

Indirect rotor field oriented control strategy for single phase induction motor drives

Abstract. This paper discusses the indirect field oriented control strategy for single-phase induction motor (SPIM) drives. The suggested model is implemented using relatively simple and effective decoupling scheme to compute the control algorithm. Due to the natural asymmetry of the single-phase induction motor some transformations are carried out. Firstly the mutual inductances are employed to define a transformation for the stator variables. Secondly the time dependent resistance terms in the stator equations are neglected. Therefore, the model asymmetries are eliminated and the implementation of the vector control in SPIMs becomes a practical task. The proposed indirect rotor field oriented control system is applied to a 1.1kw SPIM and its performance is evaluated by digital simulation.

Streszczenie. W artykule przedstawiono sterowanie polowo-zorientowane pośrednie jednofazowego silnika indukcyjnego. Opisano sposób eliminacji asymetrii modelu silnika poprzez wykorzystanie indukcyjności wzajemnej do transformacji zmiennych stojana oraz pominięcie składników rezystancji zależnych od czasu. Daje to możliwość implementacji sterowania wektorowego w maszynie indukcyjnej jednofazowej. (Sterowanie polowe pośrednie zorientowane względem wirnika dla jednofazowego silnika indukcyjnego).

Keywords: single-phase induction motor, field oriented control, decoupling system.

Słowa kluczowe: jednofazowy silnik indukcyjny, sterowanie polowo-zorientowane, odsprężanie.

Introduction

Single-phase motors are widely used in home and industrial appliances. The main advantage of these motors is their ability to operate from a single-phase power supply. Therefore, they can be used wherever a single-phase power is available. There are also other aspects for their popularity: low manufacturing cost, reliability, and simplicity. However, compared with three-phase systems, they offer lower efficiency. In many applications it may be desirable to change the speed of the motor e.g. if we want to control the air-flow of a ventilator. Then it is useful to use some techniques for varying a.c. induction motor speed.

In literature, Different static converter topologies to supply the single-phase induction machine have been used in [1-12]. Many papers have proposed the vector control strategy to improve the performance of a single phase induction motor [1,7,8,9,10,11,13].

In this paper the analysis of the indirect field oriented control strategy for single-phase motor drives is presented. However, winding asymmetry in SPIMs causes extra coupling between two stator windings and results in unbalanced machine operation and produces current and torque pulsations and limits SPIM drive applications [12]. Therefore, in order to derive the symmetrical model some transformations are carried out. In a first step, the mutual inductances are employed to define a transformation for the stator variables. Then in a second step, the time dependent resistance terms in the stator equations are neglected. The proposed indirect rotor field oriented control system is applied to a 1.1 kw SPIM and its performance is evaluated by digital simulation.

Mathematical model of the single phase induction machine

Neglecting the core saturation, the dynamic model of single phase induction machines in a stationary reference frame can be represented as [14]:

$$(1) \quad \frac{d\psi_{sd}}{dt} = -R_s i_{sd} + U_{sd}$$

$$(2) \quad \frac{d\psi_{sq}}{dt} = -R_s i_{sq} + U_{sq}$$

$$(3) \quad 0 = R_r i_{rd} + \frac{d\psi_{rd}}{dt} + \omega_m \psi_{rq}$$

$$(4) \quad 0 = R_r i_{rq} + \frac{d\psi_{rq}}{dt} - \omega_m \psi_{rd}$$

The fluxes are related to the currents by the following equations:

$$(5) \quad \psi_{sd} = L_{sd} i_{sd} + M_{srd} i_{rd}$$

$$(6) \quad \psi_{sq} = L_{sq} i_{sq} + M_{srq} i_{rq}$$

$$(7) \quad \psi_{rd} = L_r i_{rd} + M_{srd} i_{sd}$$

$$(8) \quad \psi_{rq} = L_r i_{rq} + M_{srq} i_{sq}$$

The electromagnetic torque is given by:

$$(9) \quad T_{em} = P (M_{srq} i_{sq} i_{rd} - M_{srd} i_{sd} i_{rq})$$

The mechanical equation is :

$$(10) \quad J \frac{d\omega_m}{dt} = P (T_{em} - T_r) - F \omega_m$$

These equations were derived as for an asymmetric two-phase machine [14]. In these equations, variables U_{sd} , U_{sq} , i_{sd} , i_{sq} , i_{rd} , i_{rq} , ψ_{sd} , ψ_{sq} , ψ_{rd} , ψ_{rq} are auxiliary and main voltages, currents and fluxes of the stator and rotor in the stationary reference frame respectively. R_{sd} , R_{sq} and R_r denote the stator and rotor resistances; L_{sd} , L_{sq} , L_r , M_{srd} , and M_{srq} denote the stator, the rotor self, and mutual inductances. ω_m , T_{em} , and T_r are the machine speed, the electromagnetic torque, and the load torque, in this order; and P , J and F are the machine pole pairs, the moment of inertia, and viscous friction coefficient, respectively.

Note that (1)–(9) are general equations for the two-phase machine. It is seen that there is an asymmetry in the model. This asymmetry is due to the unequal resistances and inductances of the main and auxiliary windings. Since the machine studied is asymmetrical, it can be seen from (9) that the machine produces torque and current oscillations. Some asymmetries of the model can be eliminated using a transformation as presented in [14]:

$$U'_{sq} = \frac{N_{sd}}{N_{sq}} U_{sq}, \psi'_{sq} = \frac{N_{sd}}{N_{sq}} \psi_{sq}, i'_{sq} = \frac{N_{sq}}{N_{sd}} i_{sq}, U'_{rd} = \frac{N_{sd}}{N_r} U_{rd},$$

$$\psi'_{dr} = \frac{N_{sd}}{N_r} \psi_{rd}, i'_{rd} = \frac{N_r}{N_{sd}} i_{rd}, U'_{rq} = \frac{N_{sd}}{N_r} U_{rq}, \psi'_{rq} = \frac{N_{sd}}{N_r} \psi_{rq},$$

$$i'_{rq} = \frac{N_r}{N_{sd}} i_{rq}, \quad R'_{sq} = \left(\frac{N_{sd}}{N_{sq}} \right)^2 R_{sq}, \quad R'_r = \left(\frac{N_{rd}}{N_r} \right)^2 R_r,$$

$$L'_{sq} = \frac{N_{sd}}{N_{sq}} L_{sq}, \quad L'_r = \left(\frac{N_{sd}}{N_r} \right)^2 L_r,$$

In these equations N_{sd} , N_{sq} and N_r represent the number of stator and rotor windings respectively then the ratio M_{srd}/M_{srq} will be approximately equal to N_{sd}/N_{sq} . Thus, the transformation employed corresponds approximately to refer the auxiliary winding variables to the main winding[1,9]. In the above equations if the stator inductances are slightly different it can be shown that $L_{sd} \approx L_{sq}$ [1]. Thus the asymmetry in the flux equations (5) and (6) will be eliminated. Using (1) to (9) equations, the dynamic model of single phase induction machines in a synchronously rotating reference frame can be described by the following equations:

$$(11) \quad \frac{d\psi'_{sd}}{dt} = \omega \psi'_{sq} - R_{sdd} i'_{sd} - R_{sdq} i'_{sq} + U_d$$

$$(12) \quad \frac{d\psi'_{sq}}{dt} = -\omega \psi'_{sd} - R_{sqd} i'_{sd} - R_{sqq} i'_{sq} + U_q$$

$$(13) \quad \frac{d\psi'_{rd}}{dt} = \omega_{sr} \psi'_{rq} - R'_r i'_{rd}$$

$$(14) \quad \frac{d\psi'_{rq}}{dt} = -\omega_{sr} \psi'_{rd} - R'_r i'_{rq}$$

$$(15) \quad \psi'_{sd} = L_{sd} i'_{sd} + M_{srd} i'_{rd}$$

$$(16) \quad \psi'_{sq} = L_{sq} i'_{sq} + M_{srd} i'_{rq}$$

$$(17) \quad \psi'_{rd} = L'_r i'_{rd} + M_{srd} i'_{sd}$$

$$(18) \quad \psi'_{rq} = L'_r i'_{rq} + M_{srd} i'_{sq}$$

$$(19) \quad T_{em} = \frac{P}{L_r} M_{srd} (i'_{sq} \psi'_{rd} - i'_{sd} \psi'_{rq})$$

From equations (11) and (12) it must be noted that the stator voltages U_{sd} and U_{sq} contain time dependent resistance terms, R_{sqd} , R_{sdd} , R_{sqd} and R_{sdq} due to unequal resistances of stator main and auxiliary windings. In fact, the relations between the stator resistances are presented as[15]:

$$(20) \quad R_{sqd} = \frac{R_{sd} + R_{sq}}{2} - \frac{R_{sd} - R_{sq}}{2} \cos(2\theta_{rf})$$

$$(21) \quad R_{sdd} = \frac{R_{sd} + R_{sq}}{2} + \frac{R_{sd} - R_{sq}}{2} \cos(2\theta_{rf})$$

$$(22) \quad R_{sdq} = R_{sqd} = \frac{R_{sd} - R_{sq}}{2} \sin(2\theta_{rf})$$

Also, if the magnitude of the variable terms in (20)-(22) are small with respect to the constant terms, it may be possible to neglect the difference of stator windings. Consequently the model (11)-(19) is very useful for further vector applications.

Indirect field oriented control

For indirect rotor flux oriented control, the d-axis of the reference frame is oriented along the rotor flux vector which is set be equal to the rated flux, and, consequently, $\psi'_{dr} = \psi_r$ and $\psi'_{qr} = 0$. After arranging the equations (11) to (19), the new mathematical model of single phase induction motor

can be represented according to the usual d axis and q axis components in a synchronously rotating rotor flux reference frame as:

$$(23) \quad \frac{M_{srd}}{\tau_r} i'_{sd} = \frac{\psi_r}{\tau_r} + \frac{d\psi_r}{dt}$$

$$(24) \quad \frac{M_{srd}}{\tau_r} i'_{sq} = \omega_{sr} \psi_r$$

$$(25) \quad T_{em} = \frac{P}{L_r} M_{srd} (i'_{sq} \psi_r)$$

Where ψ_r is the rotor-flux magnitude, $\omega_{sr} = \omega - \omega_m$ is the slip frequency, $\omega = d\theta_r/dt$ and θ_r are respectively the frequency and the position of the rotor-flux vector.

Expression (25) shows that, if rotor flux is kept constant, i'_{sd} can be used to control the flux magnitude and i'_{sq} can be used to control the electromagnetic torque.

Decoupling system

In field oriented control of SPIMs, like three phase motors, the stator currents must be controlled. If the employed inverter is of PWM type with voltage control, the voltage command signals should be produced as the outputs of the current controllers. Since it is necessary to calculate the voltage command for a voltage-source inverter, the stator voltage equations for rotor flux control can be derived by (11), (12), (15), (16), (17) and (18):

$$(26) \quad U_{sd} = R_{sdd} i'_{sd} + \sigma_d L_{sd} \frac{di'_{sd}}{dt} - \sigma_q L_{sq} \omega i'_{sq} + \frac{M_{srd}}{L_r} \frac{d\psi_r}{dt}$$

$$(27) \quad U'_{sq} = R_{sqd} i'_{sq} + \sigma_q L_{sq} \frac{di'_{sq}}{dt} + \sigma_d L_{sd} \omega i'_{sd} + \frac{M_{srd}}{L_r} \omega \psi_r$$

In these equations $\sigma_d = 1 - M_{srd}^2 / (L_r L_{sd})$ and $\sigma_q = 1 - M_{srd}^2 / (L_r L_{sq})$. E_d and E_q represent the decoupling terms and are given by

$$(28) \quad E_d = \sigma_q L_{sq} \omega i'_{sq}$$

$$(29) \quad E_q = -\sigma_d L_{sd} \omega i'_{sd} - \frac{M_{srd}}{L_r} \omega \psi_r$$

Thus, the dynamics of the d axis and q axis currents are now represented by simple linear first order differential equations. Therefore, it is possible to effectively control the currents with a PI controller. Fig. 1 shows the block diagram of the indirect rotor-field-oriented control scheme, which has been adapted for the single-phase machine. In this diagram T_{em}^* and ψ_r^* represent the reference electromagnetic torque and amplitude of the rotor flux, respectively. Block $e^{j\theta_r}$ performs the coordinate transformation from the reference frame aligned along with the rotor-flux vector to the stationary reference frame. Blocks *PI control* represent the speed controller, d and q-axis current controller respectively. It is seen that the two current controllers provide control voltages U_d and U_q . These voltages are supplemented by decoupling voltages E_d and E_q respectively to produce voltage commands. Block *PWM INVERTER* and *SPIM* represent the voltage-source inverter, and the single phase induction machine.

Simulation results

Validation of the proposed control schemes for Single-Phase Induction machine was performed by simulation in order to evaluate the performance of the control strategy. Selected results are presented in Figs. 2-4. The parameters of the used machine model are given in Table 1.

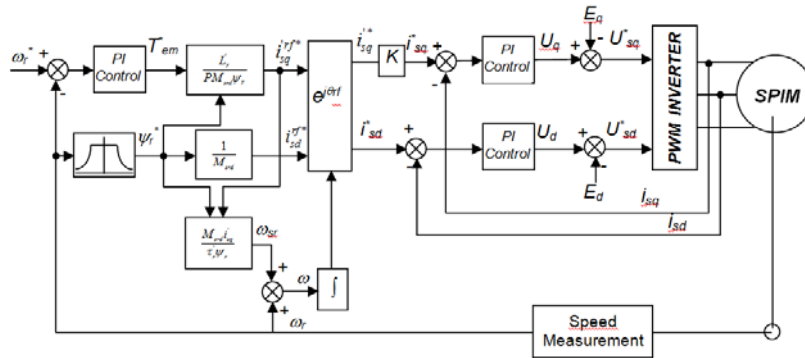


Fig.1. Block diagram of the indirect rotor flux control system

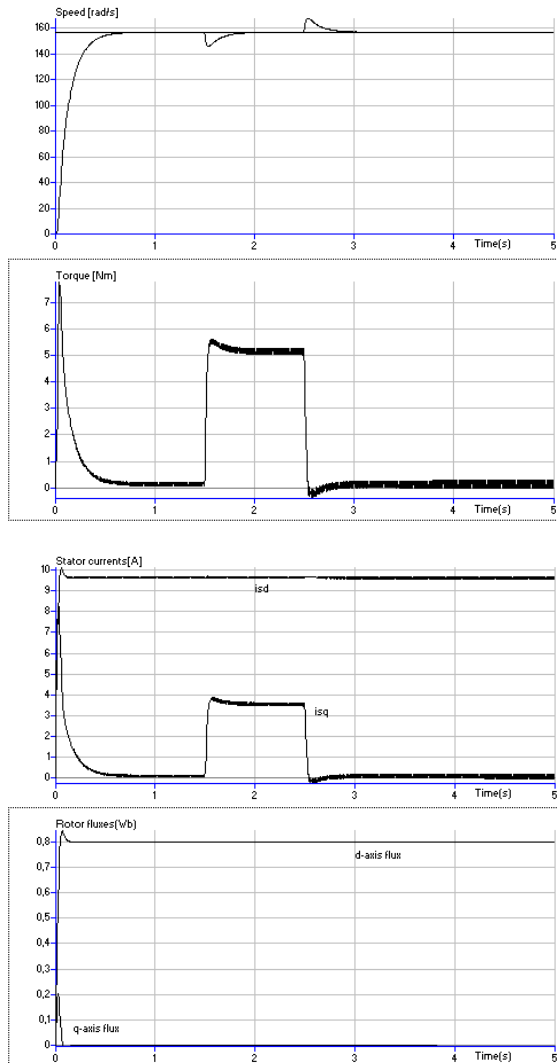


Fig.2. Simulation of the dynamic behavior of the system

Simulations of Fig.2 correspond to the response of the system to a step in the speed reference from 0 to 157 rad/s and to a step of torque equal 5 Nm between $t=1.5s$ and $t=2.5s$. Fig. 2a display the speed response showing that the system tracks the reference speed reasonably well. Fig. 2b shows the electromagnetic torque T_{em} . In the simulation of Fig. 2c d-axis and q-axis currents are presented. It can be noted from Figs. 2b and c that the q-axis current i_{sq} is the same shape as the electromagnetic torque and the d-axis current i_{sd} is similar to that of the rotor flux ψ_{rd} . It is clear from Fig.2d that the rotor flux is aligned with the d axis

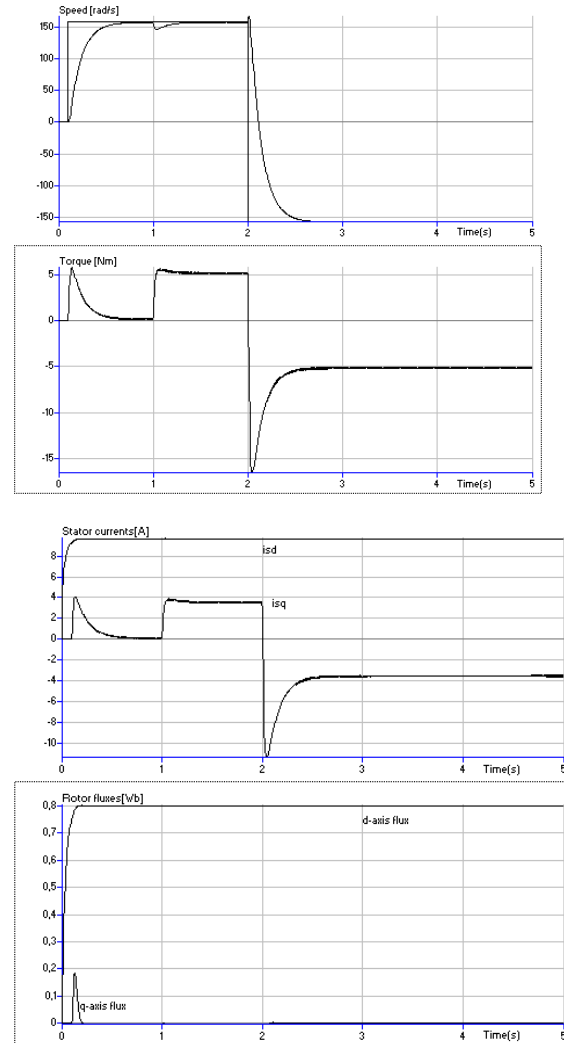


Fig.3. Simulation of the dynamic behavior of the system for reversing speed reference from 157 rad/s to -157 rad/s

($\psi_{rd}=\psi_r=0.8Wb$) while the q axis rotor flux remains null ($\psi_{rq}=0$). These results reveal that the decoupling between rotor flux and the torque is achieved.

Simulations of Fig3 correspond to the response of system for the reference and actual rotor speed, when the speed command changes from 0 to 157 rad/s in forward rotation and then changes to reverse direction of the same speed with load torque equal 5 Nm applied at 1s. It is shown that the drive can successfully reverse the speed almost accurately and quickly.

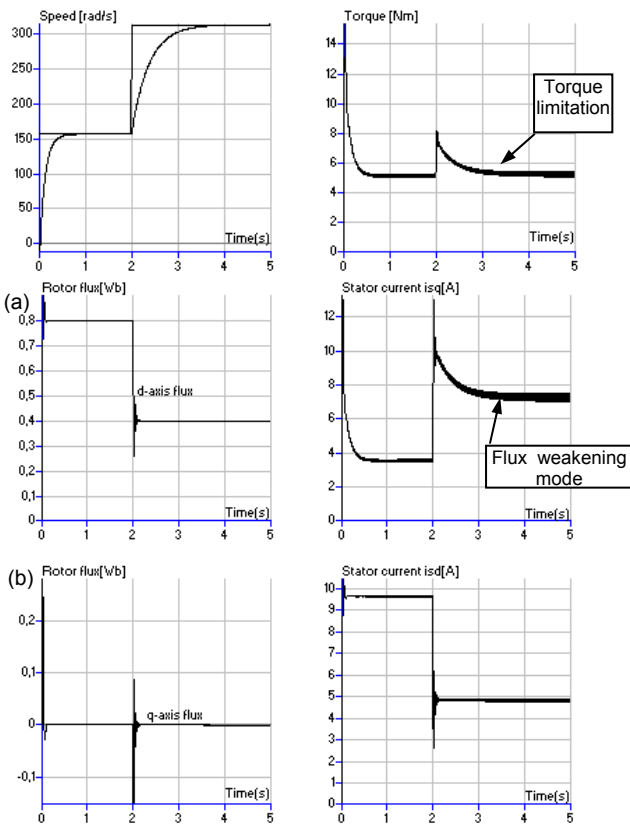


Fig.4. Simulation of the dynamic behavior of the system in the field (c) akening range

The Simulation test of Fig4 was done to check the behaviour of system in the field weakening range. The reference speed was set as steps, at a load torque of 5Nm. A first step is done to 157rad/s, followed by a step to 314rad/s, like presented in Fig.4. As shown in the plot the speed of the motor follows with very good accuracy the imposed speed.

After the motor stabilizes at 157rad/s, 5 Nm, at time $t=0.2s$, a second step of 157rad/s is applied. As it can be seen in Fig.4.c, when the motor starts accelerating, the i_{sd} current decreases, and is immediately limited at the value of 4.8A. i_{sq} current is kept for a short time also at the maximum value of 12.9A. At this point the motor is providing the maximum torque.

The motor goes into field weakening when the q-axis current starts to decrease, as it presented in Fig.4.b at $t=2.1s$. The acceleration torque cannot be kept at the maximum value and is decreasing as it can be observed on the torque curve in Fig.4.a. When the speed reaches the set value, at 314rad/s, the motor reaches a steady-state point in field weakening, at a load of 5Nm at $t=3.4s$.

Finally, It is obvious from Figs. 2-4 that the dynamic performance of the system is very satisfactory.

Table 1. The parameters of single phase induction machine

Machine ratings	Machine parameters	
Power:1.1kW	$R_{sd}=2.4\Omega$	$M_{srd}=0.0829H$
Voltage:230V	$R_{sq}=5.66\Omega$	$M_{srq}=0.0990H$
Current:7.6A	$R_r=6.161\Omega$	$J=5.83 \cdot 10^{-3} Kg \cdot m^2$
Frequency:50Hz	$L_{sd}=0.0909H$	$f=2.02 \cdot 10^{-4} N \cdot m \cdot s \cdot rad^{-1}$
Speed:1430 rpm	$L_{sq}=0.1150H$	
Number of pole pairs:2	$L_r=0.0915H$	

Conclusion

This paper investigated the indirect rotor field oriented control strategy for single phase induction motor drive system. In this type of machine winding asymmetry causes

extra coupling between two stator windings and results in unbalanced machine operation and produces current and torque pulsations and limits SPIM drive applications. Some transformations were carried out in order to overcome this problem. Therefore, some simulation work has been performed on a 1.1kW single phase induction motor in order to check the validity of the implementation of Indirect Rotor-Flux-Oriented Control strategy. Finally, the Simulation results presented show the effectiveness of the control systems at nominal and high speed. The next stage of this work is the experimental validation in order to checking the analytical results obtained.

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Authors: prof. Dr Chams-eddine Feraga. Electrical Engineering Department of Guelma University, Guelma, BP401, 24000, Algeria, e-mail: chferaga@yahoo.fr. Dr Abdallah Bouldjedri. Electrical Engineering Department of Annaba University, Algeria, e-mail: abji67@yahoo.fr.