Modeling and simulation of direct torque controlled SPMSM Drive incorporating magnetic saturation saliency

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Abstract. In this paper a comprehensive nonlinear model of surface mounted permanent magnet synchronous machine (SPMSM) is proposed considering both the structural and the saturation saliencies to enable the numerical simulation of new rotor position detection algorithms. An experiment platform is carried out to test and collect the incremental inductance values varying again the stator current levels and the rotor position. The Least Relative Residual Sum of Square (LRRSS) method is employed in the nonlinear inductance function regression. After experimentally identifying out all the parameters, a nonlinear mathematic model of SPMSM is built up. Furthermore, the direct torque control (DTC) scheme is applied to this new model to verify the model and simulate the machine performance.

Keywords: Finite element methods, nonlinear magnetic, PM machines, saturation saliency

1. Introduction

The direct torque controlled permanent magnet synchronous motor (PMSM) drive system has become competitive compared with other types of drive systems, because of its simple and instinctive sensorless control algorithm [1,2]. The practical application of the system, however, is handicapped by the difficulty of starting under full load due to the unknown initial rotor position. A lot of efforts have been made to detect the initial rotor position [3–5]. The most versatile method is to make use of the structural and magnetic saturation saliencies of the PMSM. The structural saliency, which mainly comes from the interior structure of the machine, could be employed to acquire the position of the rotor axis. The saturation saliency, which is induced by the magnetic saturation effect of the stator core, is usually used to detect the rotor polarity. However, the conventional PMSM model does not incorporate the saturation saliency [6]. The experimental trial and error method has to be employed to develop new method for the rotor position detection.

In this paper, the experiment platform of the PMSM inductance test is built up and a nonlinear mathematical model of SPMSM is carried out considering magnetic saturation saliency. A numerical nonlinear inductance model is proposed based on the stator currents and rotor position variation with all the parameters experimentally identified. Based on this new model, the DTC algorithm is applied within the MATLAB/SIMULINK environment. The control system performance is simulated and the new model is verified.

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2. Nonlinear model of SPMSM with saliencies

For SPMSM, the observable total flux linkage λ_t inside the air-gap is contributed by both the stator currents and the permanent magnet on the rotor. The three-phase flux linkages λ_{abc} are then defined as the projection of λ_t on the stator reference frame and not only induced from the stator current. The voltage equation of the stator windings can be written as

$$v_{abc} = R_s i_{abc} + \frac{d}{dt}\lambda_{abc} \tag{1}$$

where v_{abc}, i_{abc} and R_s are the phase voltages, currents and winding resistance in the stator reference frame, respectively.

For conventional linear PMSM models, the nonlinear magnetization curve is always assumed to be linear, and the linear three-phase inductance matrix, including the self- and mutual-inductances, is always independent of the stator currents. In the rotor reference frame, the d- and q-axis inductances are thereby constant. However, this linear model could not be used to describe the nonlinear saturation saliency. In the proposed nonlinear model, the magnetic saturation is considered and the inductances are expressed as incremental inductances variable with the stator current. Then a composite function can be used to express the flux linkage

$$\lambda_a = f(i_{abc}, \theta) \tag{2}$$

where θ is the rotor position angle.

Substituting Eq. (2) into Eq. (1), the following differential equations can be obtained

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = R_s \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + L^*_{abc}\frac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{\partial}{\partial\theta}\begin{bmatrix} \lambda_a \\ \lambda_b \\ \lambda_c \end{bmatrix}\omega_e \tag{3}$$

where L^*_{abc} is the nonlinear inductance matrix which is also a composite function of the stator currents and the rotor position.

3. Nonlinear inductance model

3.1. Nonlinear mathematical model

As shown above, the inductance of the stator is a function of both the stator currents and the rotor position, which are linear independent [7]. For a fixed rotor position, the inductance curve can be expressed as a multinomial

$$L(i) = l_0 + l_1 i^1 + l_1 i^2 + \cdots + l_m i^m \tag{4}$$

where $l_0, l_1, l_2 \ldots l_m$ are the inductance coefficients.

On the other hand, for a constant stator current, the inductance is a periodic function of the rotor position [8]. It can be expressed as the sum of a series of sinusoidal harmonics by using Fourier Series as Eq. (5).

$$L(\theta) = a_0 + \sum_{n=1}^{\infty}(a_n\cos(n\theta) + b_n\sin(n\theta)) \tag{5}$$

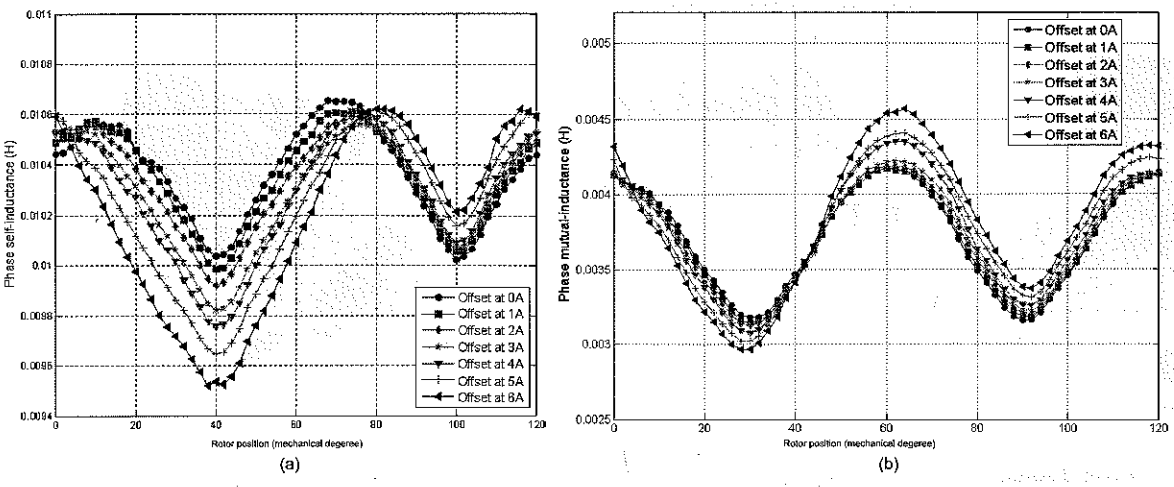

Fig. 2. Measured self- and mutual-inductance curves at different current offset levels: (a). self-inductances; (b). mutual-inductances.

The inductances are small and periodical fluctuant function. To obtain better regression results, the Least Relative Residual Sum of Square (LRRSS) method is employed. For the objective function $L(i, \theta)$, the relative residual sum of square is defined as

$$E_{re}(A) = \sum_{i=0}^{6}\sum_{\theta=0}^{2\pi}[\frac{I(i)\cdot A\cdot C(\theta) - L_{test}(i,\theta)}{L_{test}(i,\theta)}]^2 \quad (7)$$

Figure 3 is the comparison between the tested and estimated self-inductance of phase A at 0A and 6A current offsets, where $\pm$ 0.5% error bands are added. It can be found that the relative errors of the inductances are very small and the regressed objective function can be used to describe the variable self-inductance. The same regression method is applied to the mutual-inductance coefficients identification. Then a nonlinear inductance model is built up for this three-phase machine. An accurate inductance matrix can be calculated for given stator currents and rotor position. This model incorporates both the machine structural and the saturation saliencies.

4. Drive performance simulation

The basic idea of DTC oriented for induction motor is to control the torque and flux linkage by selecting the voltage space vectors properly, which is based on the relationship between the slip frequency and torque. It has been proven that the DTC scheme could be modified for PMSM drive [9].

Figure 4 shows the diagram for the DTC drive system, in which the flux linkage and torque is calculated in the stator reference frame, $\alpha - \beta$ frame. The stator flux linkage of a PMSM can be expressed as

$$\varphi_s = \int (v_s - Ri_s)\, dt \quad (8)$$

and the torque can be written as

$$T_e = \frac{3}{2}\cdot\frac{P}{2}(\varphi_\alpha i_\beta - \varphi_\beta i_\alpha) \quad (9)$$

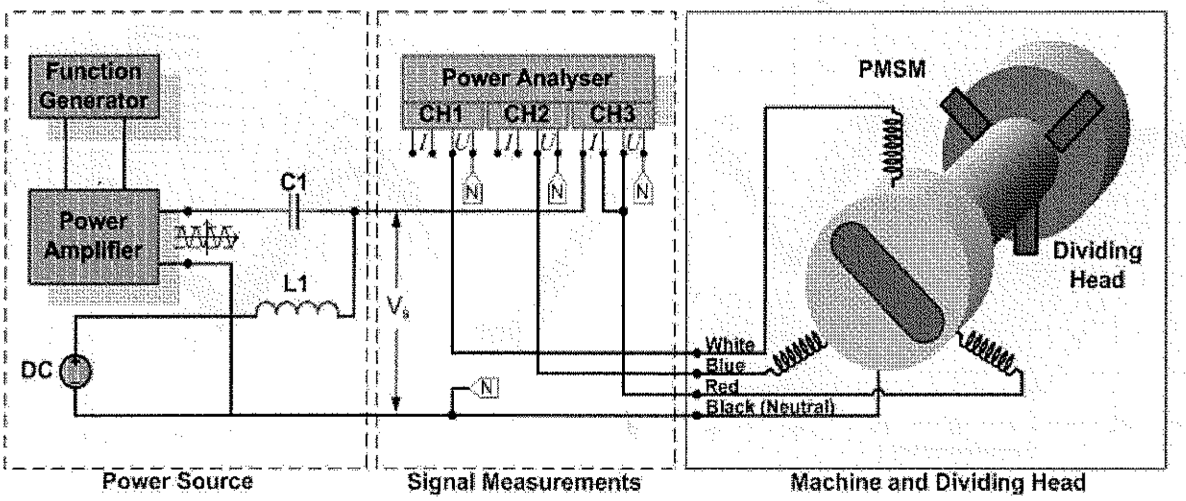

Fig. 1. The experiment platform for inductance test.

Then a composite function of both the current and rotor position is defined to express the inductance

$$L(i, \theta) = I(i) \cdot A \cdot C(\theta) \tag{6}$$

where

$$I(i) = [1\ i^1\ i^2 \cdots i^m];$$

$$C(\theta) = [1\ \sin(\theta)\ \cos(\theta) \cdots \sin(n\theta)\ \cos(n\theta)]^T;$$

$$A = \begin{bmatrix} a_{0,0} & a_{0,1} & \cdots & a_{0,2n} \\ a_{1,0} & a_{1,1} & \cdots & a_{1,2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m,0} & a_{m,1} & \cdots & a_{m,2n} \end{bmatrix}$$

is the identifiable parameter matrix.

3.2. Parameters identification

As shown in Fig. 1, an experiment platform is carried out on an SPMSM to identify the parameters and test the inductances. During the test, the stator currents are fixed at several different levels from 0 to 6A at which the magnetic circuit is fully saturated. At each current offset, by applying a smaller AC current component the incremental inductance of a particular rotor position is measured. By changing the rotor position with a dividing head, a series of inductance is recorded with a resolution of 6 electrical degrees. Figure 2 shows the measured self-inductance curves at different stator current levels.

According to the magnetization curve and the FFT of the measured inductance curves, the dimension of matrix A is set to 7×17, by setting $m = 6$ and $n = 8$ to acquire an accurate enough surface regression.

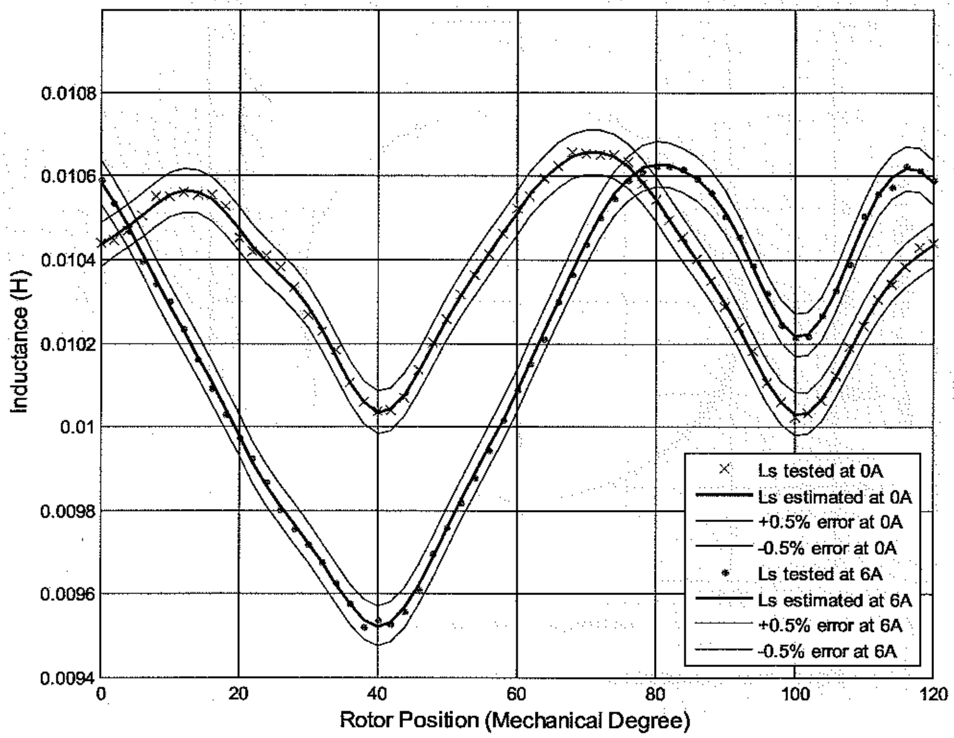

Fig. 3. Measured and estimated self-inductance at different current offsets.

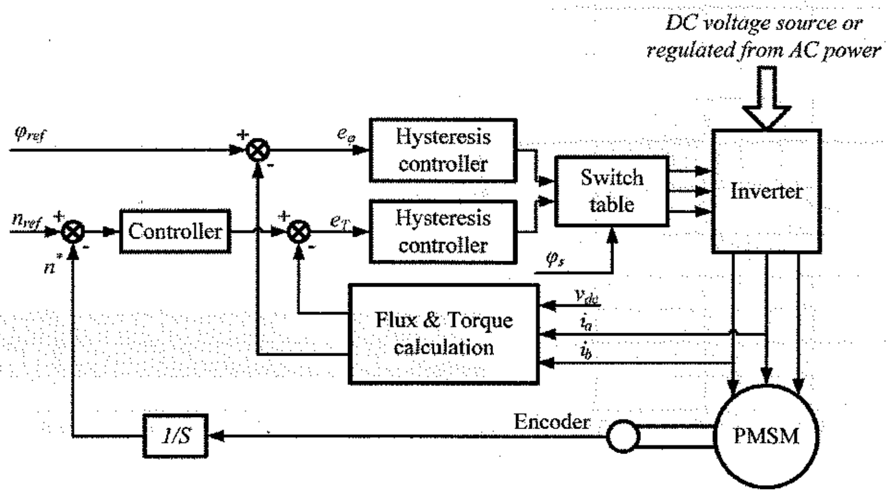

Fig. 4. Diagrams of DTC drive system for PMSM.

Figure 5 shows the flux linkages of the $\alpha - \beta$ axes, which are smoothly rotating as a round. It can be found that the machine flux ripple is small.

Then the SPMSM is operating at 2000 rpm with no-load and an additional 2 Nm load torque is added

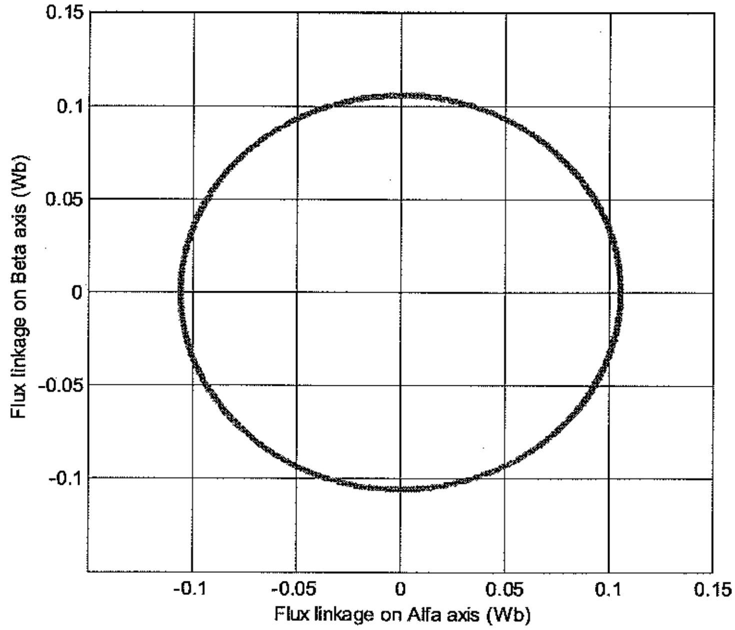

Fig. 5. Flux linkage of the proposed drive scheme for SPMSM.

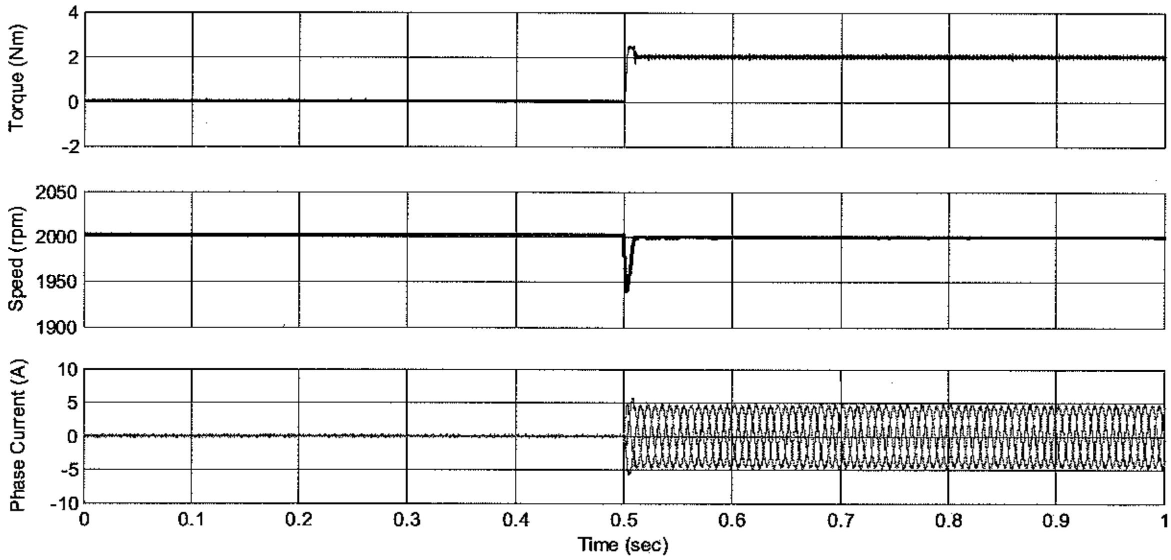

Fig. 6. The torque, speed and phase current performance of the proposed drive scheme for SPMSM.

to the rotor shaft. The torque, speed and phase current performance are shown in Fig. 6. After adding the load torque, the stator current increased to a higher level and the inductances of the new model are saturated. As shown in Fig. 6, the torque ripple is bigger when the saturation effect takes place, which is similar to the real machine operation.

5. Conclusion

The nonlinearity of the PMSM machine model is mainly caused by the saturable inductances of the stator windings. In this paper, a composite function is designed to express the inductance as the function of both the stator current and the rotor position which are de-coupled. A nonlinear model of PMSM is setup based on this function.

An experimental platform is carried out to identify the inductance coefficients. After taking a set of inductance measurements, the self- and mutual-inductances at different current level and different rotor positions are recorded. The LRRSS method is employed and the regression results show good agreement with the experiment results.

With the identified coefficients, the new SPMSM model is built up in MATLAB/SIMULINK. The traditional DTC drive scheme is applied to verify the performance and the simulation results show that the nonlinear model can be applied to numerically simulate the SPMSM. Based on this new comprehensive model, simulation of the new proposed novel drive methods will be possible which will avoid the experimental trial and error process, reduce the develop cycle time and save the research costs.

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