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A new Self-Organizing Extreme Learning Machine soft sensor model and its applications in complicated chemical processes

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ABSTRACT

The control of product quality of complex chemical processes strictly depends on the measure of the key process variables. However, the online measure device is extremely expensive, and these devices are hard to protect. Meanwhile, there is a delay for these online measure devices. Therefore, the soft sensor technology plays a vital role in measuring the key process variables. Extreme Learning Machine (ELM) is an efficient and simple single layer feed-forward neural networks (SLFNs) to building an exact soft sensor model. However, unsuitable selected hidden nodes and random parameters will greatly affect the performance of the ELM. Therefore, this paper proposes a novel Self-Organizing Extreme Learning Machine (SOELM) algorithm constructed by the biological neuron-glia interaction principle to solve the issue of the ELM. Firstly, the weights between input layer nodes and the CNS are tuned iteratively by the Hebbian learning rule. Then the network structure is adjusted self-organizing by Mutual Information (MI) among different structures of networks. Secondly, the weights between the CNS and output layer nodes are obtained by the ELM. The experimental results based on different UCI data sets prove that the SOELM has a better generalization capability and stability than that of the ELM. Moreover, our proposed method is developed as a soft sensor model for accurately predicting the key variables of the Purified Terephthalic Acid (PTA) process.

1. Introduction

Complex chemical processes make a difference in developing the industry development in most countries. At the same time, the PTA (purified terephthalic acid) production is the main process in chemical industries. Meanwhile, the demand of PTA 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 (Li and Sun, 2013). Meanwhile, some complicate chemical process are solved by soft sensor, as the synthesis of chemical product depends on soft chemical process (Rizwan and Farheen, 2015), and the automation of a reactor flow system (Edwin and Peter, 1998), and monitoring the process of curing of epoxy/graphite fiber composites (Hong et al., 1998). In summary, it is an effective way to improve the productivity and energy efficiency of the complex chemical process by building the soft sensor model.

Under some circumstances, accurately estimating the key process variables is extremely helpful to improve the control performance in the industrial processes (Ge and Song, 2010). In the process industry, measuring devices could be very expensive, could introduce significant delays, and the implemental technology could be extremely difficult, so we can't be easy to measure the key process variable online (Liu et al., 2013). Therefore, soft sensors have attracted more and more attention as a substitution of the hard device for either the monitoring purpose or the control purpose (Ge and Song, 2010), However, based on mechanism models, building an accurate soft sensor is more and more difficult and time consumed because many industries are more and more complicated especially the chemical and petrochemical industries. Some researchers have successfully adopted the Extreme Learning Machine (ELM) to develop soft sensors for complicated industrial processes (Zhang and Yin, 2016; Mortaza et al., 2016; Chakchai et al., 2016).

Although many self-organizing learning algorithms were proposed in the past, the study of self-organizing ELM has not been seen recently. This paper proposed a novel Self-Organizing Extreme Learning Machine (SOELM) algorithm constructed by neurons and glias according to biological neuron-glia interaction principles. The glia provide energy for the neuron, and the stability of the CNS depends on the entropy of all neurons. At the same time, the novel SOELM algorithm is also proposed to determine the self-organizing network

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structure adaptively including hidden nodes and linking weights. The CNS is analyzed and designed based on distributions of neurons and glias. The weights between the input layer and the CNS are obtained by Hebbian learning rule. The weights between the CNS and output layer nodes are derived by the ELM algorithm. The experimental results based on standard data sets prove that the SOELM has a better generalization capability and stability than that of conventional ELM. In order to accurately predict the key production of the PTA system in complex chemical processes, our proposed SOELM soft sensor model which is data-driven based method can remarkably improve the intelligent control capabilities for complex process because of its self-organized structure and robust generalization performance.

The organization of this paper is as follows: Section 1 presents the importance of soft sensor in complicated industrial processes and my related works. Section 2 presents the research status of ELM and some associated neural networks. Furthermore, the study status of neuron and glia in biology and neural network, Hebbian learning rule are also presented. The details of ELM method are described in Section 3. The structure and the learning algorithm of our proposed method are provided in Section 4. Comparisons and parameters are discussed by standard data sets in Section 5. Section 6 presents a case study: the prediction of key process variables in PTA chemical data based on SOELM soft sensor model, and compare with ELM method. Finally, the discussion and conclusions are given in Sections 7 and 8, respectively.

2. Literature review

The Extreme Learning Machine (ELM) algorithm of neural network was first proposed by Guang-bin Huang et al. in 2004, in which all the parameters were not to be tuned iteratively. The weights between hidden layer and output layer nodes were obtained by the solving of Moore-Penrose generalized inverse matrix (Huang et al., 2006). So the ELM algorithm has a faster training speed and has been applied in many fields, such as data mining, machine learning, pattern recognition etc. (Wang et al., 2015b; Fossaceca et al., 2015). Recently, many researchers have studied and improved the performance of ELM. Ke-feng Ning et al. presented a novel robust ELM method based on a Bayesian framework which replaced the Gaussian distribution with a heavy-tailed distribution (Ning et al., 2015). Men and Wang (2015) proposed a randomized ELM speedup algorithm. In this method, the key matrix could be efficiently approximated by applying the randomized approximation method. Schaik and Tapson (2015) improved the conventional ELM to achieve online learning. The pseudo-inverse was solved by an incremental method, so the improved ELM could be applied in online learning to process large data sets. Although many ELM algorithms were proposed recently to improve the speed or extend applied fields of ELM, the traditional and improved ELMs still cannot adaptively obtain hidden nodes to determine the network structure based on training data sets.

Neurons and glias are two kinds of nervous cells in Central Neural System (CNS). The neurons have always been pivotal roles in a complex nervous system. In the past decades, the glia was known to support and nourish cells. However, some researchers have still thoroughly uncovered more and more mysteries about functions of glias in CNS in recent years. Nearly half of cells in human brain are made up of the glia, in which one kind of glias is astrocyte (Ullian et al., 2001). The neurons transmit electric signals to each other, and then the brain performs many complex activities according to the processing of signals. The synapse of neuron is responsible for receiving the electric signals transmitted by the dendrite of another neuron, so the number of the synapse affects activities of neurons. Although the synapses could be formed by neurons without glias, neurons may require glia-derived cholesterol to form numerous and efficient synapses (Pfrieger, 2002). The enough cholesterol was produced by neurons in the CNS to survive and grow, but the glia provided additional functions for the formation of numerous mature synapses (Mauch et al., 2001). The glia were involved in inducing the formation of new synapses, eliminating existing synapses, controlling the location of synaptic inputs, and stabilizing synaptic structure (Allen and Barres, 2009). Recently, some researchers discovered a mystery that certain ions were used for transmitting signals to glias (Haydon, 2001). The Ca2+, which is one of the most important ions, could change a membrane potential of the neuron (Ikuta et al., 2012b). As a result, the transmissions of the electric signals rely on the neurons and glias.

Glias outnumber neuronal cells by a ratio of 10 to 1. The complexity of a neuronal system is increased with an increasing in the ratio of glia versus neuronal cells (Granderath and Klambt, 1999). Meanwhile, the neuron migration, the axon growth and guidance depended on the neuron-glia interactions (Faissner, 2009). Annalisa Buffo et al. provided an extensive overview of the available literature and some novel insights about the origin and differentiation of variety of the glia (Buffo and Rossi, 2013). In a word, the transmission of electric signals in human brain not only depends on the neuron, but also the glia. Currently, the glia has been widely applied in artificial neural networks. Chihiro Ikuta et al. proposed a chaos glial network which connected to Multi-Layer Perceptron (MLP) for solving the Two-Spiral Problem (TSP), and some improved methods based on these references were proposed (Ikuta et al., 2010, 2011a, 2011b, 2012a, 2012c, 2013). According to the recent achievements in the neuroscience field, Ban Xiao-Juan et al. established a new artificial neuron model called Energy Artificial Neuron (EAN) based on the energy concept from the glia and realized a self-growing and self-organizing neural network based on the EAN model (Ban et al., 2011).

Hebbian learning rule was first proposed by Donald Hebb (Hebb, 2000). It is an unsupervised learning algorithm. It described how neurons excite each other and how this excitation subsequently changes with time based on biological principles (Kuriscak et al., 2015). In the 1970s, researchers began to study artificial neural networks which could simulate biological principles of the human brain (Willshaw and Von, 1976). It was applied in tuning weights between the input layer and the hidden layer nodes in artificial neural networks, which the variation of weights depends on input and output signals of every neuron.

The study of self-organizing structure of network is an important topic in neural network area. Many researchers proposed many effective self-organizing algorithms. Nasr and Chtourou (2011) proposed a novel hybrid algorithm for a feed-forward neural network based on a two stage learning approach. The structure of this network was adjusted in first stage and network parameters were adjusted by a fuzzy neighborhood-based hybrid learning algorithm in second stage. M.H. Ghaseminezhad et al. proposed a novel self-organizing map (SOM) neural network for discrete groups of data clustering because of the lack of solving for clustering discrete groups of data in the classic SOM (Ghaseminezhad and Karami, 2011; Kohonen, 1981). Han and Qiao (2012) proposed a self-organizing radial basis function (SORBF) neural network whose hidden nodes could be grown or pruned based on the node activity (NA) and mutual information (MI) to achieve the appropriate network complexity and maintain overall computational efficiency. Shen Furao et al. presented the incremental network and automated to adjust the number of hidden nodes (Chang et al., 2013; Han et al., 2012; Hsu et al., 2012; Qiao and Han, 2012; Li et al., 2004). Chow and Wu (2004) proposed the cell-splitting grid (CSG) algorithm, and proved that the CSG algorithm outperformed SOM and other SOM-related algorithms in vector quantization while maintaining relatively good topology preservation. In addition, Shen Furao and Osamu Hasegawa proposed an incremental network for online unsupervised classification and topology learning. This incremental network is just for unsupervised classification task, but not applied in solving regression problems (Furao and Hasegawa, 2006; Furao et al., 2007). Bernd Fritzke proposed a self-organizing network to model a given probability distribution. However, the distributions of most problems in real world are not known for us generally (Fritzke,