International Journal of Engineering Research and Technology. ISSN 0974-3154, Volume 12, Number 12 (2019), pp. 2294-2297

Building a Magnetic Flux Model of Induction Motors and Testing on Hardware Systems Using DSP C2000

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Abstract

Nowadays, three-phase AC motors, or induction motors (IMs), are widely used in industrial applications. In IM-driven systems requiring high control quality, the field-oriented control (FOC) method is often applied. In order to use the FOC control structure, it is required to identify the generated magnetic flux of the motor accurately. In this paper, the authors deal with the method of building the magnetic flux model of the IM motor. Besides, the accuracy of the model is proved experimentally using the DSP C2000 hardware system.

Keywords: IM, C2000, FOC, V/f Control, PWM.

I. INTRODUCTION

For specific applications that require operators or researchers, intervention in the control structure to customize the technology process is necessary. It is impossible with commercially available equipment. C2000 DSP with an open structure, strong computing power [1-5] and competitive price opens up the prospect of building a complete control structure for the IM motor. With the permanent magnet (PM) motor, [6-13] the magnetic flux of the motor was pre-formed because the rotor is made of permanent magnets. Therefore, it is possible to implement the FOC control structure when the angle of magnetic flux is precisely determined. The magnetic flux of the IM motor is formed when the motor is powered. This leads to determining the value of the flux of IM motors becomes more difficult than the PM motors. There are two methods to control the IM. The first one uses the V/f principle [14-16], in which the flux does not need to be accurately determined. The other uses the FOC method [6, 17-19], requiring construction of the magnetic flux model.

II. DYNAMIC MODEL

Equations for the flux of stator and rotor is shown in equation (1).

$$\begin{cases} \boldsymbol{\psi}_\mathbf{s} = L_s \mathbf{i}_\mathbf{s} + L_m \mathbf{i}_\mathbf{r} \\ \boldsymbol{\psi}_\mathbf{r} = L_m \mathbf{i}_\mathbf{s} + L_r \mathbf{i}_\mathbf{r} \end{cases} \tag{1}$$

In which:

$L_s = L_m + L_{\sigma s}$ and $L_r = L_m + L_{\sigma r}$. Ls is stator inductance, Lm is mutual inductance, Ls stator inductance, Lr rotor inductance, Lm mutual inductance , Lσs and Lσr are stator and rotor inductors, i_s is stator current, and i_s is rotor current. The IM motor in this study is a squirrel-cage induction motor, so the rotor voltage is zero. Therefore, equations for the stator and rotor voltages are as follows:

$$\mathbf{u}_\mathbf{s} = R_s \mathbf{i}_\mathbf{s} + \frac{d\boldsymbol{\psi}_\mathbf{s}}{dt} + j\omega_s \boldsymbol{\psi}_\mathbf{s} \tag{2}$$

$$0 = R_r \mathbf{i}_\mathbf{r} + \frac{d\boldsymbol{\psi}_\mathbf{r}}{dt} + j\omega_r \boldsymbol{\psi}_\mathbf{r} \tag{3}$$

In which $\omega_r = \omega_s - \omega$, with ω_r is the slip velocity, ω_s is the synchronous velocity, and ω is the rotor velocity.
From (1), (2) and (3), we have:

$$\begin{cases} \mathbf{u}_\mathbf{s} = R_s i_s + \frac{d\boldsymbol{\psi}_\mathbf{s}}{dt} + j\omega_s \boldsymbol{\psi}_\mathbf{s} \\ 0 = R_r \mathbf{i}_\mathbf{r} + \frac{d\boldsymbol{\psi}_\mathbf{r}}{dt} + j\omega_r \boldsymbol{\psi}_\mathbf{r} \\ \boldsymbol{\psi}_\mathbf{s} = L_s \mathbf{i}_\mathbf{s} + L_m \mathbf{i}_\mathbf{r} \\ \boldsymbol{\psi}_\mathbf{r} = L_m \mathbf{i}_\mathbf{s} + L_r \mathbf{i}_\mathbf{r} \end{cases} \tag{4}$$

Eliminating the rotor current and the stator flux from (4), we obtain a set of equations describing the motor on the coordinate system dq as follows:

$$\begin{cases} \frac{di_{sd}}{dt} = -\left(\frac{1}{\sigma T_s} + \frac{1-\sigma}{\sigma T_s}\right) i_{sd} + \omega_s i_{sq} \\ + \frac{1-\sigma}{\sigma T_r}\psi'_{rd} + \frac{1-\sigma}{\sigma}\omega\psi'_{rq} + \frac{1}{\sigma L_s}u_{sd} \\ \frac{di_{sq}}{dt} = -\omega_s i_{sd} - \left(\frac{1}{\sigma T_s} - \frac{1-\sigma}{\sigma T_r}\right) i_{sq} \\ -\frac{1-\sigma}{\sigma}\omega\psi'_{rq} + \frac{1-\sigma}{\sigma T_r}\psi'_{rq} + \frac{1}{\sigma L_s}u_{sq} \\ \frac{d\psi'_{rd}}{dt} = \frac{1}{T_r} i_{sd} - \frac{1}{T_r}\psi'_{rd} + (\omega_s - \omega)\psi'_{rq} \\ \frac{d\psi'_{rd}}{dt} = \frac{1}{T_r} i_{sq} - (\omega_s - \omega)\psi'_{rd} - \frac{1}{T_r}\psi'_{rq} \end{cases} \tag{5}$$

Selecting the rotation system dq with q axis perpendicular to the flux generated by the rotor, we have $\psi_{rd} = 0$.
Substituting ψ_{rd} into (5), we have:

$$\frac{di_{sd}}{dt} = -\left(\frac{1}{\sigma T_s} + \frac{1-\sigma}{\sigma T_s}\right) i_{sd} + \omega_s i_{sq} + \frac{1-\sigma}{\sigma T_r}\psi'_{rd} + \frac{1}{\sigma L_s}u_{sd} \tag{6}$$

$$\frac{di_{sq}}{dt} = -\omega_s i_{sd} - \left(\frac{1}{\sigma T_s} - \frac{1-\sigma}{\sigma T_r}\right) i_{sq} - \frac{1-\sigma}{\sigma}\omega\psi'_{rd} + \frac{1}{\sigma L_s}u_{sq} \tag{7}$$

$$\frac{d\psi'_{rd}}{dt} = \frac{1}{T_r}i_{sd} - \frac{1}{T_r}\psi'_{rd} \tag{8}$$

$$0 = \frac{1}{T_r}i_{sq} - (\omega_s - \omega)\psi'_{rd} \tag{9}$$

From this, we determine the torque equation and the equations for calculating and controlling rotor flux:

$$m_M = \frac{3}{2}z_p(1-\sigma)L_s\psi'_{rd}i_{sq} \tag{10}$$

and

$$0 = i_{md} + T_r\frac{di_{md}}{dt} - i_{sd} \tag{11}$$

$$0 = \omega_r T_r i_{md} - i_{sq} \tag{12}$$

$$i_{md} = \frac{\psi_{rd}}{L_m} \tag{13}$$

Thus, i_{sd} is to control flux, and i_{sq} is to control torque.

III. THE ALGORITHM FOR THE MAGNETIC FLUX MODEL APPLIES TO C2000

The magnetic flux model is crucial to motor control. That is, the magnetic flux model provides all state variables for motor control. It also provides the coordinate transfer angle for the voltage and current coordinate transformations. For microcontrollers, the ability to perform calculations depends on the sampling time. As a result, selecting of the microcontroller and the control algorithm directly determines the control quality of the drive system using the IM motor.

Equation (8) is used to determine the rotor flux. Therefore, the formula to calculate the magnetic flux becomes:

$$\psi_{rd} = L_m\int\left(\frac{1}{T_r}i_{sd} - \frac{1}{T_r}\psi_{rd}\right)dt \tag{14}$$

To apply to microcontroller easily, the above equation is discretized as follows:

$$\psi_{rd}(k) = L_m\left(\frac{T_s}{T_r}i_{sd}(k-1) - \left(1-\frac{T_s}{T_r}\right)\psi_{rd}(k-1)\right) \tag{15}$$

The above expression is implemented on the Matlab/Simulink model for the C2000 microcontroller series, as shown in Figure 1.

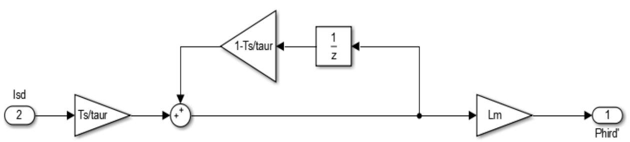

Figure 1. The calculation model of magnetic flux implemented on DSP C2000

The condition for the equation (14) to be exact is that the dq coordinate system must be in sync with the rotation angle of the rotor flux, and the d-axis must have the same direction with the magnetic flux vector. This leads to the need to calculate an accurate angle of the rotor flux. Based on equation (9), it is easy to determine the value of the synchronous angular velocity as follows:

$$\omega_s = \frac{1}{T_r}\frac{i_{sq}}{\psi'_{rd}} + z_p\omega \tag{16}$$

Discretizing the above equation, we get:

$$\omega_s(k+1) = \frac{1}{T_r}\frac{i_{sq}(k-1)}{\psi'_{rd}(k-1)} + z_p\omega(k-1) \tag{17}$$

In asynchronous motors, the angle of the rotor flux depends on the stator current. The initial angle of the rotor flux is zero resulting in the integral of the synchronous angle being the angle of the rotor flux. The structure implemented on the C2000 model from (17) is shown in Figure 2.

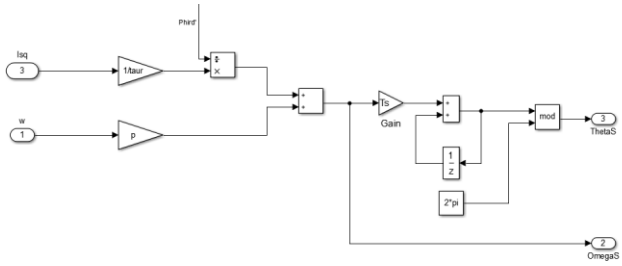

Figure 2. Calculation of **φ**s

In real applications, the process of collecting parameters such as Ia, Ib current always uses low pass filters. Therefore, the measured current signals will lag behind the actual current. The obtained angle of the magnetic flux model will be delayed compared to the actual value. To have an appropriate transfer angle, it is necessary to have an angle adjustment stage before the voltage coordinate transformation stage. The complete magnetic flux model is built as given in Figure 3.

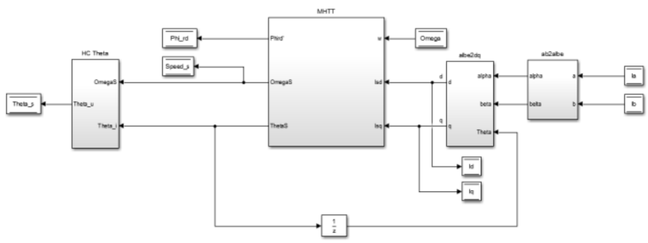

Figure 3. The complete model of the magnetic flux

IV. METHOD OF VERIFYING THE MAGNETIC FLUX MODEL ON C2000 MICROCONTROLLER

To determine the accuracy of the magnetic flux model, the authors propose a solution that allows collecting model parameters. Based on calculation equations, the system's working ability is verified. One of the advantages of the

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magnetic flux model is its ability to work independently. A voltage source that has a definite frequency and a specified synchronous angle is connected to the motor. Comparing the angle of the voltage source and the angle obtained from the magnetic flux model, we determine the angle error. The hardware system is shown in Figure 4.

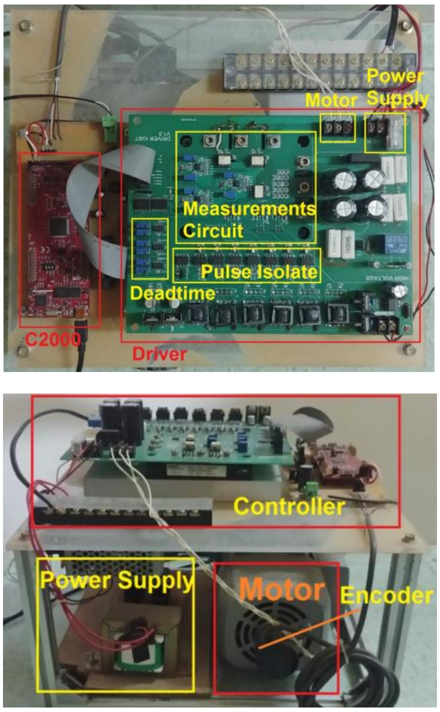

Figure 4. Controller and driver

The configuration of the supply voltage for motor testing is described in Figure 5.

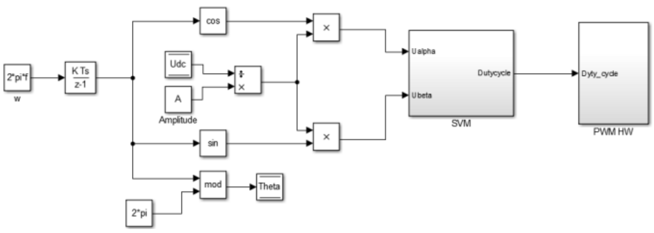

Figure 5. Motor control voltage

The collected parameters include rotor flux, synchronizing angle of the inverter, synchronous angle of the model, current Id, Iq.

V. EXPERIMENTAL RESULTS

The whole structure of the magnetic flux model and the voltage source was designed on Matlab/Simulink software and compiled for C2000 microcontroller. The conditions and model parameters are provided in Table 1.

Table 1. Motor parameters used in experiments

Motor parameters	Symbol	Value
Rated power	P_{nom}	0.1 kW
Rated speed	n_{nom}	1407 vg/ph
Rated current	I_{nom}	0.7 A_{RMS}
Number of pairs of poles	z_p	2
Rotor resistance	R_r	13.7 Ω
Stator resistance	R_s	21.8 Ω
Rotor inductance	L_r	0.707 H
Stator inductance	L_s	0.6716 mH
Mutual inductance	L_m	0.6313 mH
Power factor	$\cos\varphi$	0.67
Coefficient of total dissipation	σ	0.1607
Moment of inertia	J	0.001 kgm^2

Experimental results are shown in Figure. 6 and Figure. 7. Figure 7 shows that the synchronizing angle of the inverter and synchronous angle of the model are almost the same. The error between the two values is the angle error of the synchronous magnetic field and the rotor flux.

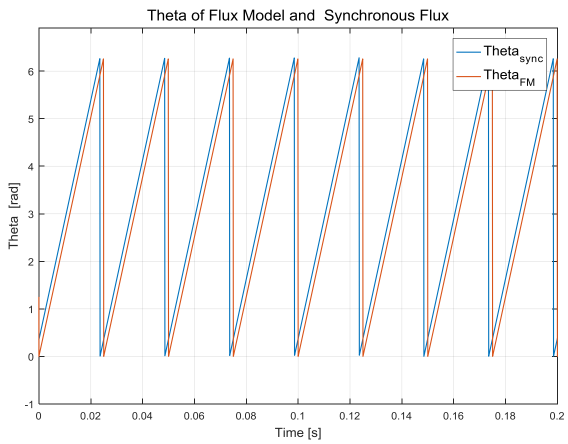

Figure 6. Experimental results of measuring the magnetic flux angle

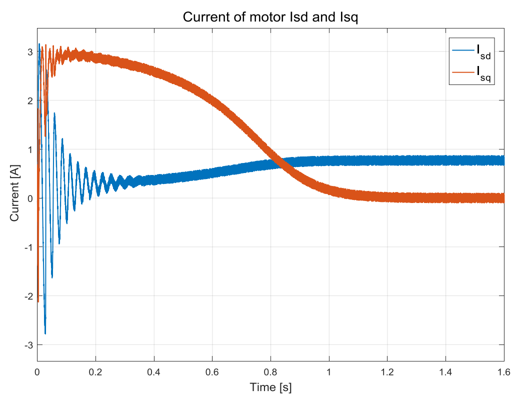

Figure 7. Experimental results of I_{dq} of the magnetic flux model

VI. CONCLUSION

Experimental results have proved the calculation ability of algorithms for magnetic flux models of three-phase asynchronous motors of C2000 series microcontrollers. The construction of an accurate magnetic flux model allows implementing the FOC control structure for the IM motor. In our future projects, the FOC control method and advanced control algorithms on hardware platforms using DSP C2000 will be implemented and installed on real systems.

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