A NOVEL SCHEME FOR CONTROLLING THE INDUCTION MOTOR DRIVE

A. M. El Sawy*, Y. S. Mohamed*, Adel A. El baset*, and Montaser A. Mohamed**
*Electrical. Eng. Dept., Faculty of Engineering, Minia University, Egypt.  
**High Institute of Engineering and Technology, El Minia, Egypt

(Received June 7, 2010 Accepted July 15, 2010)

This paper investigates the performance characteristics of controlled induction motor drive system using vector control, direct torque control, or sliding mode control techniques. A trial to combine the advantages of two control systems for obtaining improved performance is also presented.

The mathematical models of the induction motor in the stationary and synchronous reference frames are presented. The performance characteristics of the vector control and direct torque control of the induction motor drive are also studied for different operating conditions. It is found that the direct torque controlled system is simple and robust in face of uncertainty at low and high speeds compared to the vector controlled system. Moreover, it has fast flux and torque responses. However, the direct torque controlled system has the drawback that large ripple amplitudes are noticed in the current and torque waveforms.

In order to overcome the above problem, two schemes are discussed. The first scheme consists of traditional direct torque control with sliding mode speed controller. The other scheme is based on the sliding mode torque/flux controller. Computer simulations have been carried out to demonstrate the effectiveness of the two schemes at different operating conditions. The Simulation results have proven that significant improvement in the drive performance can be achieved with the second scheme. Thus, the current and torque ripples are reduced. Moreover, Robustness against load disturbance and parameters uncertainty are evident.

1. INTRODUCTION

Vector control techniques [1-2] have made possible the application of induction machines for high-performance applications. The vector control scheme enables the control of the induction machine in the same way as a separately excited DC motor. However, the main drawbacks of this method are: sensitivity of the drive performance to the parameters variation and inadequate rejection of external disturbances and load changes.

The direct torque control (DTC) has been getting increased attention and becoming an industrial alternative to the field oriented control strategy. It was developed to overcome vector control relatively poor transient response and reliance on induction motor parameters [2-4]. DTC provides a very quick and precise torque
response without the complex field orientation block and the inner current regulation loop. Unfortunately the classical DTC algorithm has some significant limitations. It has inherent drawbacks such as variable switching frequency, high torque and current ripples, high noise level at low speeds and also the difficulty to control torque and flux at low speeds.

The sliding mode control (SMC) technique is considered an effective, high frequency switching control strategy for nonlinear systems with uncertainties. It has many good properties such as good performance against unmodeled dynamics, insensitivity to parameters variation, external disturbance rejection and fast dynamic response. Various SMC techniques for induction motors have been proposed in many literature articles [5-9].

In this paper, the performance characteristics of the induction motor drive are investigated when controlled by vector control, direct torque control, or sliding mode control techniques. Then the advantages of the direct torque and sliding mode are combined in order to improve the drive performance. Two control schemes are designed. In the first scheme, the SMC is used as a speed controller in a traditional direct torque control scheme. This resulted in a slight improvement in the performance characteristics of the induction motor drive. However, the flux, torque, and current ripples where still having large amplitudes. In the second scheme a sliding mode torque/flux controller has been employed instead of the conventional one. The design is based on two integral sliding surfaces. Significant improvements in the performance characteristics of the induction motor drive are gained from this scheme. These improvements include: reducing current and torque ripples, fast torque and flux response, and robustness against load disturbance and parameters uncertainty.

2. MATHEMATICAL MODEL

2.1 Stator Model of the Induction Motor in the Stationary Frame

The equations which describe the behavior of the induction motor in the \( \alpha - \beta \) fixed reference frame are written as [1, 2]:

\[
V_{as} = i_{as} R_s + p\lambda_{as} \tag{1}
\]
\[
V_{fs} = i_{fs} R_s + p\lambda_{fs} \tag{2}
\]
\[
0 = i_{as} R_r + p\lambda_{ar} + \omega_r \lambda_{fr} \tag{3}
\]
\[
0 = i_{fs} R_r + p\lambda_{fr} - \omega_r \lambda_{ar} \tag{4}
\]

Where the stator and rotor flux linkage components are given as:

\[
\lambda_{as} = L_s i_{as} + L_m i_{ar} \tag{5}
\]
\[
\lambda_{fs} = L_s i_{fs} + L_m i_{fr} \tag{6}
\]
\[
\lambda_{ar} = L_r i_{ar} + L_m i_{as} \tag{7}
\]
\[
\lambda_{fr} = L_r i_{fr} + L_m i_{fs} \tag{8}
\]

Using equations (5-8), the stator and rotor flux linkages are related by the following equations:

\[
\lambda_{as} = \sigma L_s i_{as} + (L_m / L_r) \lambda_{ar} \tag{9}
\]
\[ \lambda_{fs} = \sigma L_s i_{fs} + (L_m / L_r) \lambda_{fr} \]  
(10)

Where \( \sigma = 1 - (L_m^2 / L_s L_r) \) is the leakage coefficient.

Substituting the values of \( \lambda_{cs} \) and \( \lambda_{fs} \) from equations (9, 10) into equations (1, 2), we obtain:

\[ V_{cs} = i_{cs} R_s + \sigma L_s p i_{cs} + (L_m / L_r) p \lambda_{car} \]  
(11)

\[ V_{fs} = i_{fs} R_s + \sigma L_s p i_{fs} + (L_m / L_r) p \lambda_{fr} \]  
(12)

Combining equations (5-8), the rotor current can be expressed in terms of the stator current as:

\[ i_{ar} = (\lambda_{ar} - L_m i_{cs}) / L_r \]  
(13)

\[ i_{br} = (\lambda_{br} - L_m i_{cs}) / L_r \]  
(14)

Combining equations (3, 4), and (11-14), the induction motor model can be represented by the following differential equations:

\[ p i_{cs} = a_{11} i_{cs} + a_{12} i_{fs} + a_{13} \lambda_{cs} + a_{14} \lambda_{fr} + b_1 V_{cs} \]  
(15)

\[ p i_{fs} = a_{21} i_{cs} + a_{22} i_{fs} + a_{23} \lambda_{cs} + a_{24} \lambda_{fr} + b_2 V_{fs} \]  
(16)

\[ p \lambda_{cs} = a_{31} i_{cs} + a_{32} i_{fs} + a_{33} \lambda_{cs} + a_{34} \lambda_{fr} \]  
(17)

\[ p \lambda_{fr} = a_{41} i_{cs} + a_{42} i_{fs} + a_{43} \lambda_{cs} + a_{44} \lambda_{fr} \]  
(18)

Where:

\[ a_{11} = \left( -\frac{R_s}{\sigma L_s} - \frac{1-\sigma}{\sigma T_r} \right), \quad a_{12} = 0, \quad a_{13} = \frac{L_m}{\sigma L_s L_r T_r}, \quad a_{14} = \frac{P L_m}{\sigma L_s L_r}, \]

\[ b_1 = \frac{1}{\sigma L_s}, \quad a_{21} = 0, \quad a_{22} = a_{11}, \quad a_{23} = -a_{14}, \quad a_{24} = a_{13}, \]

\[ b_2 = b_1, \quad a_{31} = \frac{L_m}{T_r}, \quad a_{32} = 0, \quad a_{33} = -\frac{1}{T_r}, \quad a_{34} = -P, \]

\[ a_{41} = 0, \quad a_{42} = a_{31}, \quad a_{43} = -a_{34}, \quad a_{44} = a_{33}. \]

The mechanical equation which describes the motion of the induction motor is given by [1]:

\[ T_e = j p \omega_r + f \omega_r + T_L \]  
(19)

Where \( p \) is the time derivative operator, and \( T_e \) is the electromagnetic torque which is given by [1]:

\[ T_e = (3/2) P (L_m / L_r) (\lambda_{ar} i_{fs} - \lambda_{fr} i_{cs}) \]  
(20)

### 2.2 Stator Model of the Induction Motor in the Synchronous Frame

The stator model which describes the behavior of the induction motor in the \( d-q \) synchronously rotating reference frame can be written as [1]:
\[ V_{ds} = i_{ds} R_s + p\lambda_{ds} - \omega_s \lambda_{qs} \quad (21) \]
\[ V_{qs} = i_{qs} R_s + p\lambda_{qs} + \omega_s \lambda_{ds} \quad (22) \]

3. RESULTS AND DISCUSSIONS

3.1 Vector Control

In this section, the performance of direct vector control (DVC) of the induction motor drive has been studied at different operating conditions. The induction motor parameters and data used for the simulation procedure are [10]: 3-phase, Y-connected, 1.1-kW, 380-V, 50-Hz, 2.77 A. The motor detailed parameters are listed below in Table (1).

Table (1): Parameters and data of the induction motor

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of pole pairs</td>
<td>2</td>
</tr>
<tr>
<td>Magnetising inductance (H.)</td>
<td>0.475</td>
</tr>
<tr>
<td>Stator resistance ((\Omega))</td>
<td>5.46</td>
</tr>
<tr>
<td>Rated current (Amp.)</td>
<td>2.77</td>
</tr>
<tr>
<td>Rotor resistance ((\Omega))</td>
<td>4.45</td>
</tr>
<tr>
<td>Reference rotor flux linkage (Wb)</td>
<td>0.8</td>
</tr>
<tr>
<td>Stator inductance (H)</td>
<td>0.492</td>
</tr>
<tr>
<td>Rated torque (N.m.)</td>
<td>7</td>
</tr>
<tr>
<td>Rotor inductance (H)</td>
<td>0.492</td>
</tr>
<tr>
<td>Rectifier voltage (V)</td>
<td>400</td>
</tr>
</tbody>
</table>

The gains of the PI - speed controller are chosen by using trial and error as:
Proportional gain = 1 \(, \) integral gain = 30.

The following main points are concluded:

a) The DVC of the induction motor drive operates well at medium and high speeds. It can withstand load change and / or mismatched stator resistance.

b) At low speeds, and detuned stator resistance, the DVC of the induction motor drive system has poor flux response. Mismatched stator resistance can also be estimated which affects the flux estimation and thereby the angle of rotor flux position required for axes transformation. The amplitude of the rotor flux rises in order to compensate for the excess in voltage drop on the stator resistance. This would cause iron saturation [11].

3.2 Direct Torque Control

The performance of the DTC system is investigated at different operating conditions. It is concluded that the DTC offers many advantages such as fast dynamic response, robustness against most of the parameter variation, and configuration simplicity. However, the following drawbacks are reported [12]:

a) Variable switching frequency.
b) High torque and current ripples.
c) High noise level at low speeds.
d) High flux ripples.
3.3 Combined Sliding and Direct Vector Control

The sliding mode controller has been employed as a speed controller in a direct vector controlled induction motor drive scheme. The performance characteristics of the sliding mode speed controller have been studied. Compared to the DVC with traditional PI speed controller, it is concluded that this system provides:

a) Faster current and torque responses.

b) Smaller current and torque ripples.

c) Smaller amplitudes of the rotor flux oscillations.

However, this system has the same drawbacks of the traditional DVC scheme at low speed and mismatched stator resistance. Thus, the rotor flux increases to compensate for the excess in voltage drop on the stator resistance which disturbs the flux estimation necessary for axes transformation. This would cause the iron to be severely saturated and may lead to unstable system [13].

3.4 Combined Sliding and Direct Torque Control

Two control schemes are designed. In the first scheme a speed controller in a traditional direct torque control scheme is used. This results in a slight improvement in the performance characteristics of the induction motor drive. However, the flux, torque and current ripples are still having large amplitudes.

In the second scheme a sliding mode torque/flux controller has been employed instead of the conventional one. The design is based on two integral sliding surfaces. The details of this scheme are described in the following sections.

3.4.1 Design of sliding mode torque/flux controller for DTC scheme

The problems of the classical DTC are solved using sliding mode control. Two integral sliding surface functions are designed in order to generate the d-q reference voltages. The electromagnetic torque can be written as [1]:

\[ T_e = \left(3/2\right) p (i_{qs} \lambda_{ds} - i_{ds} \lambda_{qs}) = K_T u_T \]  \hspace{1cm} (23)

Let the torque control signal be:

\[ u_T = i_{qs} \lambda_{ds} - i_{ds} \lambda_{qs} \]  \hspace{1cm} (24)

and the flux control signal be the square of the flux norm which is defined as:

\[ u_{\lambda} = (\lambda_{ds}^2 + \lambda_{qs}^2)^{1/2} \]  \hspace{1cm} (25)

Let the torque and flux errors be:

\[ e_T = u_T^* - u_T \] \hspace{1cm} (26)

\[ e_{\lambda} = u_{\lambda}^* - u_{\lambda} \] \hspace{1cm} (27)

Where \( u_T^* \) is the torque command which is equal to the control effort of the torque controller and \( u_{\lambda}^* \) is the flux command. Therefore, the switching functions are chosen as:
\[ s_T = e_T + K_T \int e_T \, dt \] (28)

\[ s_\lambda = e_\lambda + K_\lambda \int e_\lambda \, dt \] (29)

Where \( K_T, K_\lambda \) are positive gains. Once the system states stay on the sliding surface, it can be said that \( \dot{s}_T = \dot{s}_\lambda = 0 \) where:

\[ \dot{s}_T = \dot{e}_T + K_T e_T \] (30)

\[ \dot{s}_\lambda = \dot{e}_\lambda + K_\lambda e_\lambda \] (31)

Combining equations (24), (26), (28) and (30) one can obtain:

\[ \dot{S}_T = u_T - u_T + K_T e_T \]

\[ = u_T - (i_{qs} \lambda_{ds} + i_{qs} \lambda_{qs}) + (i_{ds} \lambda_{qs} + i_{ds} \lambda_{qs}) + K_T e_T \] (32)

Substituting the values of \( \dot{\lambda}_{qs} \) from equation (22) in equation (30) would result:

\[ \dot{S}_T = u_T - (i_{qs} \lambda_{ds} + i_{qs} \lambda_{ds}) + [i_{ds} \lambda_{qs} + i_{ds} (V_{qs} - i_{qs} R_s - \omega_s \lambda_{ds})] + K_T e_T \]

Or

\[ \dot{S}_T = C_T + D_T V_{qs} \] (33)

Similarly, combining equation (25), (27), (29), and (31) would yield:

\[ \dot{s}_\lambda = u_\lambda - \dot{u}_\lambda + K_\lambda e_\lambda \]

\[ = u_\lambda - (\dot{\lambda}_{ds} \lambda_{ds} + \dot{\lambda}_{qs} \lambda_{qs}) + K_\lambda e_\lambda \] (34)

Substituting the value of \( \dot{\lambda}_{ds} \) from equation (21) into equation (34), this yield:

\[ \dot{S}_\lambda = u_\lambda - [\dot{\lambda}_{ds} (V_{ds} - i_{ds} R_s + \omega_s \lambda_{qs}) + \dot{\lambda}_{qs} \lambda_{qs}] + K_\lambda e_\lambda \]

or

\[ \dot{S}_\lambda = C_\lambda + D_\lambda V_{ds} \] (35)

Since SMC is designed to obtain the reference voltages in the DTC scheme, therefore the values of \( V_{qs} \) and \( V_{ds} \) in equations (34) and (35) are replaced by the reference stator voltages \( V_{qs}^* \) and \( V_{ds}^* \).

The time derivatives of the sliding surface in equations (33) and (35) can be combined to give:

\[ \dot{\mathbf{s}} = \mathbf{C} + \mathbf{D}_u \]

Where: \[ \dot{\mathbf{s}} = \begin{bmatrix} \dot{s}_T \\ \dot{s}_\lambda \end{bmatrix}^T \], \( \mathbf{C} = \begin{bmatrix} C_T & C_\lambda \end{bmatrix}^T \), \( \mathbf{D} = \begin{bmatrix} D_T & D_\lambda \end{bmatrix}^T \),
and \[ u = [V_{qs}^*, V_{ds}^*]^T. \]

Considering the parameters are in the nominal condition. If the system uncertainties are considered, then equation (36) will become:
\[ \dot{s} = C + \Delta C + (D + \Delta D)u = C + Du + W_1 \]

(37)

Where \( \Delta C \) and \( \Delta D \) are the uncertainties induced by the model parameters variation and load disturbance, and \( W_1 \) is a lumped uncertainty matrix containing terms related to the torque and flux loops.

The control effort \( u \) is designed such that the torque and flux state trajectory are forced towards the sliding surfaces. Once, the system trajectory reaches the sliding surface, it stays on it and slides to the origin. However, this control strategy produces some drawbacks associated with large control chattering that may excite unstable system dynamics. Moreover, the sensitivity of the controlled system to uncertainties still exists in the reaching phase (the time during which the system state trajectory reaches the sliding surface). To overcome these problems, the total sliding mode control law can be written as [14]:

\[ u = -D^{-1} \left[ C_T + K_{CT} s_T + \rho_T \text{sat}(s_T) \right. \]
\[ \left. + C_\lambda + K_{C\lambda} s_\lambda + \rho_\lambda \text{sat}(s_\lambda) \right] \]

(38)

Where \( K_{CT}, K_{C\lambda} \) are positive gains, and \( \text{sat}(s) \) can be chosen to reduce the undesirable chattering effect of the sliding mode technique [15]:

\[ \text{sat}(s) = \frac{s}{|s| + \lambda} \]

(39)

Where \( \lambda \) is a small positive gain and \(|s| \gg \lambda\).

3.4.2 Configuration scheme

The block diagram of the proposed sliding mode torque control of an induction motor drive system is shown in figure (1). It consists of two main control loops. The inner loop is dedicated for controlling the electromagnetic torque and the stator flux. The reference d-q stator voltages are directly generated from the torque and flux errors based on two integral surfaces. The outer loop has been employed to control the motor speed. The speed loop develops the torque command required for the torque/flux loop. A PI-controller has been usually employed for this purpose.

On the other hand, the commanded three phase stator voltages are obtained using coordinate translation of \( V_{ds}^* \) and \( V_{qs}^* \). These voltages are fed to sinusoidal pulse width modulation in order to generate the switching logic necessary for operating the inverter.
3.4.3 Simulation Results

Computer simulations are carried out to show the effectiveness of the proposed control system. All the parameters in the proposed algorithm are chosen by using trial and error to give the best transient control performance.

The parameters of the proposed control scheme are chosen as:

\[ K_T = 50, \ K_\lambda = 50, \ K_{CT} = 500, \ K_{C\lambda} = 500, \ \rho_T = 2000 \text{ and } \rho_\lambda = 2000. \]

Figures (2, 3) show the motor performance at 1000 rpm and 100 rpm reference speeds respectively. The stator resistance is detuned by 50%. Also the moment of inertia and friction coefficient are increased by 100%.

The results are summarized as shown in Table (2).
Figure (2): Simulation results at constant high speed assuming step load and mismatched parameters.

Table (2): Performance of the DTC scheme with torque/flux Sliding mode controller.

<table>
<thead>
<tr>
<th></th>
<th>High speed (1000 rpm)</th>
<th>Low speed (100 rpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed dip at load step</td>
<td>4 %</td>
<td>20 %</td>
</tr>
<tr>
<td>Restoring time (sec.)</td>
<td>0.065</td>
<td>0.06</td>
</tr>
<tr>
<td>Average speed ripples</td>
<td>±0.02 %</td>
<td>±0.04 %</td>
</tr>
<tr>
<td>Average current ripples</td>
<td>about 0.1 %</td>
<td></td>
</tr>
<tr>
<td>Average torque ripples</td>
<td>± 3 %</td>
<td>± 0.4 %</td>
</tr>
<tr>
<td>Average Flux ripples</td>
<td>about 0.15 %</td>
<td></td>
</tr>
</tbody>
</table>
4. CONCLUSIONS

This paper investigates the successful application of direct torque control of the induction motor drive based on sliding mode technique. Two control schemes are designed. The first scheme is used as a speed controller in a traditional direct torque control scheme. This results in a slight improvement in the performance characteristics of the induction motor drive. However, the flux, torque and current ripples have large amplitudes.

In the second scheme a sliding mode torque/flux controller has been employed instead of the conventional one. The design is based on two integral sliding surfaces. Significant improvements in the performance characteristics of the induction motor drive are gained from this scheme. These improvements are listed as follows:

a) The speed dip due to load stepping is reduced significantly.

b) The time elapsed to restore the reference speed is shortened greatly.

c) The magnitude of the speed ripples is reduced.

d) The current and torque ripples are also reduced.

e) Robustness against load disturbance and parameters uncertainty.

f) Fast torque and flux responses.
REFERENCES

طريقة جديدة للتحكم في المحرك الحثي

هذا البحث يعرض خواص الأداء للمحرك الحثي باستخدام نظام عديدة من التحكم منها التحكم الإتجاهي والتحكم المباشر للعزم، وتحسن الأداء للمحرك وذلك بالاستفادة من مميزات دمج نوعين من المحركات. تم عمل نماذج رياضية للمحرك الحثي للحصول على أداء المحرك مع نظام التحكم الإتجاهي والتحكم المباشر للعزم عند نقاط التشغيل المختلفة.

من الدراسة تبين أن التحكم المباشر للعزم بسيط ومتبني وله سرعة استجابة عالية لكل من القيمة والتعيين عند السرعات المنخفضة والعالية مقارنة بنظام التحكم الإتجاهي. ولكن التحكم المباشر للعزم له عيوب منها كبر قيمة التواقيع المصحوبة للتيار والعزم. للتغلب على مشكلة التواقيع تم اقتراح نظام يعتمد على استخدام محكمين ازلاق لكل من القيمة والعزم والسرعة.

تم استخدام الحاسب لتوضيح فاعليّة النظام المقترح المكون من محكمين عند نقاط التشغيل المختلفة. النتائج المعروضة تظهر أن النموذج المقترح يؤدي إلى التحسين الواضح والمؤثر في أداء المحرك. لذلك تم تقليل قيمة التواقيع المصحوبة للتيار والعزم، وأيضاً المدة ضد كلاً من التفسير المفاجئ للعزم وكذلك التغير الغير متوقع للثوابت المحرك.

A. M. El Sawy et al.