Speed Sensorless of an Induction Motor Using Self-tuning Fuzzy Identification

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Abstract

This paper presents a novel method for sensor-less speed estimation of the induction motor, based on the self-tuning fuzzy identifier incorporating a three-layered network. The back-propagation algorithm is used to adjust the parameter of membership function, as well as to minimize the difference between the actual flux output and the output as predicted by the self-tuning fuzzy identifier, so as to enable precise estimation of speed tracks of the actual motor speed. The experimental results demonstrated that the self-tuning fuzzy identifier possesses a fairly good tracking capability and can accurately and rapidly identify the actual speed of the induction.

1. Introduction

Vector-controlled induction motors have been widely used in high-performance ac drives. Generally, to orient the injected stator current vector and to establish the speed loop feedback, information of rotor speed is essential for controlling the induction motor. In modern control techniques for induction motor drives, either a shaft mounted tachometer, photo encoder or digital shaft position encoder is used to obtain the speed information. These speed sensors, however, increase the cost and also spoil the robustness of the induction motor. In addition, for some special applications such as very high-speed motor drives, some difficulties are encountered in mounting these speed sensors. From this point of view, as well as for general purpose, low cost drives, which will also reduce the effects of speed measurement error at low speeds, sensor-less speed estimation is preferable. In the last few years, numerous researches proposing the sensor-less speed vector control of electrical drives have been published, wherein different methods have been employed to identify the rotor speed [1].

Fuzzy systems theory has been an active research area in the recent years. Application of fuzzy systems to identification of dynamics system and their control has emerged as a promising alternative to process control because, firstly, fuzzy systems are constructed from the fuzzy IF-THEN rules so that the linguistic descriptions can be naturally incorporated into these fuzzy identifiers [2]. Secondly, adaptive laws can be developed in order to adjust the parameters of the fuzzy identifiers to make them match the input-output pair [3]. More significantly, the parameters of the adaptive fuzzy system have clear physical meanings, based on which a good initial value can be chosen, thereby greatly speeding up the convergence of training procedure [4].

In this paper, we propose a novel method for sensor-less speed estimation of the induction motor, based on the self-tuning fuzzy identifier incorporating a three-layered network [5]. Induction motor rotor fluxes are selected to represent the desired and actual state variable. The widely used back-propagation algorithm is used as the learning algorithm in this network to adjust the parameter of membership function. This algorithm is to minimize the difference between the motor's actual output flux and the output flux as predicted by the self-tuning fuzzy identifier, so that a precise estimate of the speed tracks of the actual motor speed can be obtained.

2. Induction motor model

The mathematical model of the electrical dynamics and torque equations of the induction motor in the d, q synchronously rotating reference frame, by appropriately selecting the stator currents and rotor flux as state variables, can be expressed as [6]

3. The proposed speed estimation scheme

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A self-tuning fuzzy identifier can be employed for induction motor speed estimation. Figure 1 illustrates the block diagram for such speed estimation using self-tuning fuzzy identifier. Appropriate induction motor rotor fluxes are selected to represent the desired and actual state variables. Two independent estimators are used, such that one provides the reference model output, while the other yields the fuzzy model output. The fuzzy model output with a self-tuning fuzzy identifier is compared with the desired reference value, and the error between the outputs of these two models is then used to adjust the parameter of membership function by using the back propagation algorithm. The output of fuzzy model is thus made to coincide with the desired value, and the estimated speed thus tracks the actual motor speed precisely through the self-tuning fuzzy identifier.

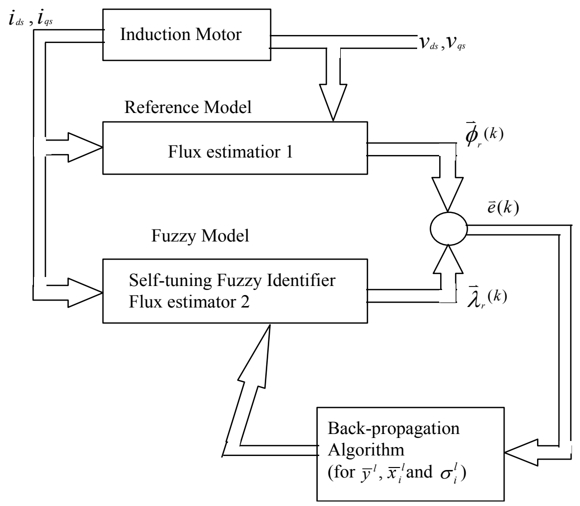

Fig. 1 The block diagram of speed estimation scheme with self-tuning fuzzy identifier

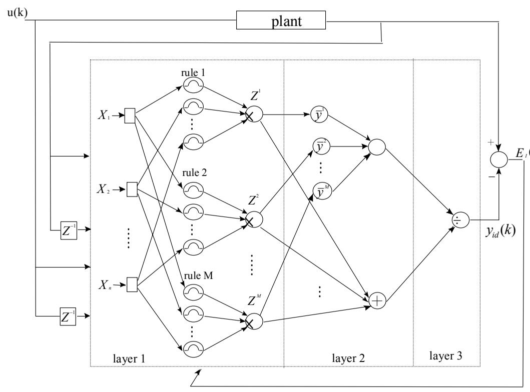

Fig. 2 The block diagram of self-tuning fuzzy identifier

3.1. Design of Self-Tuning Fuzzy Identifier

Consider discrete nonlinear system expressed as:

$$y(k) = f(y(k-1),...,y(k-n+1),u(k-1),...,u(k-m)) \quad (1)$$

where f is an unknown function which we want to identify, u and y are the input and output of the plant, n and m are order of u and y, respectively. We now consider the identification of the unknown function f, based on fuzzy systems. Figure 2 shows the block diagram of the proposed self-tuning fuzzy systems. This fuzzy identifier consists of a three-layered network structure, with each layer having a precise function. In the following section, we shall describe the design procedure for the proposed self-tuning fuzzy identifier and develop a back-propagation algorithm to adjust the parameter of membership function, so that the output $y_{id}(k)$ of the self-tuning fuzzy identifier can accurately identify the output $y(k)$ of the nonlinear systems.

3.1.1. Fuzzifier.

The fuzzifier performs mapping from a crisp input point x_1, x_2, …, x_n into a fuzzy set of membership functions. In this paper, the following Gaussian function is selected as the membership function:

$$\mu_i^l(x_i) = \exp\left[-\left(\frac{x_i - \bar{x}_i^l}{\sigma_i^l}\right)^2\right] \quad (2)$$

where J =1,…, M, and M is the number of control rules. Also, $\bar{x}_i^l$ and σ_i^l are the centers and width of the membership functions, and x_i, i=1,…,n are input signals of the fuzzy identifier.

3.1.2. Fuzzy inference engine and the related fuzzy rule base.

Using the product-inference rule, the z^l, l=1,…M of layer 1 in Fig. 2 can be obtained by multiplication of all the fuzzified values and can be given by

$$z^l = \prod_{i=1}^{n} \exp\left[-\left(\frac{X_i - \bar{X}_i^l}{\sigma_i^l}\right)^2\right] \quad (3)$$

3.1.3. Defuzzifier

The overall output of the fuzzy identifier (layer 3 in Fig. 2) is based on the procedure given above. Therefore,

$$y_{id} = \frac{\sum_{l=1}^{M} \bar{y}^l z^l}{\sum_{l=1}^{M} z^l} \quad (4)$$

3.2. Back-Propagation Training Algorithm for self-tuning Fuzzy Identifier

First, the error function is defined by

$$E_I(k)=\frac{1}{2}\left(y_{id}(k)-y(k)\right)^2 \tag{5}$$

Our objective is to develop a self-tuning fuzzy identifier y_{id}, as in Eq. (4) such that $E_I(k)$ of Eq. (5) is minimized. Hence, the identification problem now becomes that of training the parameters $\bar{y}^l$, $\bar{x}_i^l$, σ_i^l of membership function such that $E_I(k)$ of Eq. (5) is minimized.

In this paper, the back-propagation algorithm is based on the steepest descent method. The derivation result of this back-propagation algorithm is as follows:

$$\bar{y}^l(k+1)=\bar{y}^l(k)-\alpha_I\frac{y_{id}(k)-y(k)}{\sum_{l=1}^{M}z^l(k)}z^l(k) \tag{6}$$

$$\bar{x}_i^l(k+1)=\bar{x}_i^l(k)-\alpha_I\left(y_{id}(k)-y(k)\right)\left(y^l(k)-y_{id}(k)\right)\frac{2\left(x_i(k)-\bar{x}_i^l(k)\right)z^l(k)}{\left(\sigma_i^l(k)\right)^2\sum_{l=1}^{M}z^l(k)} \tag{7}$$

$$\sigma_i^l(k+1)=\sigma_i^l(k)-\alpha_I\left(y_{id}(k)-y(k)\right)\left(\bar{y}^l(k)-y_{id}(k)\right)\frac{2\left(x_i(k)-\bar{x}_i^l(k)\right)^2z^l(k)}{\left(\sigma_i^l(k)\right)^3\sum_{l=1}^{M}z^l(k)} \tag{8}$$

where $l=1,\ldots,M$, $j=1,\ldots,n$ and $k=1, 2,\ldots$

The training algorithms given in Eqs. (6), (7) and (8) perform an error back-propagation procedure for the self-tuning fuzzy identifier.

3.3. Principle of Speed Estimation

The model chosen for estimation of speed using a fuzzy system is based on two independent rotor flux observers, deduced from the induction motor model. The first one is considered as the reference estimator and is derived as follows:

$$\frac{d\vec{\phi}_r}{dt}=\frac{L_r}{L_m}I(\vec{V}_s-R_s\bar{I}_s-\sigma L_s\frac{d\bar{I}_s}{dt})-\sigma L_s\omega_e J\,\bar{I}_s \tag{9}$$

where $\vec{\phi}_r=\left[\phi_{dr},\phi_{qr}\right]^T$, $\vec{v}_s=\left[v_{ds},v_{qs}\right]^T$, $\bar{I}_s=\left[i_{ds},i_{qs}\right]^T$ and

$$I=\begin{bmatrix}1&0\\0&1\end{bmatrix},\ J=\begin{bmatrix}0&-1\\1&0\end{bmatrix}.$$

The second flux observer is derived from the third and the fourth row as follows :

$$\frac{d\vec{\lambda}_r}{dt}=[\frac{-1}{\tau_r}I+p(\omega_r-\omega_e)J]\vec{\phi}_r+\frac{L_m}{\tau_r}I\,\bar{I}_s \tag{10}$$

where $\vec{\lambda}_r=\left[\lambda_{dr},\lambda_{qr}\right]^T$, $\tau_r=L_r/R_r$ is the rotor time constant .

The observer is selected, based on Eq. (9), to generate the desired value of rotor flux $\vec{\phi}_r$, and can be regarded as a reference model of the induction motor, since Eq. (9) does not involve the quantity ω_r. Besides, the other observer based on Eq. (10), which does involve ω_r, generates the actual rotor flux $\vec{\lambda}_r$ and may be regarded as a fuzzy model with adjustable parameters.

By applying the backward difference method, Eq. (10) can be discriminated and described as-

$$\vec{\lambda}_r(k)=(1-\frac{T_s}{\tau_r})I\,\vec{\phi}_r(k-1)-P\omega_eT_sJ\vec{\phi}_r(k-1)+P\omega_r(k-1)\,T_s\,J\vec{\phi}_r(k-1)+\frac{L_mT_s}{\tau_r}I\,\bar{I}_s(k-1) \tag{11}$$

where T_s is the sampling period.

Since the speed ω_r is unknown and may vary with time, the estimation process becomes time varying due to the unknown $P\omega_r(k-1)T_sJ\vec{\phi}_r(k-1)$ term in Eq. (11). For resolving this identification problem, we propose a self-tuning fuzzy identification as shown in Fig. 2, to estimate the unknown term in Eq. (11). The predicted output of this fuzzy model is calculated as follows:

$$\vec{\lambda}_r(k)=(1-\frac{T_s}{\tau_r})I\vec{\phi}_r(k-1)-P\omega_eT_sJ\vec{\phi}_r(k-1)+y_{id}(\cdot)+\frac{L_mT_s}{\tau_r}I\,\bar{I}_s(k-1) \tag{12}$$

where $y_{id}(\cdot)$ is a self-tuning fuzzy identifier.

In this work, the back-propagation algorithm is applied on line and is implemented as Eqs. (6), (7) and (8), so that $\vec{\lambda}_r$ follows $\vec{\phi}_r$ as closely as possible. That is, the motor speed response can be predicted accurately by the self-tuning fuzzy identifier.

4. Experimental results

To verify the proposed speed estimation scheme, an indirect field-oriented control induction motor is set up. The values of induction motor parameters used in the experiments to verify the proposed speed estimation scheme are listed in the Table 1. For a speed command of 500 rpm, the actual speed response and estimated speed response are shown in Figs. 3(a) and 3(b), respectively. The waveforms depicted in those figure show that the estimated speed closely tracks the actual speed quite well after an adaptation transient. Moreover, for speed command of 500rpm to 900rpm and 900rpm to 500rpm, the actual speed response and estimated speed response are shown in Figs. 4(a) and 4(b), respectively. It can be seen that after back-propagation adaptation, the transient, which corresponds to the learning period of the self-tuning fuzzy identifier, the estimated speed closely tracks the actual speed. According to those figures, it can be concluded that the proposed speed estimation scheme with self-tuning fuzzy identifier can identify the induction motor speed correctly and rapidly.

Table 1 Parameters of the induction motor

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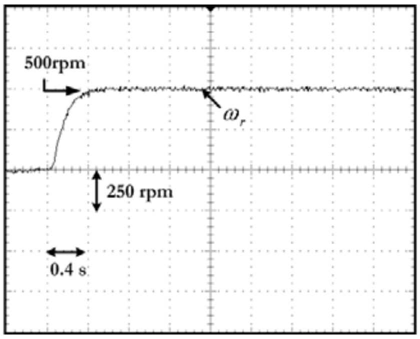
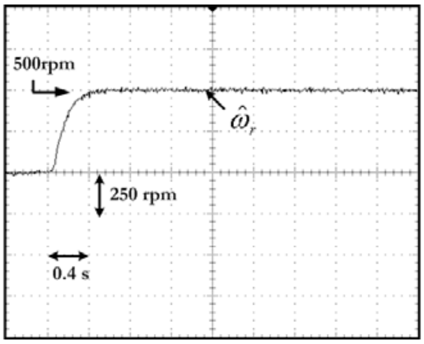
1 HP, 3-phase, 60Hz, 220V, number of poles P=2,
R_s =2.3 ohm, R_r =2.4 ohm,
L_s=0. 345 H, L_r =0. 345 H, L_m=0. 336 H,
J=0. 0027Kg-m^2, B=0. 000069 Nt-m/sec.



(a) Actual speed response

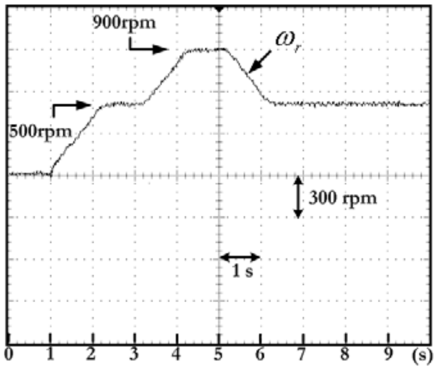


(b) Estimated speed response

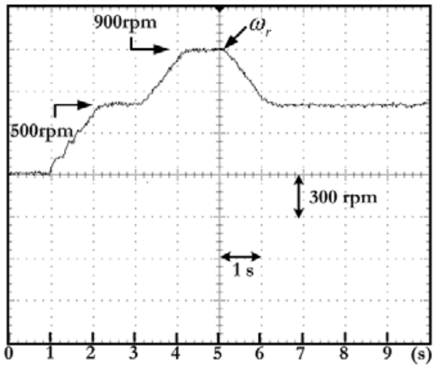
Fig. 3 The actual and estimated speed responses for a speed command of 500 rpm

5. Conclusions

A novel method for sensor-less speed estimation of the induction motor, based on self-tuning fuzzy identifier with three-layered network, has been proposed. This method is demostrated to minimize the difference between the desired flux output of the motor and the output predicted by the self-tuning fuzzy identifier, such that estimated speed tracks the desired motor speed precisely. The theoretical analysis and experimental results demonstrate that the self-tuning fuzzy identifier possesses a fairly good tracking capability and also that the proposed speed estimation scheme can accurately and rapidly identify the actual induction motor's speed.



(a) Actual speed response



(b) Estimated speed response

Fig. 4 The actual and estimated speed responses for speed command of 500rpm to 900rpm and 900rpm to 500rpm

6. References

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