whole set of measured data.

From Figs. 4-6 and Table 1, we can conclude that the tree partition method makes a balance between the performance and speed. With over 70% fit for small data sets and almost 50% fit for a whole 40-day data set, the performance of this method went beyond expected. The wavelet network gave somewhat expected results because it is the best method for implementing fast and/or online nonlinear identification using nonlinear approximators. On the other hand, the neural network trained with such kind of data that are noisy and represent different but not separable operating conditions has proved to be too subjective and easily falls into local minimums during its operation. When we tested it against the whole data set, it showed a modest fit of 5%.

5. Conclusions

The paper have presented several advanced method for nonlinear system identification using nonlinear approximators, applied on a data form water treatment plant in the KEK—Kosovo power plant. From the presented methods we have concluded that tree partition method has shown best results for processes with large amount of noisy data that is subject to different but no separable operating conditions. Nevertheless, this cannot be generalized for all type of processes, since all of them introduce certain specifics in the process of identification, and all methods must be considered.

References