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).

\[
\begin{align*}
\psi_s &= L_s i_s + L_m i_r \\
\psi_r &= L_m i_s + L_r i_r
\end{align*}
\]

In which:

\[ L_s = L_m + L_{sv} \quad \text{and} \quad L_r = L_m + L_{rv}. \]

\( L_s \) is stator inductance, \( L_m \) is mutual inductance, \( L_s \) stator inductance, \( L_r \) rotor inductance, \( L_{mv} \) mutual inductance, \( L_{sv} \) and \( L_{rv} \) are stator and rotor inductors, \( i_s \) is stator current, and \( i_r \) 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:

\[
\begin{align*}
u_s &= R_s i_s + \frac{d\psi_s}{dt} + j\omega \psi_s \\
0 &= R_r i_r + \frac{d\psi_r}{dt} + j\omega \psi_r
\end{align*}
\]

In which \( \omega = \omega_r - \omega_s \) with \( \omega_s \) is the slip velocity, \( \omega_r \) is the synchronous velocity, and \( \omega \) is the rotor velocity.

From (1), (2) and (3), we have:

\[
\begin{align*}
u_s &= R_s i_s + \frac{d\psi_s}{dt} + j\omega \psi_s \\
0 &= R_r i_r + \frac{d\psi_r}{dt} + j\omega \psi_r \\
\psi_s &= L_s i_s + L_m i_r \\
\psi_r &= L_m i_s + L_r i_r
\end{align*}
\] (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:

\[
\begin{align*}
\frac{di_{sd}}{dt} &= -\frac{1}{\sigma T_s} i_{sd} + \omega_j i_{dq} \\
&+ \frac{1 - \sigma}{\sigma T_r} \frac{\psi_{sr}}{\psi_{rr}} + \frac{1}{\sigma L_s} u_{sd} \\
\frac{di_{qd}}{dt} &= -\omega_j i_{qd} - \left( \frac{1}{\sigma T_s} \frac{1 - \sigma}{\sigma T_r} \right) i_{dq} \\
&- \frac{1 - \sigma}{\sigma} \frac{\psi_{sr}}{\psi_{rr}} + \frac{1}{\sigma L_s} u_{sd} \\
\frac{\psi_{sd}}{dt} &= \frac{1}{T_s} i_{sd} - \frac{1}{T_r} \psi_{sd} + (\omega_s - \omega) \psi_{dr} \\
\frac{\psi_{qd}}{dt} &= \frac{1}{T_r} i_{qd} - (\omega_s - \omega) \psi_{rd} - \frac{1}{T_r} \psi_{dq}
\end{align*}
\]

Selecting the rotation system dq with q axis perpendicular to the flux generated by the rotor, we have \( \psi_{dr} = 0 \).

Substituting \( \psi_{dr} \) into (5), we have:

\[
\frac{di_{sd}}{dt} = -\frac{1}{\sigma T_s} i_{sd} + \omega_j i_{dq} \\
&+ \frac{1 - \sigma}{\sigma T_r} \frac{\psi_{sr}}{\psi_{rr}} + \frac{1}{\sigma L_s} u_{sd}
\] (6)

\[ L_{sv} \] and \[ L_{rv} \] are stator and rotor inductors, \[ i_s \] is stator current, and \[ i_r \] is rotor current.
\[
\frac{di_{sd}}{dt} = -\sigma j_{sd} \left( \frac{1}{\sigma T_r} - \frac{1}{\sigma T_s} \right) + \frac{1}{\sigma L_s} \psi_{rd} + \frac{1}{\sigma T_r} \psi_{rd}
\]
(7)

\[
\frac{d\psi_{rd}}{dt} = \frac{1}{T_r} i_{rd} - \frac{1}{T_s} \psi_{rd}
\]
(8)

\[
0 = \frac{1}{T_r} i_{eq} - (\alpha - \omega) \psi_{rd}
\]
(9)

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

\[
m_d = \frac{3}{2} z_p (1 - \sigma) \psi_{rd} i_{sd}
\]
(10)

and

\[
0 = i_{nd} + T_r \frac{di_{nd}}{dt} - i_{sd}
\]
(11)

\[
0 = \omega T_r i_{md} - i_{sq}
\]
(12)

\[
i_{md} = \frac{\psi_{rd}}{L_a}
\]
(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:

\[
\psi_{rd} = L_s \int \left( \frac{1}{T_r} i_{rd} - \frac{1}{T_s} \psi_{rd} \right) dt
\]
(14)

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

\[
\psi_{rd}(k) = L_s \left( \frac{T_r}{T_s} i_{rd}(k-1) - \frac{T_r}{T_s} \psi_{rd}(k-1) \right)
\]
(15)

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

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:

\[
\omega_s = \frac{1}{T_r} \frac{i_{sd}}{\psi_{rd}} + z_p \omega
\]
(16)

Discretizing the above equation, we get:

\[
\omega_s(k+1) = \frac{1}{T_r} \frac{i_{sd}(k-1)}{\psi_{rd}(k-1)} + z_p \omega(k-1)
\]
(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.

In real applications, the process of collecting parameters such as \(I_a, I_b\) 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 1. The calculation model of magnetic flux implemented on DSP C2000](image)

![Figure 2. Calculation of \(\phi_s\)](image)

![Figure 3. The complete model of the magnetic flux](image)
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.

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

The collected parameters include rotor flux, synchronizing angle of the inverter, synchronous angle of the model, current $I_d$, $I_q$.

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.

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**Table 1. Motor parameters used in experiments**

<table>
<thead>
<tr>
<th>Motor parameters</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power</td>
<td>$P_{\text{nom}}$</td>
<td>0.1 kW</td>
</tr>
<tr>
<td>Rated speed</td>
<td>$n_{\text{nom}}$</td>
<td>1407 vg/ph</td>
</tr>
<tr>
<td>Rated current</td>
<td>$I_{\text{nom}}$</td>
<td>0.7 A RMS</td>
</tr>
<tr>
<td>Number of pairs of poles</td>
<td>$z_p$</td>
<td>2</td>
</tr>
<tr>
<td>Rotor resistance</td>
<td>$R_r$</td>
<td>13.7 Ω</td>
</tr>
<tr>
<td>Stator resistance</td>
<td>$R_s$</td>
<td>21.8 Ω</td>
</tr>
<tr>
<td>Rotor inductance</td>
<td>$L_r$</td>
<td>0.707 H</td>
</tr>
<tr>
<td>Stator inductance</td>
<td>$L_s$</td>
<td>0.6716 mH</td>
</tr>
<tr>
<td>Mutual inductance</td>
<td>$L_{\text{m}}$</td>
<td>0.6313 mH</td>
</tr>
<tr>
<td>Power factor</td>
<td>$\cos \phi$</td>
<td>0.67</td>
</tr>
<tr>
<td>Coefficient of total dissipation</td>
<td>$\sigma$</td>
<td>0.1607</td>
</tr>
<tr>
<td>Moment of inertia</td>
<td>$J$</td>
<td>0.001 kgm$^2$</td>
</tr>
</tbody>
</table>

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.

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**Figure 4.** Controller and driver

**Figure 5.** Motor control voltage

**Figure 6.** Experimental results of measuring the magnetic flux angle

**Figure 7.** Experimental results of $I_{\text{d}}$ 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.

REFERENCES


