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A Neuro Adaptive Control Strategy for Movable Power Source of Proton Exchange Membrane Fuel Cell Using Wavelets

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***Abstract*—**Movable power sources of proton exchange membrane fuel cells (PEMFC) are the important research done in the current fuel cells (FC) field. The PEMFC system control influences the cell performance greatly and it is a control system for industrial complex problems, due to the imprecision, uncertainty and partial truth and intrinsic nonlinear characteristics of PEMFCs. In this paper an adaptive PI control strategy using neural network adaptive Morlet wavelet for control is proposed. It is based on a single layer feed forward neural networks with hidden nodes of adaptive morlet wavelet functions controller and an infinite impulse response (IIR) recurrent structure. The IIR is combined by cascading to the network to provide double local structure resulting in improving speed of learning. The proposed method is applied to a typical 1 KW PEMFC system and the results show the proposed method has more accuracy against to MLP (Multi Layer Perceptron) method.

***Keywords*—**Adaptive Control, Morlet Wavelets, PEMFC.

I. Introduction

A proton exchange membrane fuel cell (PEMFC) is a new electric power generation device that directly transforms chemical energy of hydrogen and oxygen into electrical energy through electrochemical reaction without burning in the presence of an electrolyte made of a solid polymer, with the aid of the catalyst. PEMFC has many advantages such as cold starting, low operation temperature, none electrolyte corrosion, zero pollution, no noise, Module type structure, high generation efficiency and high generating power density.

In the recent five years, many great engine manufacturing companies developed PEMFC power used for vehicle one after another and positively processes the road test because PEMFC was regarded as the future ideal clean vehicle power [I].

To aim at the problems control system of PEMFC movable power sources caused by time-change, long- hysteresis, uncertainty, strong-coupling and nonlinearing, in this paper an adaptive PI algorithm is proposed by utilizing the simple PI controller structure based on self-tuning schemes of the wavenet (wavelets+ neural networks) parameters.

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II. Principles of PEMFC Movable Power Sources

The key component of a PEMFC movable power source is the PEMFC stack, and it is made of many PEMFC cells. The basic PEMFC cell composition includes bipolar plate, the gas channel, the sealing gasket, the current collector, and the membrane electrode assembly (MEA). In PEMFC, MEA is the most important component so that it is called the heart of PEMFC. MEA is composed by porous gas diffusion anode, porous gas diffusion cathode and proton exchange membrane. Its quality directly affects the PEMFC operating performance.

The PEMFC internal electrochemical reaction, in essence, is the process that combines hydrogen and oxygen over a platinum catalyst to produce water. The PEMFC mechanism is shown in Fig. 1. In the PEMFC the gases flow in the gas channels of the bipolar plates and filter into the porous anode/cathode electrode layer when the humid hydrogen and oxygen enter at the gas inlets.

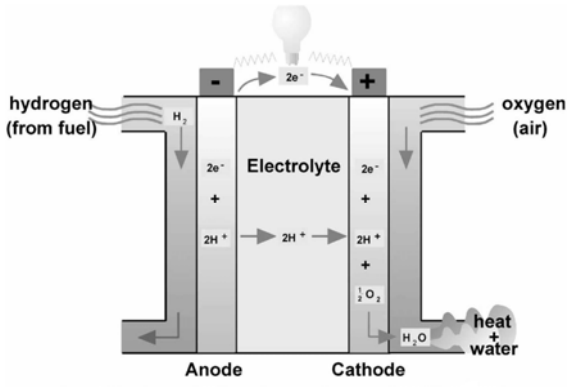


Fig. 1 Schematic diagram of PEMFC mechanism

In the anode layer, hydrogen molecules are decomposed into hydrogen ions and electrons in the presence of Platinum, which is the catalyst. The hydrogen ions diffuse across the proton exchange membrane and transfer to the cathode electrode layer, while the electrons flow across the load to the cathode electrode layer because of obstructed by the proton exchange membrane. At the same time, in the cathode layer, oxygen molecules are decomposed into active oxygen atoms with the aid of platinum that is the catalyst, and then react with the hydrogen ions and the electrons to produce water. Thus, PEMFC produce direct current electricity E^0, as well as water and heat Q^0 as the byproducts [2].

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PEMFC electrochemical reactions are described below:

$$\text{Anode-reaction: } H_2 \xrightarrow{pt} 2H^+ + 2e^- \quad (1)$$

$$\text{Cathode-reaction: } \frac{1}{2}o_2 + 2H^+ + 2e^- \xrightarrow{pt} H_2o + Q^o \quad (2)$$

$$\text{Overall reaction: } \frac{1}{2}o_2 + H_2 \xrightarrow{pt} H_2o + Q^o + E^o \quad (3)$$

In conclusion, PEMFC can generate electricity continuously as long as hydrogen and oxygen are supplied in the definite operating condition [3].

The main factors that determine the amount of PEMFC generating power are the active working area and working status of MEA. The amount of electricity that a PEMFC cell produces is very low commonly (only a potential of 0.7~0.8V when generating a current a density of approximately 0.5A/cm^2) [2]. Thus, many PEMFC cells are connected in series to form a PEMFC stack to meet the required power for a specific application [4].

While running, PEMFC stack needs to maintain the certain temperature, humidity and pressure. Water, as the production of the electrochemical reaction, needs to remove out so as to prevent the electrode from "drowning to death". Of course, the certain vapor must be kept in the PEMFC stack to prevent the electrode from "dry to end" so as to avoid its performance's dropping even damaged. Therefore, the PEMFC stack must run with the peripheral equipments to assure its good working conditions.

A PEMFC movable power source is mostly composed of the PEMFC stack, the reactant supply and the assistant device. The PEMFC stack is the generating set, and may be made to each kind of combination forms, shapes and sizes any according to its practical need. Generally, the PEMFC stack is made of the cascading cuboids structure. The reaction supply mainly has three types which are the high-pressure gas tank, the chemical hydrogen tank and the metal hydride tank, the assistant device is mainly used to control the input/output and operating condition of the PEMFC stack.

PEMFC movable power sources are mainly used in the portable power supply of the electronic installation, the military covert power supply, and the civil emergency power supply of the transportation vehicle [5]. Therefore, it is requested that PEMFC movable power sources must be light, starting quickly, and have to have good stability, good performance of anti-vibration and anti-impact and be suitable for bad conditions. Moreover, the oxidant mostly used the air in PEMFC movable power sources, and the cooling type has the water- cooling and the air-cooling according to the generation power. In a word, PEMFC movable power sources must be requested to simplification and practicality to achieve tractability, robustness and low solution cost.

III. System Controls of PEMFC Movable Power Sources

PEMFC movable power source system control belongs to the complex electrochemical process control [6]. Firstly, PEMFC movable power source system control has the characteristics of multi- input/output and nonlinear. Many variables need to be controlled on real time in the PEMFC movable power source. For example: temperatures, the pressure, the flux, the load and so on... Moreover, the mapping of the input and output variables has the extremely complex nonlinear relation, and the change of disturbance factors intensifies the nonlinear. Secondly, PEMFC movable power system control has the characteristics of time-changing, distribution parameter and strong-coupling. Then, PEMFC movable power source system control has the characteristics of long-hysteresis and restraint. The controlled object has a big lag as a result of the electrochemical reaction.

At last, PEMFC movable power source system control has complex characteristics of uncertainty and random disturbance. The control process has the dynamic uncertainly owing to the changes of the reactant and the internal status of PEMFC stack (especially the dynamic status of MEA). In addition, there are bad qualities of the random disturbance and the transmission noise in PEMFC stack.

On the basis of these characteristics, the traditional control method of PEMFC movable power source system control is not often able to meet the effective control result.

IV. Neuro Adaptive Control System of PEMFC Movable Power Source

On the basis of various tests of a 1KW PEMFC movable power source, a neuro-adaptive control based on advanced control strategy of 1KW PEMFC movable power source is presented and simulated in order to obtain its best control effect in the typical working conditions. PEMFC movable power source system control is generally preset according to the experimental data and the operation experience. This experience control method both wastes energy and does not achieve the good control quality. For the sake of a study of PEMFC movable power source system control, here present a neuro adaptive control strategy of PEMFC movable power source. On the basis of the experimental of 1KW PEMFC movable power source, the input-output data are set.

Before beginning tracking operation use a neuro network based PI controller, the unknown nonlinear PEMFC must be identified according to a certain model. In this particular identification process, the model consists of a neural network topology with the wavelet transform embedded in the hidden units. In cascades with the network is a local infinite impulse response (IIR) block structure as shown in Fig. 3. The algorithm of neural network adaptive wavelets is similar to those in where any desired signal $y(t)$ can be modeled by generalizing a linear combination of a set of Morlet daughter wavelets $h_{a,b}(t)$, where $h_{a,b}(t)$ are generated by dilation, a, and translation, b, from a mother wavelet:

$$h_{a,b}(t) = h(\frac{t-b}{a}) = \cos[\omega_o(\frac{t-b}{a})]\exp[-0.5*(\frac{t-b}{a})^2], a>0 \quad (4)$$

$$\tau = \frac{t-b}{a} \quad (5)$$

The approximated signal of the network $\hat{y}(t)$ can be modeled by:

$$\hat{y}(t) = \sum_{i=0}^{M} c_i z(t-i)u(t) + \sum_{j=1}^{N} d_j \hat{y}(t-j)v(t) \quad (6)$$

$$z(t) = \sum_{k=1}^{K} w_k h_{a_k,b_k}(t) \quad (7)$$

K is the number of wavelets, w_k is the k[th] weight coefficient. M and c_j are the number of feed forward delays and coefficient of the IIR filter, respectively, N and d_j are the number of feed back and recursive filter coefficients. The signals $u(t)$ and $v(t)$ are the input and co-input to the system at time t, respectively. Input $v(t)$ is usually kept small for feedback stability purposes.

The neural network parameters a_k, b_k, c_i, w_k and d_j can be optimized in the LMS sense by minimizing a cost function or the energy function, E, over all time t. Thus,

$$e(t) = y(t) - \hat{y}(t) \quad (8)$$

is a time varying error function at time t, where $y(t)$ is the desired (target) response. The energy function is defined by:

$$E = \frac{1}{2}\sum_{t=1}^{T} e^2(t) \quad (9)$$

To minimize E we may use the method of steepest descent and each coefficient vector $\underline{a}, \underline{w}, \underline{b}, \underline{c}$ and $\underline{d}$ of the network is updated in accordance with the rule:

$$\underline{f}(n+1) = \underline{f}(n) + \mu_f \Delta \underline{f} \quad (10)$$

where the subscripted μ_f values are fixed learning rate parameter and $\Delta \underline{f} = -\partial E / \partial f$.

V. System Model and PI Controller Design

Consider a general dynamical system that is represented in discrete domain by the state equations:

$$x(k+1) = f(x(k),u(k),k) \quad (11)$$

$$y(k) = g(x(k),k)$$

where $x(k) \in R^n$ and $u(k), y(k) \in R$. Further, let the unknown functions $f, g \in C^1$. The only accessible data are the input u and output y. It should be if the linearized system around the equilibrium state is observable, an input-output representation exists which has the form

$$y(k+1) = \varphi(y(k), y(k-1),..., y(k-n+1), u(k), u(k-1),..., u(k-n+1)) \quad (12)$$

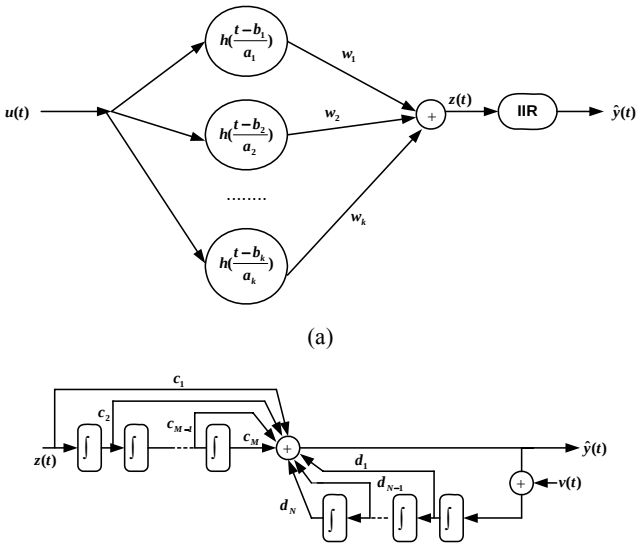


Fig. 2 IIR Adaptive wavelet network structure (a) neural network architecture (b) IIR model

i.e. a function $\varphi(.)$ exists that maps $y(k)$ and $u(k)$, and their $n-1$ previous values, into $y(k+1)$. In view of this, a neural network model $\hat{\varphi}$ can be trained to approximate φ over the domain interest. The considerations are based on the neural network controller design of the control system. The following alternative model of an unknown plant that can simplify the computation of the control input is described by the equation

$$y(k+1) = \phi(y(k)) + \Gamma(y(k)).u(k) \quad (13)$$

for a discrete-time process of dimension 1 where $y(k)$ and $u(k)$ denote the input and the output at the kth instant of time. If $\phi(.)$ and $\Gamma(.)$ are unknown, the idea is to use the neural network adaptive wavelets model to approximate the system dynamics i.e. ,

$$\hat{y}(k+1) = \hat{\phi}(y(k),\Theta\phi) + \hat{\Gamma}(y(k),\Theta_\Gamma)u(k) \quad (14)$$

Comparing the model of (14) with the (6), we can conclude that

$$\hat{\phi}(y(k),\Theta_\phi) = \sum_{j=1}^{N} d_j \hat{y}(k-j)v(k) \quad (15)$$

$$\hat{\Gamma}(y(k),\Theta_\Gamma) = \sum_{i=0}^{M} c_i z(k-i) \quad (16)$$

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After the nonlinearities $\phi(.)$ and $\Gamma(.)$ are approximated by the two distinct neural network functions $\hat{\phi}(.)$ and $\hat{\Gamma}(.)$ with adjustable parameters, represented by Θ_ϕ and Θ_Γ respectively, the PI control $u(k)$ for tracking a desired output $r(k+1)$ can be obtained from:

$$u(k) = u(k-1) + P[\varepsilon(k) - \varepsilon(k-1)] + I\varepsilon(k)] \quad (17)$$

where P and I are proportional and integral gains, u(k) is a plant input at kT, where T is a sampling interval, and

$$\varepsilon(k) = r(k) - y(k) \quad (18)$$

P and I parameters are considered as part of the function of E and can be optimized and updated according to the cost function E of (9),

$$P(k) = P(k-1) + \mu_P e(k)\Gamma(k)(\varepsilon(k) - \varepsilon(k-1)) \quad (19)$$

$$I(k) = I(k-1) + \mu_I e(k)\Gamma(k)\varepsilon(k) \quad (20)$$

where $\hat{\Gamma}$ comes from (16), and μ is the fixed learning rate of each adaptive PI parameter. Fig. 3 depicts the block diagram of the resulting network topology based on the PI controller for self-tuning controls PEMFC's. In this diagram, y is output power, r is maximum output power and u is inlet reactants.

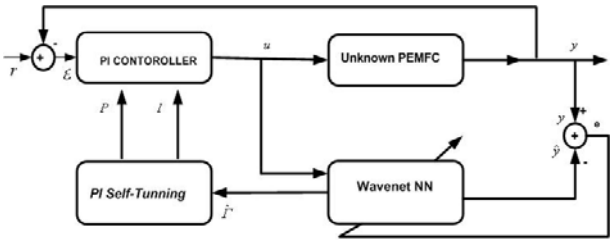


Fig. 3 Closed loop block diagram

VI. Simulation Results

A. Approximation of PEMFC

In this section, it will be shown through simulations Morlet mother wavelet basis functions perform their learning ability. Using the data from the PEMFC extracted from experiment, the wavenet network with different size and Morlet mother wavelets is employed to approximate the PEMFC data. IIR block structure with feedforward coefficients M=3 and feedback coefficients N=3 is also implemented. Moreover, wavelets are local basis functions that provide less interfering than global ones, leading to a noncomplex dependency in the NN parameters. This section will confirm this idea by providing several observations derived from the results of the MATLAB simulations. Assuming the training data are stationary and sufficiently rich, good performance can usually be achieved with a small learning rate. Thus, all learning rate parameters for weights, dilations, translations, IIR feedforward coefficients, and feedback coefficients are fixed at 0.0055, 0.03, 0.0250, 0.015, and 0.015, respectively. All initial weights w_k and dilations a_k are set to 0 and 10, respectively. Note that if the dilation parameters are set too wide, they can cause several overlapping partitions and thus cannot be rallied. Setting a_k too narrow may result in longer convergence.

Initial translation parameters b_k are spaced equally apart throughout the training data to provide non-overlapping partitions throughout the neighboring intervals. Finally, the initial IIR coefficients c and d should be set so that system has poles inside the unit circle, thus both are set to 0.15. The number of coefficients for each feedforward and feedback M and N are both set to 3 as well. The learning epoch will terminate when the desired normalized error of 0.023 is reached. The following simulations will describe the results of the wavenet network performance employing Morlet mother wavelets.

B. Control

After model identification is completed, the tracking operation takes command of the neuro process control to track the desired set point r. The co-input $v(t)$ is set to 0.95. In Fig. 4 the results of the PEMFC control using the proposed self-tuning neuro wavenet controller with 57 Morlet is compared with the results of the PEMFC control using the combined MLP control. In this figure, a sequence of step-shaped is applied to the system. The resulting evolution of the closed loop converges rapidly to the desired optimal rotational speed with simple first-order dynamics. As can be seen in Fig. 4, proposed method is better than MLP method regarding simulation accuracy. The proposed controller can be efficiently implemented on digital signal processors.

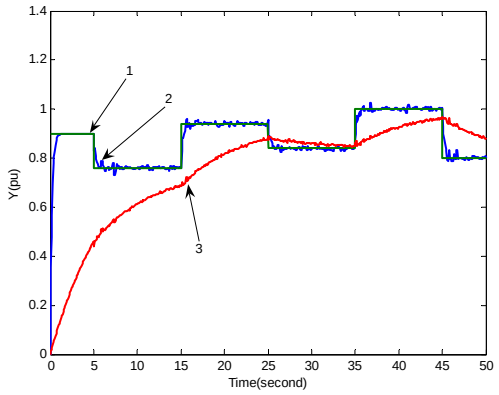


Fig. 4 Neuro Wavenet Controller Responses to a sequence of step shaped input: 1-Setpoint Reference 2- Wavenet controller Response 3- MLP controller Response

VII. Conclusion

This paper discussed the application of wavenet networks in the implementation of adaptive controllers for PEMFC's. They were proposed to cope with the intrinsic nonlinear behavior of PEMFC. The approach used, based on a single layer feedforward neural networks with hidden nodes of adaptive Morlet wavelet functions controller and an infinite impulse response (IIR) recurrent structure, allowed fast

convergence to a simple linear dynamic behavior, even in the presence of parameter changes and model uncertainties. The resulting controller showed to be simple enough to be synthesized using signal processors.

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