

SENSORLESS SPEED ESTIMATION OF INDUCTION MOTOR IN A DIRECT TORQUE CONTROL SYSTEM

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ABSTRACT: Fast and robust torque control in a very wide range of speed is very needed by various industrial AC drive applications. Therefore, since 1986 [1], direct torque control (DTC) has been introduced to satisfy this desire. In order to achieve more economical control, conventional speed sensor has been replaced by sensorless speed estimation. The sensorless schemes are used to improve reliability and decrease maintenance requirements. In this paper, concerned sensorless techniques of induction machine controlled by DTC algorithm are open-loop estimators and MRAS schemes [2], [3]. To demonstrate clearly the advantages and disadvantages between two kinds of sensorless techniques, obtained simulation results are compared. By enhancing speed estimation, the pure integrator is replaced by a low-pass filter to avoid DC drift and saturation problems [2].

Keywords: Sensorless, DTC (Direct Torque Control), IM (Induction Motor).

1. INTRODUCTION

Nowadays, comparing with the field oriented control (FOC), direct torque control (DTC) is known as a simpler and easier scheme to perform [2], [4], [5]. With DTC technique, the instantaneous values of flux and torque are estimated from the stator voltages and currents in order to compare with the command values. Residual results are used to determine the optimum inverter switch states through a look-up table to supply for induction motor. As a result, torque can be controlled directly.

The stator voltage being used for the estimation is obtained from DC link voltage the switching states of the inverter (The inverter is assumed to be supplied from an ideal AC-DC converter which takes AC voltage from the AC grid and provides the inverter a constant DC input). The switching states of the inverter is controlled directly by the central processor, therefore, the On-Off states of the transistors in the inverter are available to the processor. From the pre-defined value of DC link voltage, the processor can determine the stator phase voltage space vectors corresponding to those switching states. The stator phase currents are obtained from current sensors.

In conventional speed control of DTC the actual value of rotor speed is required. The controller receives the signals of rotor speed from the speed sensors. Unfortunately, the accuracy of the control system will decrease with the appearance of noises, causing low reliability. Furthermore, the conventional sensors make the higher cost, increase the complexity of the systems because of noise filtering. The filtering will help to improve the quality of feedback speed, however, additional digital filters require higher computing capacities for faster signal processing and transmission. Therefore, they mount additional costs on the overall systems.

Recently, many researches have been carried out for the design of speed sensorless control schemes [2], [3]. In these new schemes the speed is obtained from the determined stator voltages and measured stator currents instead of using a sensor. In this paper, two sensorless techniques are presented, an open loop and a close-loop (MRAS) scheme, which can overcome the necessity of the speed sensor.

This paper is organized as follows. First, DTC algorithm is introduced in Section 2. Then, the proposed rotor speed estimation is presented in Section 3. In the Section 4, some simulation results are presented. Finally, some concluding remarks are stated in the last Section.

2. THE DTC ALGORITHM

2.1 Dynamic Model of Induction Machine

All the equations in this paper are defined in stationary reference frame. Voltage and flux equations:

$$\underline{U}_s^s = R_s \cdot \underline{I}_s^s + \frac{d\underline{\psi}_s^s}{dt} \quad (1)$$

$$0 = R_r \cdot \underline{I}_r^s - j\omega_r \cdot \underline{\psi}_r^s + \frac{d\underline{\psi}_r^s}{dt} \quad (2)$$

$$\underline{\psi}_s^s = L_s \cdot \underline{I}_s^s + L_m \cdot \underline{I}_r^s \quad (3)$$

$$\underline{\psi}_r^s = L_r \cdot \underline{I}_r^s + L_m \cdot \underline{I}_s^s \quad (4)$$

Torque equations:

$$T_e = \frac{3}{2} p \frac{L_m}{(L_s \cdot L_r - L_m^2)} \underline{\psi}_r^s \otimes \underline{\psi}_s^s \quad (5)$$

$$T_e - T_m = J \frac{d\omega_r}{dt} \quad (6)$$

The symbol \otimes in equation (5) denotes vector product. By using space vector theory, there are eight voltage space vectors (six non-zero and two zero vectors) for an induction feeding by a conventional voltage inverter [2], [4].

2.2 Synthesis of the Takahashi's DTC Approach

In the equation (1), by neglecting the effect of stator voltage drop across stator resistance, stator flux can be estimated directly from the stator voltage and the change of the stator flux depends on the change of the stator voltage.

$$\frac{d}{dt} \underline{\psi}_s^s \approx \underline{U}_s^s \quad (7)$$

By defining $\sigma = (1 - \frac{L_m^2}{L_s \cdot L_r})$, $T_R = \frac{L_r}{R_r}$ and rearranging the equation from (1) to (4), a formula of the rotor flux is obtained.

$$\underline{\psi}_r^s = \frac{\frac{L_m}{L_s}}{1 + s \cdot T_R \cdot \sigma - j\omega_r \cdot T_R \cdot \sigma} \underline{\psi}_s^s \quad (8)$$

Equation (8) implies that rotor flux is varied by the change of stator flux. Because of the lager of rotor time constant (T_R), rotor flux vector is assumed stationary during a small time interval when stator flux vector is rotating. The torque value in the equation (5) can be expressed in another way.

$$T_e = \frac{3}{2} p \cdot \left(\frac{1}{\sigma \cdot L_s} \right) \left(\frac{L_m}{L_r} \right) \cdot |\underline{\psi}_r^s| |\underline{\psi}_s^s| \cdot \sin(\delta_s - \delta_r) \quad (9)$$

From (7) to (9), it is important to note that, the torque of an induction machine is produced by the interaction between rotor and stator flux space vectors. In a time interval small enough, rotating of the stator flux space vector in appropriate direction, according to the demanded torque, can result in a rapid and desirable changes of actual electromagnetic torque. It should be emphasized that the suitable stator flux space vector will be obtained by using the optimized inverter switching look-up table of Takahashi [1], [2], [5].

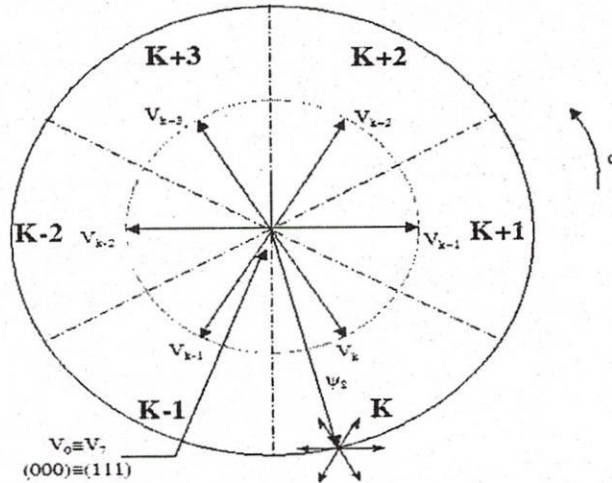


Figure 1. The changes of stator flux with the choosing switching states.

Table 1. The Takahashi's optimized switching table.

Order	$\uparrow T_e$	$\downarrow T_e$	Not order T_e
$\uparrow \psi_s$	V_{k+1}	V_{k-1}	$V_{0,7}$
$\downarrow \psi_s$	V_{k+2}	V_{k-2}	$V_{0,7}$

3. THE SENSORLESS ESTIMATION TECHNIQUES

3.1 Open-loop speed estimation

The open-loop speed estimation is based on the residual between the speed of rotor flux and the slip speed [2]. The scheme described below uses the monitored stator voltages and currents to reconstruct the rotor flux, torque by equations from (1) to (5).

$$\omega_r = \frac{\psi_{R\alpha}^s \frac{d}{dt} \psi_{R\beta}^s - \psi_{R\beta}^s \frac{d}{dt} \psi_{R\alpha}^s}{(\psi_{R\alpha}^s)^2 + (\psi_{R\beta}^s)^2} - \frac{2 R_r}{3 p} \frac{1}{|\underline{\psi}_r^s|} T_e \quad (10)$$

This scheme requires several machine parameters, some of which vary with temperature, skin effect and saturation. Thus, the speed can only be obtained accurately if these parameters are accurately known.

3.2 Model Reference Adaptive System (MRAS)

In a MRAS system, rotor flux vector is estimated in a reference model, which is independent of speed, and then compared with the one estimated by using an adaptive model, which is using speed as a parameter. The reference and adaptive model are obtained by rearranging the equations from (1) to (4).

Reference model equations:

$$\underline{\Psi}_R^s = \frac{L_R}{L_m} \left[\left(\int \underline{U}_s^s - R_s \cdot \underline{I}_s^s \right) dt - \sigma \cdot L_s \cdot \underline{I}_s^s \right] \quad (11)$$

Adaptive model equations:

$$\underline{\Psi}_R^{-s} = \int \left[\left(-\frac{1}{T_R} + j \cdot \omega_R \right) \cdot \underline{\Psi}_R^{-s} + \frac{L_m}{T_R} \cdot \underline{I}_s^s \right] dt \quad (12)$$

Error between two model:

$$\epsilon_\omega = \text{Im}(\underline{\Psi}_R^s \cdot \underline{\Psi}_R^{-s*}) = (\Psi_{R\beta}^s \cdot \Psi_{R\alpha}^{-s} - \Psi_{R\alpha}^s \cdot \Psi_{R\beta}^{-s}) \quad (13)$$

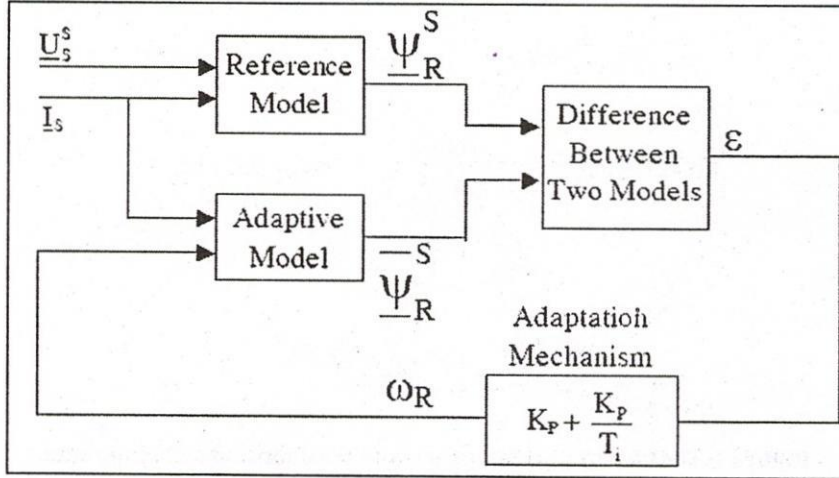


Figure 2. MRAS-based speed estimator scheme

The error between two models is the input of a PI control whose output is the estimated rotor speed, this estimated speed is used to adjust the adaptive model until satisfactory performance obtained [2], [4]. Since the MRAS is an close-loop system, the accuracy can be increased. However, the models contain pure intergrators, which cause inaccuration of the estimation system because of DC drift and saturation at the outputs of the intergrators. To avoid the problem, low-pass filters are used.

4. SIMULATION RESULTS

Two sensorless high performance drives of induction machines using DTC are simulated, one with open-loop speed estimator and one with closed loop MRAS speed estimator. Both systems are simulated for the first two seconds, including acceleration during starting from zero speed to rated speed, steady state at rated speed, and deceleration from rated speed to about 10 rad/s. Load rejection tests are carried out during steady states at rated speed as well as low speed. These tests are aimed at investigating the disturbance rejection ability of the controller by maintaining the actual speed at the commanded value of the controller when load suddenly increases and decreases.

MATLAB/SIMULINK is used to carry out the simulations above. This software allows digital simulation of the systems using analogue expression of the ordinary differential equations in the dynamic machine model as well as the controller. The numerical method for solving the equations is Runge-Kutta method. Fixed-step mode is chosen for the computational time interval, this will emulate the fixed sampling frequency of the real-time control. The sampling period is 1µs. This sampling frequency is higher than the actual sampling frequency of industrial DTC controllers, which is usually about 100kHz due to the limitation on the switching frequencies of power electronic components. However, to verify the correctness of

the suggested algorithms, highly accurate data is necessary. Nominal parameters for the test motor are provided in Table 2.

Table 2. IM test motor parameters

Parameter	Value
L_S	0.1459H
L_R	0.1490H
L_m	0.1410H
R_S	1.37 Ω
R_R	1.1 Ω
T_e	26.5Nm
J	0.1(kg.N/m)
P	2
U	240(V)
Flux Reference	0.9889Wb

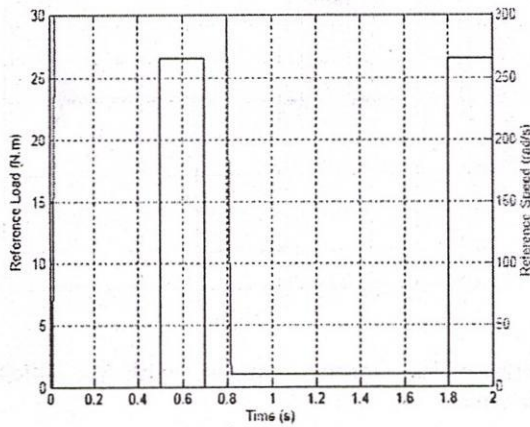


Figure 3. Reference load and speed

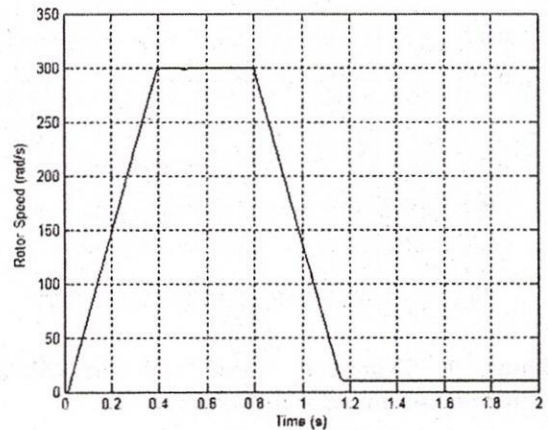


Figure 4. Rotor speed with the open-loop estimation scheme.

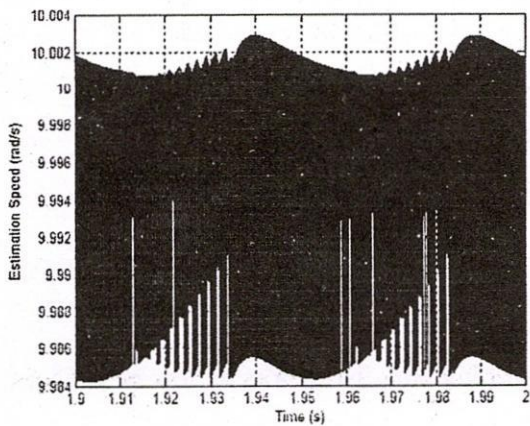


Figure 5. Estimated Speed with the open-loop estimation scheme at stable state (Zoom F.4).

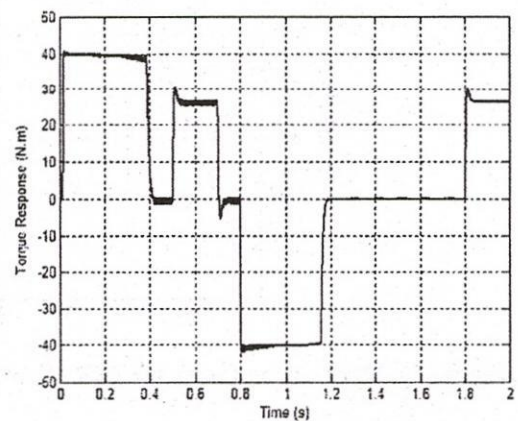


Figure 6. Torque response with the open-loop estimation scheme

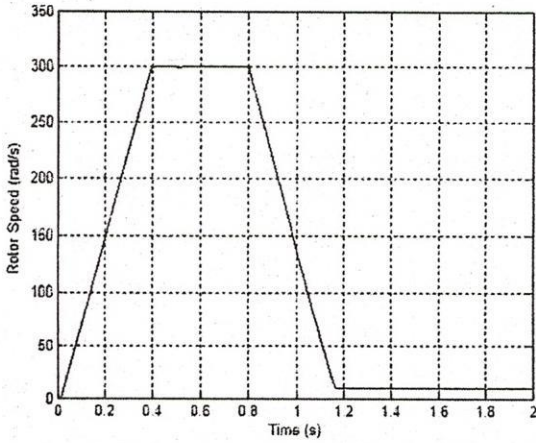


Figure 7. Rotor speed with the MRAS estimation scheme

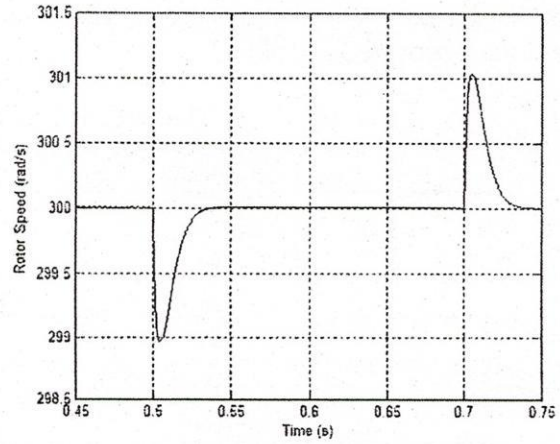


Figure 8. Transient of rotor speed when add and remove load at high-speed

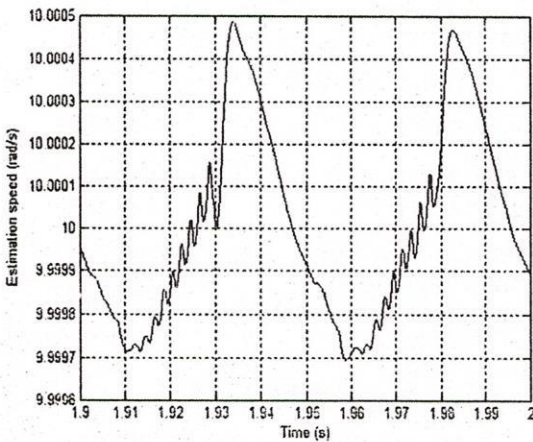


Figure 9. Estimation Speed with the MRAS estimation scheme at stability state.

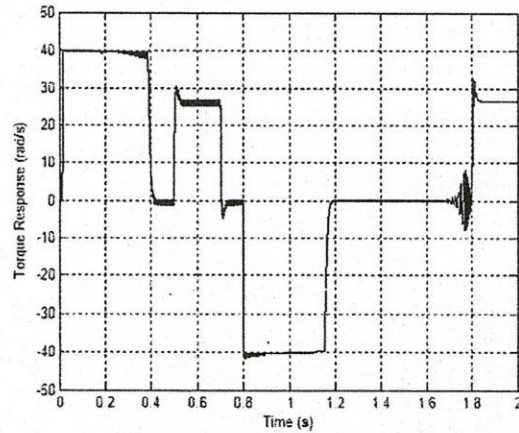


Figure 10. Torque response with the MRAS scheme.

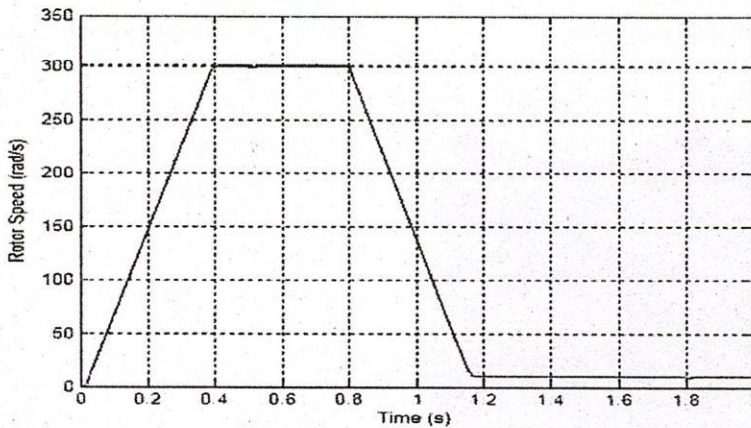


Figure 11. Rotor speed with the MRAS when replacing pure integrators by low-pass filters.

6. CONCLUSION

From the result above, the advantage and disadvantage between two schemes have been analysed. Both open-loop and closed-loop scheme have good speed responses during loading or

unloading, even at the low speed. The electromagnetic torque has fast responses because of the advantage of DTC technique (figure 6 and figure 10).

It is significant that the closed-loop scheme is more accurate than the open-loop one due to the presence of the PI controller in the closed-loop system that balances the ripples of rotor speed.

One of the concerned problems is the switching frequency, the open-loop system requires higher switching frequency than closed-loop scheme because of the lack of the PI controller (figure 5 and figure 9). This can be solved by using a Butterworth filter or other low-pass filter.

Both open and closed-loop schemes rely on the stability of machine parameters for a high accuracy. Although the closed-loop estimator is sensitive to parameter fluctuation, it is still affected by the variation of stator resistance due to thermal effect. To solve this problem, a thermal model of induction machine should be concerned.

By replacing the pure integrator in the MRAS scheme with a low-pass filter, the practical implementation will be more effective because of the elimination of DC drift and saturation problems (figure 11).

ƯỚC LƯỢNG VẬN TỐC ĐỘNG CƠ KHÔNG DỪNG CẢM BIẾN TRONG HỆ THỐNG ĐIỀU KHIỂN TRỰC TIẾP MOMENT

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TÓM TẮT: Bài báo trình bày các phương pháp ước lượng vận tốc dừng trong điều khiển trực tiếp moment (DTC) của động cơ không đồng bộ. Hai nhóm phương pháp chủ yếu được dùng là phương pháp ước lượng vận tốc mạch hở và phương pháp ước lượng vận tốc mạch hồi tiếp. Điều khiển thích ứng mô hình được dùng trong phương pháp ước lượng vận tốc mạch hồi tiếp. Điều khiển thích ứng mô hình cho phép giảm tối thiểu ảnh hưởng của sai số cũng như sự dao động của các giá trị tham số động cơ lên kết quả ước lượng vận tốc. Các kết quả mô phỏng của hai phương pháp trên sẽ được so sánh. Để kết quả mô phỏng bám sát thực tế, các mạch tích phân trong bộ điều khiển sẽ được thay thế bởi các mạch lọc tần số thấp trong các mô phỏng.

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