Sensorless Driving Method of Permanent-Magnet Synchronous Motors Based on Neural Networks

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***Abstract*—In sensorless driving of permanent-magnet synchronous motors, it is difficult to deal with the nonlinear characteristic of the magnetic circuit and the harmonics of magnetic density distribution in the air gap. Using a neural network has been considered to be a powerful tool but, unfortunately, only few simulation-based works can be found. In this paper, an experiment system and successful experiment results using our proposed sensorless driving method of permanent-magnet synchronous motors based on neural networks will be presented. The method estimates the position errors from electromotive force instead of directly estimating the position using neural networks and then using the approximate algorithm to obtain the rotor position. Experiment results show that the method has excellent possibility in practical applications.**

***Index Terms*—Approximate algorithm, magnet synchronous motors, neural networks, position-sensorless driving.**

I. Introduction

In high-performance vector-controlled permanent-magnet synchronous motors (PMSMs) drives, position information is necessary. A sensor, i.e., resolver or encoder, generally provides position information. These sensors, however, spoil the ruggedness and simplicity of PMSMs. From this point of view and for general purpose where the elimination of a sensor significantly reduces costs, position sensorless drives are preferable. Many works dealing with position sensorless drives have been proposed recently [1], [2]. But how to deal with the nonlinear characteristic of the magnetic circuit and the harmonic waveform contained in magnetic density distribution in the air gap is a difficult problem. One of the most attractive works is using neural networks to estimate the position information. But, unfortunately, only a few simulation-based work can be found [3], [4] and experimental trials are few and far between. Considering some methods may be easy to simulate but hard to implementation; thus, it is important to show a method is practical usage by the way of experiment.

In this paper, an experimental system and successful experiment results using our proposed sensorless driving method of PMSMs based on neural networks will be presented. Considering that electromotive force (EMF) contains the position information of a motor rotor, a neural network is introduced to estimate EMF. But instead of directly estimating the position from EMF, we propose a method to estimate the position error information from EMF and then use an approximate algorithm to obtain the rotor position. An experiment system has been constructed and the experimental results have successfully proved our proposed method, so the method can be believed to have great possibility in practical applications.

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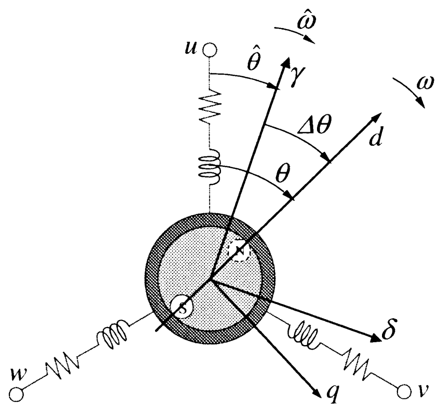

Fig. 1. Analytical model of PMSMs.

II. Basic Idea for Estimation Method

It is well known that the three-axis model of PMSMs can be transformed to the d–q axis values to obtain an equivalent two-axis model by using a rotor position angle

$$p\begin{bmatrix} i_d \\ i_q \end{bmatrix} = -\begin{bmatrix} R/L & -\omega \\ \omega & R/L \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix} + \frac{1}{L}\begin{bmatrix} v_d \\ v_q \end{bmatrix} - \frac{K_E\omega}{L}\begin{bmatrix} 0 \\ 1 \end{bmatrix} \quad (1)$$

$$T_e = pK_E i_q \quad (2)$$

where p denotes the differential operator, v_d and v_q is the stator voltages, i_d and i_q are the stator currents at d-q axis, R is the stator resistor, L is the stator inductance, and T_e is the motor torque.

Fig. 1 shows a model of PMSMs with a phase-modulation (PM) sinusoidal flux excitation where d–q axis corresponds to the actual rotor position and γ–δ axes is assumed to be the estimated position with an angular error $\Delta\theta$ from the actual rotor position.

Considering the error between an estimated and actual rotor position, the γ–δaxes equivalent model transformed from d–q

axes model can be obtained as follows using the following transform matrix:

$$\begin{bmatrix}\gamma\\ \delta\end{bmatrix} = \begin{bmatrix}\cos\Delta\theta & -\sin\Delta\theta\\ \sin\Delta\theta & \cos\Delta\theta\end{bmatrix}\begin{bmatrix}d\\ q\end{bmatrix} \quad (3)$$

$$p\begin{bmatrix}i_\gamma\\ i_\delta\end{bmatrix} = -\begin{bmatrix}R/L & -\omega\\ \omega & R/L\end{bmatrix}\begin{bmatrix}i_\gamma\\ i_\delta\end{bmatrix} + \frac{1}{L}\begin{bmatrix}v_\gamma\\ v_\delta\end{bmatrix} - \frac{K_E\omega}{L}\begin{bmatrix}-\sin\Delta\theta\\ \cos\Delta\theta\end{bmatrix} \quad (4)$$

where i_γ, i_δ and v_γ, v_δ are the stator currents and the voltages at γ–δaxes, respectively. The third term of the above equation is the EMF.

At first, we introduce a basic idea of position estimation method that give a motivation of the neural network based sensorless driving method.

Assuming the sampling period is T, a discrete equation of (4) can be obtained as follows:

$$\vec{i}(n) = \vec{i}(n-1) + (T/L)\{\vec{v}(n-1) - R\vec{i}(n-1) - \omega(n-1)LJ\vec{i}(n-1) - \vec{e}(n-1)\} \quad (5)$$

where

$$\vec{i}(n) = \begin{bmatrix}i_\gamma(n)\\ i_\delta(n)\end{bmatrix} \vec{v}(n) = \begin{bmatrix}v_\gamma(n)\\ v_\delta(n)\end{bmatrix} J = \begin{bmatrix}0 & -1\\ 1 & 0\end{bmatrix}$$
$$\vec{e}(n) = \begin{bmatrix}e_\gamma(n)\\ e_\delta(n)\end{bmatrix} = K_E\omega(n)\begin{bmatrix}-\sin\Delta\theta\\ \cos\Delta\theta\end{bmatrix}. \quad (6)$$

Note that the EMF $\vec{e}(n)$ contains the position error information and then a new idea of position-estimation method can be expressed as follows.

Denote $\vec{e}(n)$ as the one-ahead estimated EMF. It can be obtained from (5) approximately

$$\hat{\vec{e}}(n) = \vec{v}(n-1) - R\vec{i}(n-1) - \hat{\omega}(n-1)LJ\vec{i}(n-1) - (L/T)[\vec{i}(n) - \vec{i}(n-1)]. \quad (7)$$

From (6) and (7), we have the estimated position error as follows:

$$\Delta\theta(n) = \tan^{-1}\left(\frac{\hat{e}_\gamma(n)}{\hat{e}_\delta(n)}\right), \quad \hat{\omega}(n) = \frac{\left|\hat{\vec{e}}(n)\right|}{K_E}. \quad (8)$$

Using the position error, the position can be estimated as follows:

$$\hat{\theta}(n+1) = \hat{\theta}(n) + T\hat{\omega}(n) + K\Delta\theta(n) \quad (9)$$

where K is a gain parameter that insure the convergence of the position estimation. From the above equation, the rotating speed also can be estimated as follows:

$$\hat{\omega}(n+1) = \hat{\omega}(n) + K(\Delta\theta/T). \quad (10)$$

It is clear that the above process to estimate the rotor position is simple and easy to implementation, but it has several drawbacks: the parameter uncertainties and the nonlinear characteristics of the magnetic circuit have not been considered at the motor model (4). Considering that neural networks have excellent abilities in treating with many nonlinear phenomenon, if we introduce a neural network into sensorless drives of PMSMs, it will be expected to bring good possibility to treat with the inherent nonlinear characteristics in PMSMs.

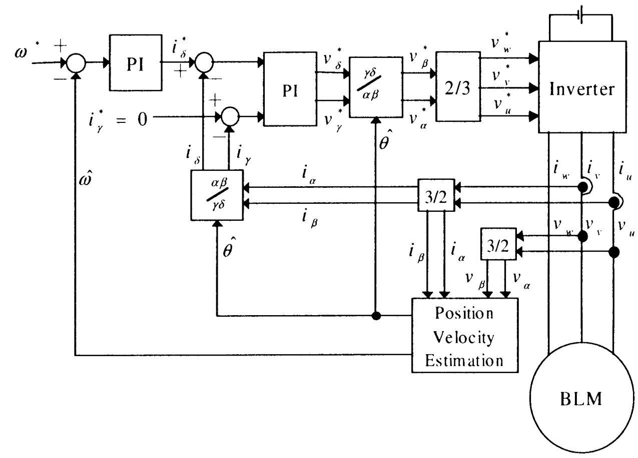

Fig. 2. Structure of the sensorless driving system.

III. Proposed Method Using Neural Networks

Considering the parameter uncertainties and nonlinear characteristics, (7) can be rewritten as a function of currents and voltages in generally

$$\hat{\vec{e}}(n) = f[\vec{i}(n), \vec{i}(n-1), \vec{v}(n-1), \hat{\omega}(n-1)]. \quad (11)$$

The inputs can be obtained from measured values and the estimated value of ω. Then, using (8), (9), and (10) obtained above, we can estimate the speed and the position of a PMSM.

Because it is difficult to directly measure the EMF when the motor is driving, it is necessary to find an indirect way to train the neural network. An indirect way to train the neural network has been proposed at [4] and a simulation shows it to be useful. But it takes more training time, so using (7) at the first stage will accelerate the training process and will take less training time.

The complete sensorless driving system based on vector control method is shown in Fig. 2. The proposed method is contained in the black box of position/velocity estimation in Fig. 2. Two polarization-index (PI) controllers have been used in the speed control loop and the current control loop, respectively.

A three-phase neural model with seven elements at input layer, 14 elements at the hidden layer, and two elements at the output layer is used as an implementation of (11). In order to treat with the different speeds and the different loads, speed references rising from 0 to 1200 r/min with step 400 r/min and, under different constant loads, 0, 5, and 10 kg·cm, respectively, have been selected as the teaching data. These teaching data are taken from the real motor using a sensor driving method. We combine these three types teaching data to teach the EMF estimate neural network using the way mentioned above. The square training error is less than 3.364×10^{-3}. Then, we embed the trained neural network into the proposed system.

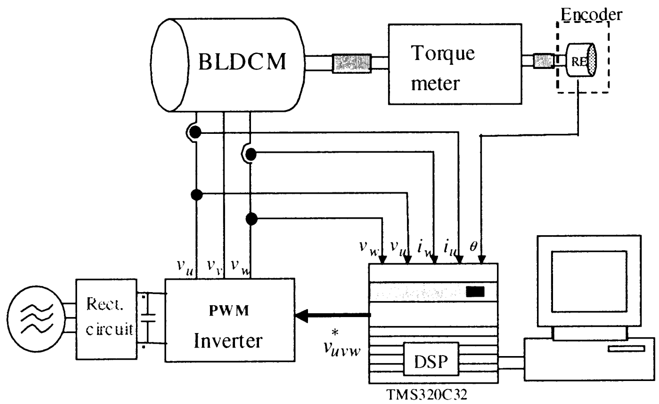

Fig. 3. Structure of experimental system.

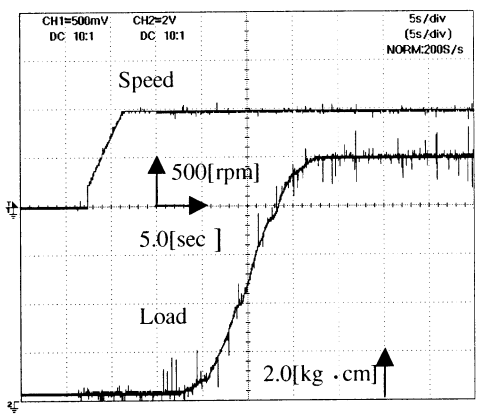

Fig. 4. Speed constant characteristic with load change.

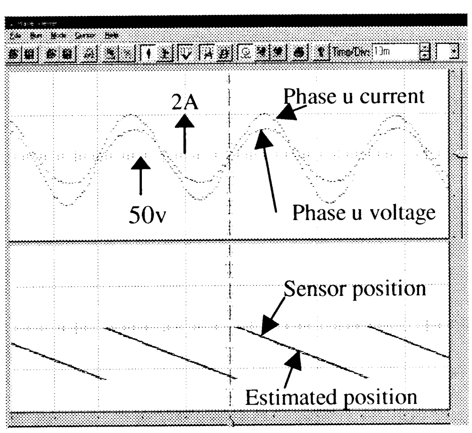

Fig. 5. The waves of voltage, current, and position.

IV. Implementation and Experimental

The experimental system is shown in Fig. 3. A motor with 600 W, 120 V, 3 A at rated is used in the experiment.

In the experimental system, a digital signal processor (DSP) (TMS320C32) is used to implementation of the proposed position sensorless driving algorithm. Synchronous motor starting method is used at the start.

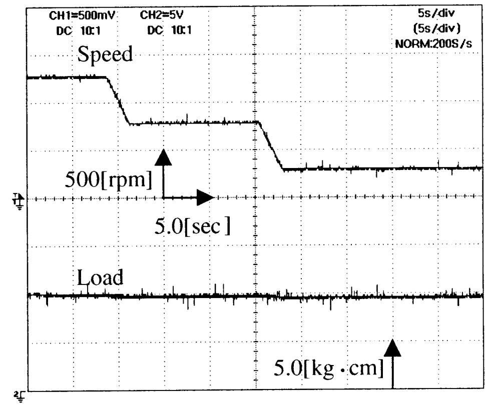

Fig. 6. Speed control with a constant load.

Fig. 4 shows the constant speed (1000 r/min) characteristics when the load is changed from 0 to 10 kg·cm. From the results, the speed is constantly controlled very well, even when the load torque changed widely.

Fig. 5 shows the voltage and current of phase u, the sensor position, and the estimated position when motor speed is 1000 r/min and under 10 kg·cm load condition (related to Fig. 4). Both the voltage and current wave after filtering are similar to sinusoidal waveform and the error between the sensor position and estimateds position are small enough.

Fig. 6 shows the variable speed control characteristic under the constant load torque 10 kg·cm. It shows the proposed system has higher speed control ability.

These experimental results clearly show that the proposed method is successful at the sensorless driving system of PMSMs.

V. Conclusion

From our experiment results, the usefulness of neural networks in sensorless driving systems has been confirmed. Considering the interpolation ability of neural network, the system shows a high ability for variable speed control and different load torques through the experimental results.

We successfully show the practical driving of PMSM using neural networks in recent work, but it is just a beginning. How to exploit the ability of neural network will be explored in future works.

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