Back-Emf-Based Sensorless Field-Oriented Control of PMSM Using Neural-Network-Based Controller with a Start-Up Strategy

V.S. Nagarajan, M. Balaji and V. Kamaraj

Abstract This paper describes back-emf-based sensorless field-oriented control (FOC) of permanent magnet synchronous motor (PMSM) of surface-mounted type, employing neural-network-based controller for current and speed control. The dynamic response is improved. Further, rotor position is estimated by back-emf method. To overcome the shortcoming of back-emf-based control in zero and low speed, a start-up strategy is proposed, to predict the initial rotor position. The PMSM drive model is simulated in MATLAB/Simulink environment, and the results show improved dynamic response with a start-up strategy.

Keywords Neural network · Back emf · Rotor position · Startup

1 Introduction

Permanent magnet synchronous motor (PMSM) drives, having numerous advantages over the conventional DC drives and induction drives, is widely being used in the industries for various applications. The importance of PMSM lies in the fact that it has high efficiency, with high torque to inertia ratio and high power density [1].

For the past few years, in order to achieve high-performance control for nonlinear drive system, researchers have explored in depth, the application of soft computing [2] based controller design employing artificial neural network (ANN), fuzzy logic, and ANFIS. Neural networks using parallel and distributed processing units can achieve the functions of system modeling and control for nonlinear systems.

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L.P. Suresh et al. (eds.), *Artificial Intelligence and Evolutionary Algorithms in Engineering Systems*, Advances in Intelligent Systems and Computing 325,
DOI 10.1007/978-81-322-2135-7_48

There are several unique features, which make them suitable for high-performance drive applications, making the drive system robust, accurate, and insensitive to parameter variations [3]. The unknown nonlinear dynamics of the motor and the load are captured by the ANN [4]. For an instance, a nonlinear mapping between input and output of an electric drive system can be established using ANN without the need of predetermined model [5]. A neural-network-based speed and current controller is proposed for PMSM drive.

In PMSM, the stator excitation needs to be synchronized with the rotor position which necessitates a rotor position sensor or a position estimation algorithm. Sensorless control of PMSM has been explored in detail over the last few decades, because it reduces the cost and complexity, improvising the reliability of the drive system [1]. From the various available literatures employing sensorless control, back-emf-based sensorless control of PMSM is preferred and chosen, since it is employed in many industrial applications due to its control simplicity, robustness, and high machine efficiency. The major drawback in this estimation method is its application in zero- and low-speed regions. To overcome the above drawback, a start-up strategy is proposed and the performance of the drive is analyzed under loaded conditions.

The paper is organized as follows. Section 2 describes about the modeling of PMSM. Section 3 describes about the field-oriented control (FOC) of PMSM using neural-network-based controller. Section 4 describes about the rotor position estimation by back-emf method. Section 5 describes about the start-up strategy for sensorless FOC.

2 Modeling of PMSM

The modeling of PMSM is done using *d–q* transformation [6] as it is advantageous by viewing the machine parameters such as the voltages and currents as DC equivalents from the rotor side, even though an AC supply is provided at the stator side.

The model equations obtained using *d–q* transformations are as follows.

$$D\text{-axis current equation: } \frac{\mathrm{d}}{\mathrm{d}t} i_d = \frac{1}{L_d} v_d - \frac{R}{L_d} i_d + \frac{L_q}{L_d} p\omega_r i_q \tag{1}$$

$$Q\text{-axis current equation: } \frac{\mathrm{d}}{\mathrm{d}t} i_q = \frac{1}{L_q} v_q - \frac{R}{L_q} i_q + \frac{L_d}{L_q} p\omega_r i_d - \frac{\lambda p\omega_r}{L_q} \tag{2}$$

$$\text{Torque equation: } T_e = 1.5\, p[\lambda i_q + (L_d - L_q) i_d i_q] \tag{3}$$

Equation relating torque, inertia, input torque, output torque, and speed:

$$\frac{d}{dt}\omega_r = \frac{1}{J}(T_e - F\omega_r - T_m) \tag{4}$$

$$\text{Speed equation: } \frac{d\theta}{dt} = \omega_r \tag{5}$$

The inputs to the model are v_d, v_q, and T_m, which are the d- and q-axes voltages and the mechanical torque, respectively. The outputs from the model are i_d , i_q, ω_r, T_e and θ, which are d- and q-axes currents, angular velocity of rotor, electromagnetic torque, and rotor angle, respectively.

3 Field-oriented Control of PMSM Using Neural-network-based Controller

A schematic of the FOC of PMSM, using neural-network-based controller, is shown in Fig. 1. The intention of the speed and current controllers of the PMSM drive is to translate the speed and current errors into a driving voltage signal, to the input of the PMSM. This objective must be met for all load conditions and for any type of disturbances.

An ANN controller is designed to achieve the above prerequisite of the control problem. The structure of the neural-network-based controller consists of an input layer with 5-neurons, a hidden layer with 2-neurons, and an output layer with a single neuron. The tan-sigmoid activation function is used for the input and hidden layers and purelin is used for the output layer [7]. The training data for the neural network are obtained from the fundamental simulation model. The input variables to the ANN are scaled to be within (±1) [8]. The back-propagation algorithm is used by which weights and biases are updated at each sampling instant.

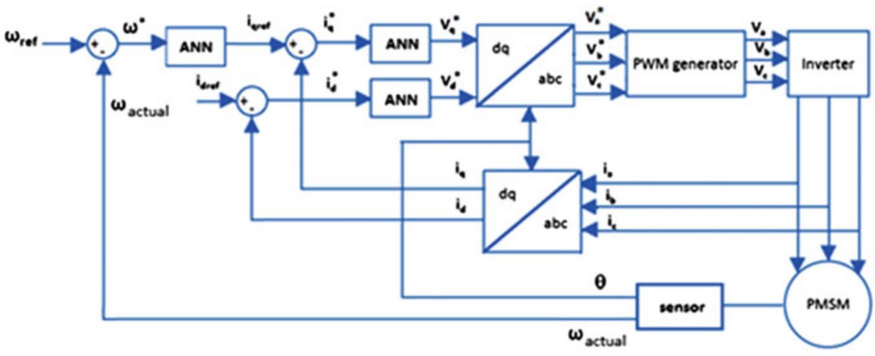

Fig. 1 Field-oriented control of PMSM using neural-network-based controller

Table 1 Machine parameters

Parameter	Value
Number of poles, p	4
Amplitude of flux induced by permanent magnets of rotor in stator phases, λ	0.175 Wb
Resistance of stator windings, R	2.875 Ω
D- and q-axes inductances, L_d and L_q	8.5 mH
Inertia, J	0.0008 kg/ m^2
Friction coefficient, F	0.001 Nms

Under the FOC scheme, decoupling of torque- and flux-producing components of the stator current is done, so that control of torque and flux separately, is feasible as in the case of DC motors [9]. Usually, the d-axis current reference is made zero in order to approximately eradicate the couplings between angular velocity and currents. With properly designed current controllers, the output satisfies $i_d^* = i_d$. Then, the d-axis flux linkage is unchanging and the developed torque is then proportional to q-axis current, which is determined by closed-loop control.

The machine parameters chosen for the simulation is shown in Table 1.

The speed response of PMSM is shown in Fig. 2 for a reference speed of N = 2,000 rpm. It is seen that the speed of the PMSM settles at 2,000 rpm at 0.02 s.

From the speed response, the transient response parameters obtained are peak overshoot which is 4.94 %, settling time which is 0.02 s and speed ripple which is 0.05 %. Therefore, the dynamic response is improvised by the neural-network-based controller.

The torque response of PMSM is shown in Fig. 3. The load applied to the PMSM is a step load with a magnitude of 0 Nm from t = 0 to 0.02 s and a magnitude of 1 Nm from t = 0.02 s. It is seen that a torque output of 1 Nm is obtained from t = 0.02 s.

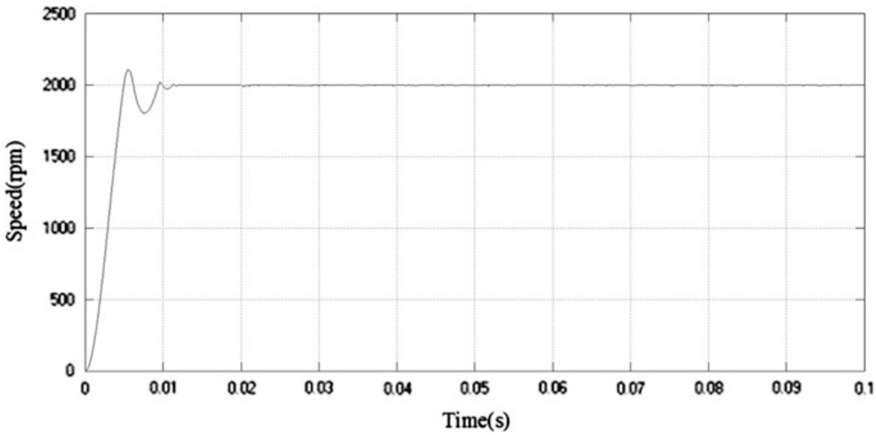

Fig. 2 Speed response

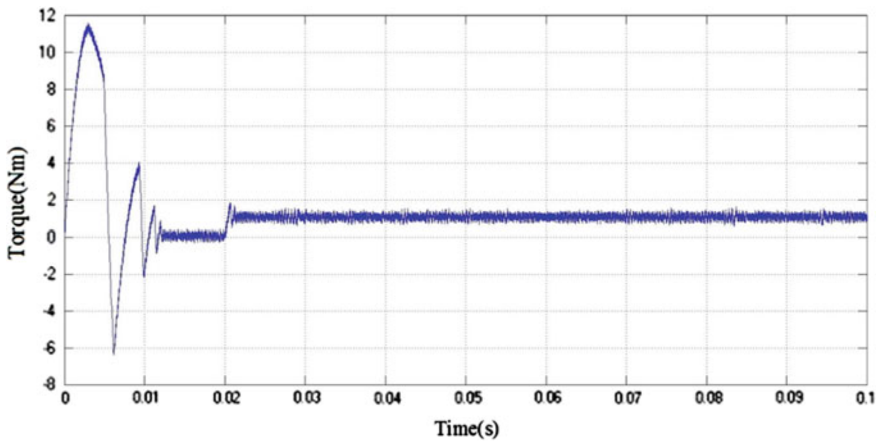

Fig. 3 Torque response

4 Rotor Position Estimation by Back-emf Method

The choice of angular-position and speed sensors and the consequent choice of the related signal conditioning circuit are not much influenced by the electrical-drive rated power. Then, the influence of the aforementioned sensor's cost grows up in percentage with respect to the electrical-drive comprehensive cost, when the rated power of an electrical machine is small or fractional [10]. A type of sensorless speed control of PMSM is based on the strategy of estimating the rotor position by analyzing the motor-induced back-electromotive force (emf) voltage, using a mathematical motor model [11]. By this back-emf method, the signals to be sensed are the currents i_α and i_β and voltages u_α and u_β . It eliminates the high cost incurred by the usage of a speed sensor with high precision and noise immunity. It therefore becomes a cost-effective and simple method that can be easily implemented.

The back emf can be estimated [12] as follows:

$$\text{Back emf equations:}\, \hat{e}_{s\alpha} = -u_\alpha + Ri_\alpha + L_d i_\alpha \tag{6}$$

$$\hat{e}_{s\beta} = u_\beta - Ri_\beta - L_q i_\beta \tag{7}$$

$$\text{Rotor position estimation equation:}\, \theta_r = \tan^{-1}\left(\frac{\hat{e}_{s\alpha}}{\hat{e}_{s\beta}}\right) \tag{8}$$

$$\text{Speed estimation equation:}\, \omega_r = \frac{\mathrm{d}\theta_r}{\mathrm{d}t} \tag{9}$$

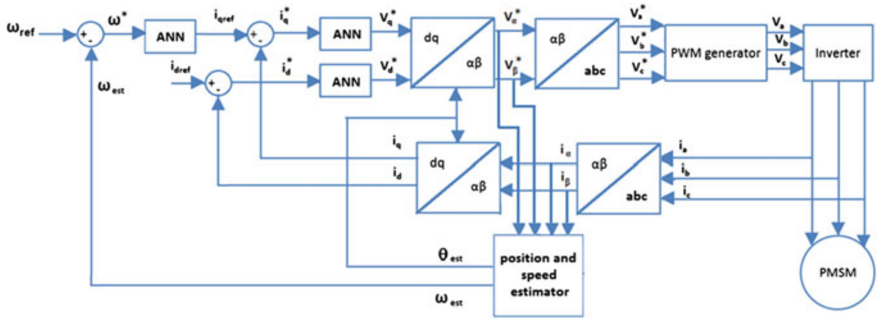

Fig. 4 Sensorless field-oriented control of PMSM using neural-network-based controller with rotor position estimation by back-emf method

The functional block diagram representing the sensorless FOC of PMSM using neural-network-based controller with rotor position estimation by back-emf method is shown in Fig. 4.

The estimated rotor position and actual rotor position for N = 2,000 rpm is shown in Fig. 5. It is seen that from $t = 0$ to 0.02 s, the rotor position estimation is not appropriately done due to the absence of back emf at the starting conditions. From t = 0.021 s, the rotor position is estimated correctly by the back-emf equations.

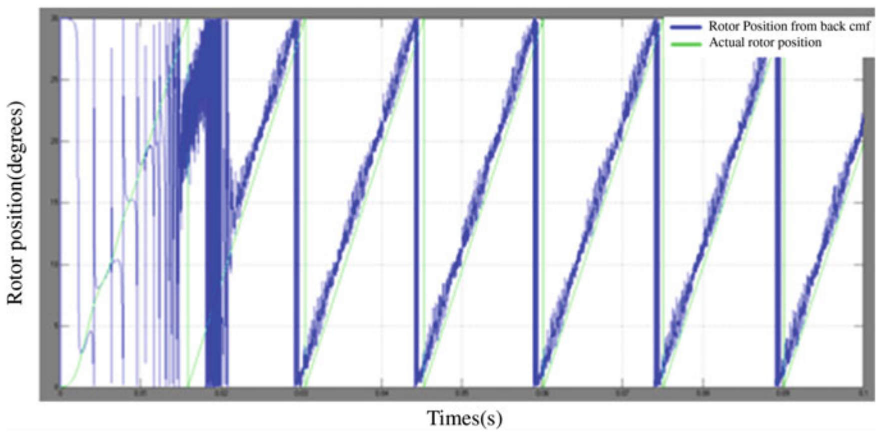

Fig. 5 Estimated rotor position versus actual rotor position

5 Start-up Strategy for Sensorless Field-oriented Control

This back-emf-based position estimation algorithm has good performance in the medium-to-high-speed range [13]. In zero- and low-speed regions, the back emf is nearly zero and hence cannot be accurately detected. Though there are various methods such as extended Kalman filter [14], high-frequency signal-injection method [15] and evaluation using drive stiffness have been discussed in the literature, the implementation of methods involves complex processing and analysis of signals and the cost involved in the implementation is high. A simple start-up is sufficient, wherein the rotor position can be predicted by integrating the reference-speed input when the back-emf algorithm fails in detection of rotor position. Suitable transition can be made by switching operations. This method is applicable only during initial conditions, when the rotor position detection is unable to be

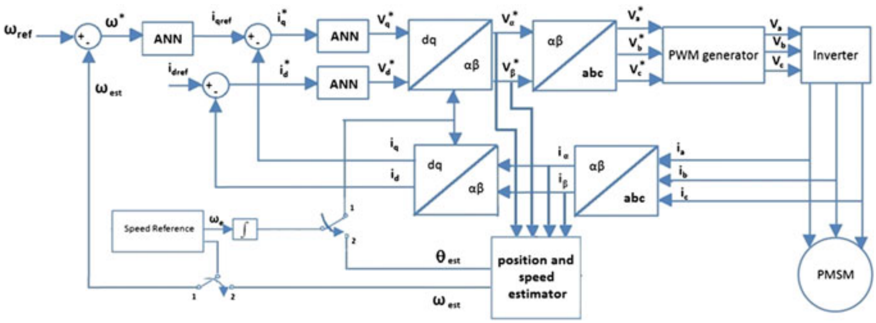

Fig. 6 Sensorless field-oriented control of PMSM using neural-network-based controller with rotor position estimation by back-emf method with start-up strategy

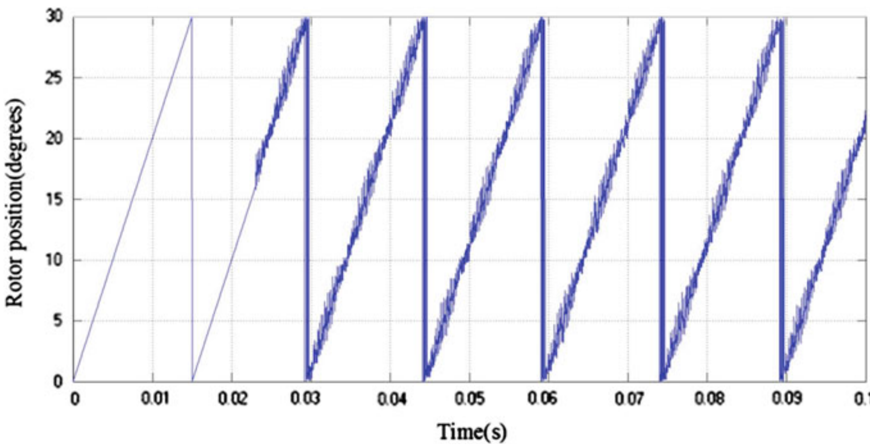

Fig. 7 Rotor position from start-up strategy switched to rotor position estimated from back emf

detected correctly (i.e., at start-up). The functional block diagram representing the sensorless FOC of PMSM using neural-network-based controller with rotor position estimation by back-emf method with start-up strategy is shown in Fig. 6.

The estimated rotor position for N = 2,000 rpm with the start-up strategy is shown in Fig. 7. It is seen that from $t = 0$ to = 0.023 s, the rotor position is estimated by the start-up strategy and from $t = 0.024$ s, the rotor position is estimated by the back-emf equations.

6 Conclusion

In this paper, neural-network-based controller is employed for FOC of PMSM. The controller is robust to load variations, having less peak overshoot, faster settling time and minimal steady-state error. Back-emf method was employed to estimate the rotor position, which is proved to be effective after a certain period of starting of PMSM drive. To overcome the difficulty posed by the back-emf method, a start-up strategy is employed which is used to predict the initial rotor position during starting condition until a particular time after which back-emf method takes over. Thus, the method of rotor position estimation has been proved to advantageous. Further studies can be carried out to reduce the ripple in speed and torque output. The effect of start-up method on various other parameters can be further analyzed. Hybrid control structures can be introduced in the control system in order to improvise the transient and steady-state conditions.

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