Speed Observer Based Load Angle Control of Induction Motor Drive

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Abstract—The performance of induction motor drives gets improved in the scalar control mode with various algorithms with speed /position feedback. In this paper load angle control of induction motor with speed observer is presented. This eliminates the physical presence of speed sensor. The basic control of rotor flux vector with stator current defines the dynamics of torque control. In this scheme, estimation of feedback variables is obtained by using algorithm with minimum number of machine parameters. The speed obtained is thus used in feedback loop to improve the machine performance. The proposed algorithm also has a capability to estimate the active and reactive power of the machine. This is further incorporated to improve the operating efficiency of the machine. The observer developed is tested for various dynamics condition to verify its operating performance in MATLAB/SIMULINK.

Index Terms—Speed sensorless induction motor, Load angle control, speed observer, Energy efficiency

I. NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( u_{s}, i_{s}, \Psi_{s}, \Psi_{r} )</td>
<td>Stator voltage, current and flux, rotor flux</td>
</tr>
<tr>
<td>( R_{s}, R_{r}, L_{m} )</td>
<td>Stator resistance, rotor resistance, stator inductance, rotor inductance, magnetizing inductance</td>
</tr>
<tr>
<td>( \Omega_{r}, \Omega_{m}, \omega_{r} )</td>
<td>Rotor speed, rotor flux linkages speed, stator current angular frequency</td>
</tr>
<tr>
<td>( x_{11}, x_{12}, x_{21}, x_{22} )</td>
<td>variables of multiscalar motor model</td>
</tr>
<tr>
<td>( K_{m}, T_{m} )</td>
<td>Rotor flux speed PI controller parameters</td>
</tr>
<tr>
<td>( a_{1}, a_{2}, b_{1}, b_{2}, \sigma )</td>
<td>Motor coefficients</td>
</tr>
</tbody>
</table>

II. INTRODUCTION

The speed sensor is an inconvenient device and has many drawbacks. An incremental shaft mounted speeder encoder is required for close loop speed or position control. A speed encoder is undesirable in a drive because it adds cost and reliability problems, besides the need for a shaft extension and mounting arrangement. Thus from the beginning of 1980’s there were serious research works throughout the world to control induction machine without the need for speed sensor [1]-[7]. It is possible to estimate the speed signal from machine terminal voltage and currents with the help of digital signal processor (DSP). Different methods are used for flux and speed estimation. The calculation method of state variable may be classified as models and observers. Models in comparison with observers are less complicated in the case of induction motor. The accuracy of these variables depends on the motor operating point, exactness of the parameter used, and the sensitivity of the model to drift in these parameters. The voltage model is not precise at low frequencies; however it is not sensitive to rotor resistance variations. On the other hand, the current model is sensitive to rotor resistance variations and is not accurate in calculating the rotor speed, especially at high speed. However, it is more precise, compared to voltage model, and at lower frequencies the mixed model integrates the advantage of both models. Because of these inaccuracies in calculating the flux linkage, in many solutions an observer by introducing an additional feedback loop is used. The load angle is the angle between the flux \( \psi_{r} \) and the stator current \( I_{s} \). Since the flux is related to the applied voltage and is fixed, thus we cannot vary the magnitude of the vector \( \psi_{r} \). But the speed at which it is rotating is not constant. Similarly in case of current vector the magnitude can be controlled but not \( \omega_{r} \). \( \omega_{r} \) depends on the applied frequency.

III. MATHEMATICAL MODEL OF INDUCTION MOTOR

Induction Motor Model

The fundamental equation, which is used to introduce the relation ship for speed observer system, is the stator circuit equation given by

\[
\vec{u}_{s} = R_{s} \vec{i}_{s} + \frac{d\vec{\psi}_{s}}{dt} + j\Omega \vec{\psi}_{s} \tag{1}
\]

The d-and q-voltage component presented in the d-q reference frame with the rotor flux linkages oriented in the d-axis are given by

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The estimated d-q components of stator flux linkages are as follows

$$\frac{d\hat{\psi}_{sl}}{dt} = \tilde{\pi}_{sl} - R_l \dot{i}_{sl} + \hat{\omega} \psi_{sl}$$  \hspace{1cm} (4)

$$\frac{d\hat{\psi}_{sq}}{dt} = \tilde{\pi}_{sq} - R_l \dot{i}_{sq} - \hat{\omega} \psi_{sq}$$  \hspace{1cm} (5)

Equation (2) and (3) present the voltage model of induction motor in d-q reference frame. This flux simulator operates in open loop without any feed back from the rotor flux error. The flux is identified correctly when the motor parameters are exactly known. In the real system, motor parameter change with operating point, and this different depends on the following properties of the selected motor model; degree of accuracy of parameter identification; degree of accuracy of current and voltage measurement and motor operating point. The use of feedback minimizes the effect of the above factors on the identification of the rotor flux linkages.

Four state variables have been proposed for describing the motor model [9]. These state variables may be interpreted as rotor angular speed, scalar and vector products of the stator current and rotor flux vectors, and the square of the rotor linkage flux, as follows:

$$x_{11} = \omega$$  \hspace{1cm} (6)

$$x_{12} = \psi_{rs} i_{rs} - \psi_{sy} i_{sy} = \psi_{r} i_{r} \sin(\delta)$$  \hspace{1cm} (7)

$$x_{21} = \psi_{rs}^2 + \psi_{sy}^2$$  \hspace{1cm} (8)

$$x_{22} = \psi_{rs} i_{rs} + \psi_{sy} i_{sy} = \psi_{r} i_{r} \cos(\delta)$$  \hspace{1cm} (9)

Where, $\delta$ is the angle between stator current and rotor flux vectors. By using nonlinear feedback, it is possible to obtain a new model for the induction motor with two fully decoupled subsystems: mechanical and electromagnetic. This property is not a function of the motor source [10].
\[ \omega_b = \delta L_r L_s \] & \[ \delta = 1 - \frac{L_m^2}{L_r L_s} \]

The use of the above relationships avoids exact measurements of the flux, resistance, and angular speed of the rotor. Increasing the accuracy of calculation of the new variables is possible using an observer of the following form:

\[
\frac{d\hat{x}_{12}}{dt} = -\frac{1}{T_1} x_{12} + v_1 + k_{01}(\hat{x}_{12} - x_{12m}) \tag{18}
\]

\[
\frac{d\hat{x}_{22}}{dt} = -\frac{1}{T_2} x_{22} + i_2^2 + v_2 + k_{02}(\hat{x}_{22} - x_{22m}) \tag{19}
\]

The index denotes the calculated values using power measurement. After assuming that motor parameters are known and constant, it is possible to identify the variable \( x_{21} \) using the following model:

\[
\frac{d\hat{x}_{21}}{dt} = -2 \frac{R_s}{L_s} \hat{x}_{21} + 2 \frac{L_m}{L_s} \hat{x}_{22} \tag{20}
\]

At steady state the left side of the above equation is zero, therefore, it is possible to show that the variable \( x_{21} \) is

\[
x_{21} = L_m x_{22m} \tag{21}
\]

IV. LOAD ANGLE AND SPEED OBSERVER

A. Load Angle Calculation

During the control of an induction motor, the position of each vector relative to the stationary coordinate system is not important. The vectors, which have position relative to each other, have significant meaning. This relationship can be observed in the electromagnetic torque description

\[
m_e = k \text{Im}(\tilde{\psi}_r \tilde{\psi}_s) = k \psi_r \psi_s \sin \delta \tag{22}
\]

The vectors of stator current and rotor flux are presented in Fig. 2. If it is assumed that the magnitude of stator current and rotor flux vectors are kept at the same level by control system, then it is possible to control the motor torque by changing load angle \( \delta \).

The definition of new state variables is possible using an observer of the following form:

\[
\frac{d\hat{\psi}_r}{dt} = \frac{L_r}{L_m} \hat{\psi}_r - \frac{L_s}{L_m} \hat{\psi}_s \tag{23}
\]

In (4) and (5), a command flux quantity in feedback path is used instead of the actual quantity. Correction part in (29) and (30) appears with \( K_i \) gain, which needs to be tuned in the simulation. The commanded components of rotor flux linkages are as follows:

\[
\psi_{r\text{com}} = 0 \quad \& \quad \psi_{s\text{com}} = L_m i_{s\text{com}} \tag{24}
\]

Based on the estimated quantities of flux components, it is possible to identify the angular speed of rotor flux linkage vector using PI controller with zero command signal

\[
\hat{\psi}_r = K_{p\text{r}} \left( 1 + \frac{1}{T_{r\text{s}}} \right) (\psi_{r\text{com}} - \psi_{r\text{m}}) \tag{25}
\]

\[
\hat{\psi}_q = K_{p\text{q}} \left( 1 + \frac{1}{T_{q\text{s}}} \right) \psi_{q\text{m}} \tag{26}
\]

\[
\hat{\omega}_\psi = \frac{R_r}{L_r} i_{s\text{q}} - \frac{L_s}{L_r} i_{s\text{s}} \tag{27}
\]

\[
\hat{\omega}_p = \frac{1}{s} \hat{\omega}_\psi \tag{28}
\]

Where \( \hat{\omega}_\psi \) is the estimated angular speed of the rotor flux linkage vector. And \( i_{s\text{q}} \& i_{s\text{s}} \) are the estimated currents using the measured currents and defined in the stationary reference frame and using the transformation from \( \alpha \beta \) system to \( dq \) reference frame using the estimated angle

\[
\theta = \frac{1}{s} \hat{\omega}_\psi \tag{29}
\]

Rotor speed estimation is good only at steady state, but during the transients there is an error, which increases with a decreasing speed response [8], [9]. This is relative to the delays provided by integrating the \( q \)-axis component of the rotor flux vector. A decrease in this error may be achieved by providing a
proper initial value for the integrator. In this case, a proper initial value might be the angular speed of rotor flux vector at steady state. From the steady state relationships, it is possible to calculate the rotor speed as follows [9, 10].

$$\alpha_{\omega m} = -a_{\omega m}x_{12} - a_{\omega q}x_{22} + a_{\omega r}$$

Where $\omega$ and $i$ are the angular frequency and stator current vector, respectively.

Using the steady state relationships of induction motor, it is possible to modify the described estimator (31) in the following form:

$$\dot{\alpha}_e = -K_x \left(1 + \frac{1}{T_{rd}}\right)y_2 + \left(1 + \frac{1}{T_{rd}}\right) \left(\alpha_{\omega m} + R_m \frac{L_m}{L_s} x_{21w}\right)$$

Where $T_{rd}$ is the time constant of the first order delay filter. The first part of (34) is the equation of PI controller (30) and the second part is the filtered value of the rotor flux vector. The block diagram of a modified speed observer is presented in Fig. 3. As will be shown in the simulation results for the speed observer system from Fig. 1, the error at steady state is about 2%. This error is less than the case of using an observer without taking into account angular speed of flux linkages calculated from the steady state condition.

V. PROPOSED CONTROL SCHEME

A. Control scheme with speed feedback

In Fig. 4, block A represents the estimator which is described and presented in Fig. 5. This is an open loop estimator which estimates the slip frequency $\omega_s$ as a result of which we can get rotor speed $\omega_r$ in the stationery reference frame. The simulation parameters are given in Table 1.

### Table 1

<table>
<thead>
<tr>
<th>Rotor Type</th>
<th>50Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage (V&lt;sub&gt;nom&lt;/sub&gt;)</td>
<td>440V</td>
</tr>
<tr>
<td>Stator resistance</td>
<td>Rs=1.05Ω</td>
</tr>
<tr>
<td>Stator inductance</td>
<td>$L_s=0.004$ H</td>
</tr>
<tr>
<td>Mutual inductance</td>
<td>$L_{m}=0.004$ H</td>
</tr>
<tr>
<td>Inertia</td>
<td>0.2 kg.m$^2$s$^{-2}$</td>
</tr>
</tbody>
</table>

Parameters of Induction Motor for Simulation

B. Proposed Speed Sensorless Control

The block B in Fig. 4 represents the estimator which is replaced by the estimator represented by block A. This modified speed sensor has many advantages over open loop estimator which can be better understand by performance result. The control strategy of modified speed sensor is as explained below.

Figure 3. Rotor angular speed observer system

Figure 4. Actual and Proposed Scheme

In the presented system, the vectors are stator current and rotor flux linkage. The load angle may be kept constant by changing the position of stator current vector as a result of tuning its pulsation. The current frequency $\omega_1$ may be changed directly using load angle controller or indirectly by changing the slip frequency $\omega_2$.

$$\omega_1 = \omega_2 + \omega_3$$

The calculated stator current frequency is provided to the PWM block. The command values of load angle $\delta$ and stator current amplitude $I_s$ are adjusted by the Proportional–integral (PI) controllers. Rotor angular speed may be measured

$$\left(\sqrt{x_{22}^2 + x_{21}^2}\right)^2 = \left(x_{22}^2 + \frac{x_{21}^2}{x_{22}^2}\right) \left(x_{21}^2 + \frac{x_{22}^2}{x_{21}^2}\right)$$

And the load angle is

$$\delta = \arctan\left(\frac{x_{22}^2}{x_{21}^2}\right)$$
Controller for state variable $X_{12}$ and $X_{21}$ are used in this research. The controller command signals of the variables $X_{12}^\text{com}$ and $X_{22}^\text{com}$ on the basis of these quantities the square of the current amplitude is calculated as

$$X_{12}^\text{com} \times X_{12}^\text{com} + X_{22}^\text{com} \times X_{22}^\text{com}$$

As a result, the control system performs using actual values of stator currents and delayed values of stator voltage, which leads to non precise variable identification.

In the proposed control system, two different current controllers, hysteresis [7] and predictive [8], [9] are used. In the control system it is possible to use command stator current and predicted voltage, which appears at the output of the predictive controller because there is an access to first harmonics of the currents and voltages. The use of predictive current controller in the control system with load angle control simplifies the structure of the control system by eliminating the stator voltage filtering block.

VI. SIMULATION AND PERFORMANCE EVALUATION

The Proposed scheme with its controller action is simulated in MATLAB/SIMULINK. The induction motor with load is presented in details with voltage source inverter in SVPWM mode in SIMULINK. The performance results are presented in the following sections:

A. Open Loop Control Scheme

The proposed control scheme is simulated in MATLAB/SIMULINK and performance is observed under different dynamic conditions.

1. Step change in load

The shaft load is changed after the free running of the motor. The performance is shown in fig. 8 to 9. The dynamic performance of motor as well as estimator under load $T_L=70$ N-m applied at time $t=2000$ ms, with with the terminal voltage $V=440V$.

The estimated torque and speed are shown the fig. 8 and 9 respectively. Because of the stator voltage characteristics it is essential to filter the voltage to get the fundamental harmonic. Filtering the voltage signal complicates the control system and provides undesired delay in the measurement channel.

B. Simulation of the Proposed Speed Sensorless control Induction Motor

1. Step change in Load

The performance results are shown for step change with load torque from 0 to 70 N-m at time $t=0.2$ sec with voltage $V=440V$ in Fig. 12 to Fig.18. The estimated and actual speed of the motor are shown the fig.12. The stator current is observed and is shown in the fig.13. There is slight increment in the stator current because of increase in load torque at 0.2 sec.
The state variables of the estimator are shown in fig 14 to fig 16. The estimated active power and reactive power is shown in fig.18. This shows that there is increment in the active power at t=0.2sec and also the slight increment in reactive power.

**CONCLUSION**

A speed observer system for sensorless control of induction is developed. The rotor speed as been calculated using steady state relationship applied to the observer system. It has high accuracy and behaves satisfactory under all the speed range. An observer system has been adopted for the nonlinear control of induction motor. The simulation results illustrated that the system operates correctly for the different motor running conditions. The proposed scheme is working in closed loop control of the induction motor control. The speed sensorless induction motor with torque angle control has better dynamic performance. The power estimate algorithm is also tested with the given induction motor model.

**References**


