1. Introduction

Induction motor (IM) enjoys many advantages over DC motor, including better power to weight ratio, lower inertia and costs (fewer maintenance requirements). Unfortunately, IM has a nonlinear and a highly interactive multivariable control structure which presents an involved control task. However, the dynamic behaviour of IM can be viewed in a manner analogous to DC motor provided the machine is modelled in an appropriate manner and decoupled control of torque and flux current components can then be achieved. Such control is termed vector or field-oriented control, and its implementation allows the IM to develop dynamic operating characteristics comparable to a DC motor.

With vector control, the object is to control IM in the same way as DC motor, and thus obtain their good dynamic response. DC machines essentially have stationary and orthogonal field and armature fluxes. Vector controllers develop similar flux components in a rotating 2-axis (α-q) coordinate system. These two components maintain orthogonality and are controlled independently in all situations by control of their corresponding stator current components.

To realise such control, a mathematical transformation is used to represent the 3-phase stator currents in an equivalent rotating 2-axis co-ordinate system. In 3-phase form, the stator currents (i₀, i₁, i₂) are stationary in space with directions defined by the stator windings along α - β - c axes. Once in space phasor form, it is convenient for IM analysis to express the phasor in terms of 2-axes rather than the original 3. A stationary 2-axis reference frame is represented by windings α and β. In rotating 2-axes form, the stator currents are resolved into direct (d) and quadrature (q) axis components with the d-axis fixed to the machine flux (Fig. 1). Hence the d - q axes rotate in space at synchronous speed.

Fig. 1 Stator current vector iₛ, a its components in stationary (α - β) and in rotating (d - q) 2-axes reference frame

With stator currents in d - q form, the torque expression of the IM is analogous to that of the DC machine. For the DC
machine, the torque $M = I_f I_q$; where the field current $I_f$ can be held constant, and the armature current $I_q$ is used to control machine torque. For IM, $M = I_d I_q$; where $I_d$ corresponds to field current $I_f$, and the $q$-axis current $I_q$ corresponds to armature current $I_a$. Control of $I_d$ and $I_q$ therefore allows DC machine performance to be obtained from induction machines.

The transformation from stationary ($\alpha - \beta$) reference frame to synchronously rotating ($d - q$) reference frame (and the inverse from $d - q$ to $\alpha - \beta$) requires the instantaneous angular position $\theta_s$ of the machine flux (hence the $d$-axis) with respect to the reference stator winding.

It is difficult to detect motor flux and, therefore, it is usually calculated in a mathematical model from measured stator currents and rotor speed. In such a case, the IM must be equipped with a speed sensor.

However, speed or position sensor still represents a considerable part of the total costs of the electrical drive. Moreover, the robustness of the system is also reduced by this sensor. In a large majority of industrial applications, inverter-fed AC drives with standard IM are used. These drives operate with a simple open-loop control and don’t require any mechanical sensor. However, they are only suitable for applications demanding low dynamic performance.

2. Principle of NFO

The basics of Natural Field Orientation (NFO) were firstly introduced by Ragnar Jönsson from Sweden and patented as “Method and apparatus for controlling an AC induction motor by indirect measurement of the air gap voltage” in 1994.

NFO is based on the same elementary theory and ideas as vector control. However, the problem of keeping track of the magnetic field position has been solved in a “natural” way. The control system does not try to measure or estimate the magnetic field. Instead, it assumes that the motor will generate a proper magnetic field as long as it gets correct control signals. The main assumption for getting correct control is to maintain magnetic flux constant. If this simple requirement is fulfilled there will always be correct field orientation.

A simple equation for induced (or back-emf) voltage can be obtained from modified equivalent IM’s circuit[1]: $U_i = j\omega L_m I_m$ (evident DC machine analogy). It is obvious that the quotient $U_i/\omega_s$ should be kept constant because this will keep the amplitude of $I_m$ constant, too. This condition is satisfied by estimating voltage $U_i$ and making the frequency $\omega_s$ proportional to $U_i$. Motor flux angular position is then achieved by $\omega_s$ integration. This knowledge is the basis for NFO control. The simplified NFO control scheme is shown in Fig. 2.

![Fig. 2 Simplified NFO Control scheme](image-url)

The induced voltage $U_i$ cannot be measured directly because it exists inside the motor. But it is possible to measure the terminal voltage $U_S$ and the stator current $I_S$ and then calculate $U_i$ according to Ohm’s law. This is made in the stator-fixed ($\alpha - \beta$) coordinates. The results of the measuring and calculation are a rotating vector of induced voltage $U_i$, which is immediately transformed to field coordinates ($d - q$). In the field coordinates the induced voltage components $U_{id}$ and $U_{iq}$ are DC voltages. For the calculation of synchronous speed $\omega_s$, only quadrature component $U_{iq}$ is used because $U_{id}$ should be zero if the parameters of the motor model are set correctly (see diagram on Fig. 3).
3. Induction motor model

An induction motor, under simplifying assumptions, may be described by a set of non-linear equations. In our case, it is suitable to use the equations in the rotor-flux reference frame ($d$-$q$).

The rotor flux reference frame rotates at speed $\omega_s$ (and angle $\theta_s$) with respect to the stator reference, and the $d$-axis is fixed to the rotor flux space phasor $\Psi_R$. Then $\Psi_R$ must be zero, and

$$-R = \Psi_{Rd} + j\Psi_{Rq} = \Psi_{Rd}$$

(1)

The equivalent rotor magnetising current $i_{mm}$ is defined as [1]

$$i_{mm} = i_S + \frac{L_R}{L_m} i_R = \Psi_{Rd} \frac{L_R}{L_m}$$

(2)

according to the modified equivalent circuit of IM (Fig. 4). Space relations between the quantities of the equivalent circuit are shown in Fig.3.

Then the IM’s voltage equations in the rotor flux reference frame can be written as

$$u_{Sd} = R_S i_{Sd} + \sigma L_S \frac{di_{Sd}}{dt} - \omega_s \sigma L_S i_{Sq} + (1 - \sigma) L_S \frac{di_{mm}}{dt}$$

(3)

$$u_{Sq} = R_S i_{Sq} + \sigma L_S \frac{di_{Sq}}{dt} + \omega_s \sigma L_S i_{Sd} + (1 - \sigma) L_S \omega_s i_{mm}$$

(4)

$$0 = \frac{R_S}{L_R} L_m (i_{mm} - i_{Sd}) + L_m \frac{di_{mm}}{dt}$$

(5)

$$0 = -\frac{R_S}{L_R} i_{Sd} + (\omega_s - \omega) L_m i_{mm}$$

(6)

The developed electromagnetic torque of IM with $p_p$ poles pairs is given by

$$m_i = \frac{L_m}{L_R} p_p \Psi_{Rd} i_{Sq}$$

(7)

The following equations for back-emf voltage $U_i$ can be written

$$u_{Sd} = u_{Sd} - R_S i_{Sd} - \sigma L_S \frac{di_{Sd}}{dt} + \omega_s \sigma L_S i_{Sq}$$

(8)

$$u_{Sq} = u_{Sq} - R_S i_{Sq} - \sigma L_S \frac{di_{Sq}}{dt} - \omega_s \sigma L_S i_{Sd}$$

(9)

Comparing eq.(3, 4) and (8, 9) gives (with simplified assumption: $i_{mm}$ const, $\sigma = 0$) expression for stator frequency calculation

$$\omega_s = \frac{u_{Sq} - R_S i_{Sd}}{(1 - \sigma) L_S i_{mm}} = \frac{u_{Sq} - R_S i_{Sd}}{L_S' i_{mm}}$$

(10)

For rotor speed, with using eq. 5, 6 and 10, it can be written

$$\omega = \frac{u_{Sq} - R_S i_{Sd}}{L_S' i_{mm}}$$

(11)

The block scheme shown in Fig. 2 represents the NFO computing core executing the rotor speed $\omega$ and the rotor flux position $\theta$, calculation. This scheme uses measured stator currents and voltages ($i_{Sd}$, $i_{Sq}$, $u_{Sd}$, $u_{Sq}$) in stator reference frame and $q$-component of stator current in rotor flux reference frame and magnetising current $i_{mm}$ from a superior control system as input values.

4. Speed control with estimated speed signal

The rotor speed and motor flux angular position are estimated using the NFO computing core, and it is introduced into a standard rotor field oriented control system with induction machine.
Feedback magnetising current signal \( i_{mR} \) is estimated using equation (5). PI controllers are used for speed and currents control loops.

The electrical signals serving as input to the NFO Control in Fig. 6 are the stator voltages and currents as represented by the orthogonal set \( u_{S1}, u_{S2}, i_{S1}, i_{S2} \) of AC quantities. The flux is set as a reference quantity \( \phi^* \), that may be subject to change for field weakening.

Executing the integration of \( \phi \) (to get flux angle) in field coordinates reduces the effect of integrator drift at low stator frequency to a normal offset that is common with analogue signal processing.

5. Simulation Results & Conclusions

The proposed algorithm was verified by computer simulation (MATLAB/Simulink) and it was found to perform well in both transient and steady states.

For the simulation the MATLAB/Simulink software was used. The parameters of induction motor were: \( P_n = 4 \text{ kW}, U_n = 220 \text{ V}, I_n = 9.2 \text{ A}, R_S = 1.25 \Omega, R_R = 1.32 \Omega, L_S = L_R = 0.136 \text{ H}, L_m = 0.12 \text{ H}, M_m = 40 \text{ Nm}, p = 3, n_n = 960 \text{ rpm} \).

In Fig. 7 starting, reversing and loading transients for 4 kW IM are presented.

![Fig. 5 NFO Computing Core](image)

![Fig. 6 Proposed scheme for speed-sensorless control of IM based on NFO algorithm](image)
The $U_d$ deviation from zero value (see the 3-rd graph in Fig. 7) can be integrated with a relatively long time constant and used as a compensating signal for the stator resistance parameter in motor model.

The basic NFO Control version used for simulation in this paper may be augmented in various ways for attaining still higher levels of accuracy and performance.

6. Proposed experimental structure

The aims of the next steps will include the finishing brand new 3-phase IGBT inverter.

For this purpose the integrated intelligent IGBT module MiniSkip 82AC06 and IGBT driver SKH160 Semidriver manufactured by SEMIKRON. Stator currents measuring is done by LEM LTS 25-NP. The information of the stator voltages can be obtained by measuring (voltage transformers, LEM LV 25-P) or by reconstruction from the sensed pulses width of PWM voltage on the terminals (TTL signal) and measured DC-link voltage UD.

NFO Control algorithm will be implemented firstly using NFO Controller DemoBoard (based on INTEL87C196MC) - see Fig. 8 - and then using Texas Instruments DSP TMS320F240.

References

[3] JÖNSSON, R. - LEONHARD, W.: Control of induction motor without a Mechanical sensor based on the principle of Natural Field Orientation, IPEC ’95, April 1995, Yokohama

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Fig. 8 Proposed experimental workstation