Speed control of Single-Phase induction motor Using Field Oriented Control

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Abstract— This paper discusses the performance of a single-phase induction motor drive under nominal load in a closed-loop vector-controlled system. The control strategy to be applied is known as indirect field oriented control. Single-phase induction motor when operating as two-phase motor has its dynamic performance increased. By applying this methods, an induction machine can be analyze and operate similar to the dc machine as this method provides the decoupling effect to the motor. By controlling the d-axis and q-axis current, the speed and torque of the single-phase induction motor can be controlled independently. With the use of a voltage-source inverter, space vector pulse width modulation can be implemented.

Index Terms—Indirect field oriented control, induction motor, single-phase induction motor, motor drive, vector control, Speed control.

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1 INTRODUCTION

Traditionally in fractional and sub-fractional horse power applications, the single-phase induction motor (SPIM) is usually found in several home, office, shopping, farm, and industry appliances such as air conditioning systems, mixers, washers, blowers, compressors, fans, vacuum cleaners, pumps, etc. 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 source is available. There are also other aspects for their popularity: low manufacturing cost, 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 induction motor (IM) speed.

Different inverter topologies for single-phase induction motor drive have been proposed. Commonly, three types of topologies are studied: two-leg, three-leg and four-leg two-phase inverters [4], [5].

The first topology is known as H-bridge voltage inverter with two-legs and a mid-point provide by a capacitive divider. The second is composed of three-legs with the mid-point provided by the common leg. The third possibility has the greatest number of switches, so the losses of the system are increased.

The application of power electronic inverters, along with pulse width modulation (PWM), increased the performance of single-phase induction motors. The most widely use PWM techniques are sinusoidal PWM and space vector PWM. In [7], [8] and [9] some PWM strategies are discussed when applied to a single-phase induction motor drive.

The purpose of this paper is to examine the operation of a single-phase induction motor when operated from a variable frequency power supply under load condition.

There is no doubt that most single-phase induction motors (split-phase, capacitor-start, capacitor-run and capacitor-start capacitor-run) usually have a main and auxiliary stator winding asymmetrical and displaced 90 degrees apart from each other. These papers use the dq model to derive the motor

equations and treat the single-phase induction motor, without startup and running capacitor, as an asymmetrical two-phase induction motor.

The performance of a single-phase induction motor drive under field oriented control has been analyzed in [1], [2] and [3]. The control method to be applied is the indirect field oriented control (IFOC).

2 MATHEMATICAL MODEL OF THE SINGLE PHASE INDUCTION MACHINE

The derivation of the motor model is based on classical assumptions: linearity of the magnetic circuit, constant air-gap length and the motor windings produce sinusoidal distribution of magnetic field in the air-gap.

Figure (1) shows the layout of the motor under study. The stator windings are unsymmetrical but they are orthogonal with a 90 electrical degree phase shift, and thus they are assumed to represent the d-q axis. Stationary reference frame is considered to facilitate the inclusion of the power inverter.
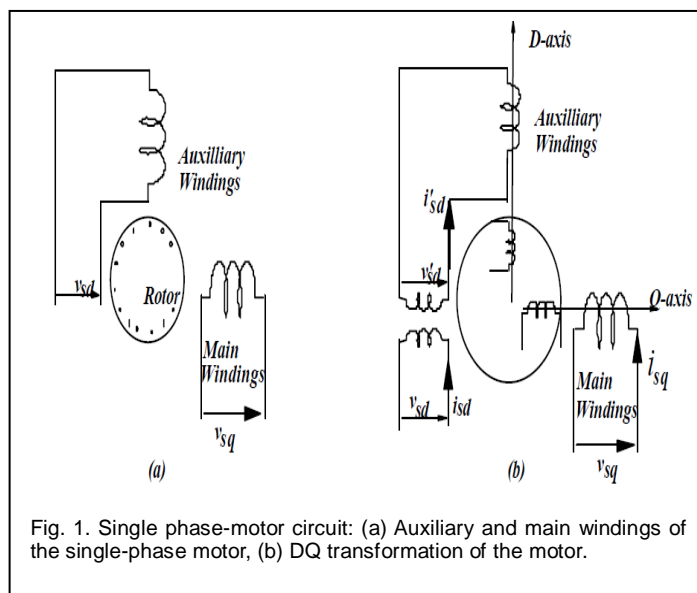

Fig. 1. Single phase-motor circuit: (a) Auxiliary and main windings of the single-phase motor, (b) DQ transformation of the motor.

The rotor has a squirrel cage winding and is represented by equivalent two coils transformed to the d-q axis as shown in Fig 1.b. Since the two stator windings; namely, the main and auxiliary coils, have different numbers of turns, they will yield different mutual reactances.

Consistent with these assumptions the dynamic model of the single-phase induction motor is derived following the approach presented in [6], which describe an asymmetric single-phase induction machine in the stationary reference frame.

2.1 In a stationary reference frame:

Neglecting the core saturation, the dynamic model of single phase induction machines in a stationary reference frame can be represented as [6]:

$$\frac{d\psi_{Sd}}{dt} = -R_{Sd} * I_{Sd} + V_{sd} \tag{1}$$

$$\frac{d\psi_{Sq}}{dt} = -R_{Sq} * I_{Sq} + V_{sq} \tag{2}$$

$$0 = \frac{d\psi_{rd}}{dt} + R_r * I_{rd} + \omega_m * \psi_{rq} \tag{3}$$

$$0 = \frac{d\psi_{rq}}{dt} + R_r * I_{rq} - \omega_m * \psi_{rd} \tag{4}$$

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

$$\psi_{sd} = L_{sd} * I_{sd} + M_{srd} * I_{rd} \tag{5}$$

$$\psi_{sq} = L_{sq} * I_{sq} + M_{srq} * I_{rq} \tag{6}$$

$$\psi_{rd} = L_r * I_{rd} + M_{srd} * I_{sd} \tag{7}$$

$$\psi_{rq} = L_r * I_{rq} + M_{srq} * I_{sq} \tag{8}$$

ψ_{rd} & ψ_{rq}

R_{sd} & R_{sq} & R_r

L_{sd} & L_{sq} & L_r : torque and the mechanical equation are

M & M

$$T_{em} = P * (M_{srq}I_{sq}I_{rd} - M_{srd}I_{sd}I_{rq}) \tag{9}$$

$$J\frac{d\omega_m}{dt} = P * (T_m - T_r) - F * \omega_m \tag{10}$$

P & J and F   variables are

I_{rd} & I_{rq} auxiliary and main currents of the rotor,

ψ_{sd} & ψ_{sq} auxiliary and main fluxes of the stator,

ψ_{rd} & ψ_{rq} auxiliary and main fluxes of the rotor,

R_{sd} & R_{sq} & R_r the stator and rotor resistances,

L_{sd} & L_{sq} & L_r the stator and rotor self-inductances,

M_{srd} & M_{srq} the mutual inductances,

ω_m & T_{em} & T_m the machine speed, the load torque, and the electromagnetic torque.

P & J and F   are the machine pole pairs, the moment of inertia, and viscous friction coefficient, respectively.

Note that: equations from (1) to (9) are general equations for the two-phase machine. It is seen that there is an asym-

metry in the model. This asymmetry is due to the unequal resistances and inductances of the main and auxiliary windings. However, to use the field orientation control of unbalanced two-phase induction motor, some asymmetries of the model can be eliminated using a transformation as presented

$$V'_{sq} = \frac{N_{sd}}{N_{sq}}V_{sq} \qquad \psi'_{sq} = \frac{N_{sd}}{N_{sq}}\psi_{sq} \qquad I'_{sq} = \frac{N_{sq}}{N_{sd}}I_{sq}$$

$$V'_{rd} = \frac{N_{sd}}{N_r}V_{rd} \qquad \psi'_{rd} = \frac{N_{sd}}{N_r}\psi_{rd} \qquad \psi'_{rq} = \frac{N_{sd}}{N_r}\psi_{rq}$$

$$I'_{rd} = \frac{N_r}{N_{sd}}I_{rd} \qquad V'_{rq} = \frac{N_{sd}}{N_r}V_{rq} \qquad I'_{rq} = \frac{N_r}{N_{sd}}I_{rq}$$

$$L'_{sq} = \frac{N_{sd}}{N_{sq}}L_{sq} \qquad R'_{sq} = (\frac{N_{sd}}{N_{sq}})^2R_{sq} \qquad R'_r = (\frac{N_{sd}}{N_r})^2R_r$$

$$L'_r = (\frac{N_{sd}}{N_r})^2L_r \qquad R_s = \frac{R_{sq}+R_{sd}}{2}$$

in [2]:

In these equations:

represent the number of stator and rotor windings respective-

N_{sd} & N_{sq} & N_r ly,

and the ratio $\frac{M_{srd}}{M_{srq}}$ will be approximately equal to $\frac{N_{sd}}{N_{sq}}$

Thus, the transformation employed corresponds approximately to refer the auxiliary winding variables to the main winding. In the above equations if the stator inductances are slightly different it can be shown that Thus the asymmetry in the flux equa- $L_{sd} = L_{sq}.$ tions (5) and (6) will be eliminated.

2.2 In a rotating reference frame:

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 [10]:

$$\frac{d\psi_{Sd}}{dt} = -R_S * I_{Sd} + \omega_s * \psi'_{sq} + V_{sd} \tag{11}$$

$$\frac{d\psi'_{sq}}{dt} = -R_S * I'_{sq} - \omega_s * \psi_{sd} + V_{sq} \tag{12}$$

$$0 = \frac{d\psi'_{rd}}{dt} + R'_r * I'_{rd} - \omega_{sr} * \psi'_{rq} \tag{13}$$

$$0 = \frac{d\psi'_{rq}}{dt} + R'_r * I'_{rq} + \omega_{sr} * \psi'_{rd} \tag{14}$$

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

$$\psi_{sd} = L_{sd} * I_{sd} + M_{srd} * I'_{rd} \tag{15}$$

$$\psi'_{sq} = L_{sq} * I'_{sq} + M_{srd} * I'_{rq} \tag{16}$$

$$\psi'_{rd} = L'_r * I'_{rd} + M_{srd} * I_{sd} \tag{17}$$

$$\psi'_{rq} = L'_r * I'_{rq} + M_{srd} * I'_{sq} \tag{18}$$

The electromagnetic torque and the mechanical equation are given by:

$$T_{em} = \frac{P}{L'_r} * M_{srd}(I'_{sq}\psi'_{rd} - I_{sd}\psi'_{rq}) \tag{19}$$

$$J\frac{d\omega_m}{dt} = P * (T_m - T_r) - F * \omega_m \tag{20}$$

Consequently the model (11)-(19) is very useful for further vector applications.

3 FIELD ORIENTED CONTROL:

Although there are various methods of driving single-phase machine one of the known methods to acquire low-cost and high performance is to remove the capacitor from the auxiliary winding so the motor can be viewed as a two-phase machine [1], [2]. That way is possible to implement the field-oriented control. Vector control, also called field-oriented control (FOC), is a variable frequency drives (VFD) control method which controls three-phase AC electric motor output by means of two controllable VFD inverter output variables:

- ✓ Frequency
- ✓ Voltage magnitude

In vector control, an IM or synchronous motor is controlled under all operating conditions like a separately excited DC motor. That is the AC motor behaves like a DC motor in which the flux linkage created by the respective field and armature (or torque component) currents are orthogonally aligned such that, when torque is controlled, the field flux linkage is not affected, hence enabling dynamic torque response.

There are two vector control methods, direct or feedback vector control(DFOC) and indirect or feed-forward vector control (IFOC), IFOC being more commonly used because in closed-loop mode such drives more easily operate throughout the speed range from zero speed to high-speed field-weakening. In DFOC, flux amount and angle feedback signals are directly calculated using so called voltage or current models.[2]

In IFOC, flux space angle feed-forward and flux magnitude signals measure stator currents and rotor speed then deriving flux space angle proper by summing the rotor angle corresponding to the rotor speed and the calculated reference value of slip angle corresponding to the slip frequency.[2]
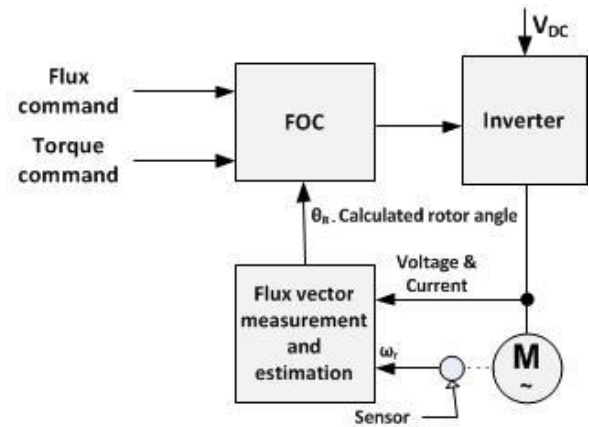

Fig. 2. a) Simplified indirect FOC

Fig. 2. b) Simplified direct FOC

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, $\psi'_{rd} = \psi_r$ and $\psi'_{rq} = 0$. 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:

From eq. 13, and 17

$$\frac{M_{srd}}{\tau'_r} I^{rf}_{sd} = \frac{\psi_r}{\tau'_r} + \frac{d\psi_r}{dt} \qquad (21)$$

From eq. 14, and 18

$$\frac{M_{srd}}{\tau'_r} I'^{rf}_{sq} = \psi_r * \omega_{sr} \qquad (22)$$

Using eq. 19 the expression for the torque can be calculated by:

$$T_{em} = \frac{P}{L'_r} * M_{srd} * I'^{rf}_{sq} \psi_r \qquad (23)$$

Where

ψ_r is the rotor-flux magnitude,
$\omega_{sr} = \omega - \omega_m$ is the slip frequency,
$\omega = \frac{d\theta_{rf}}{dt}$, and θ_{rf} are respectively the frequency and the position of the rotor-flux vector.

Expressions (21 and 23) 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.
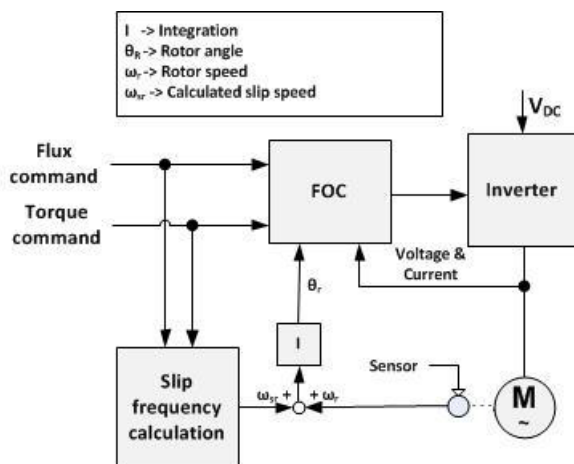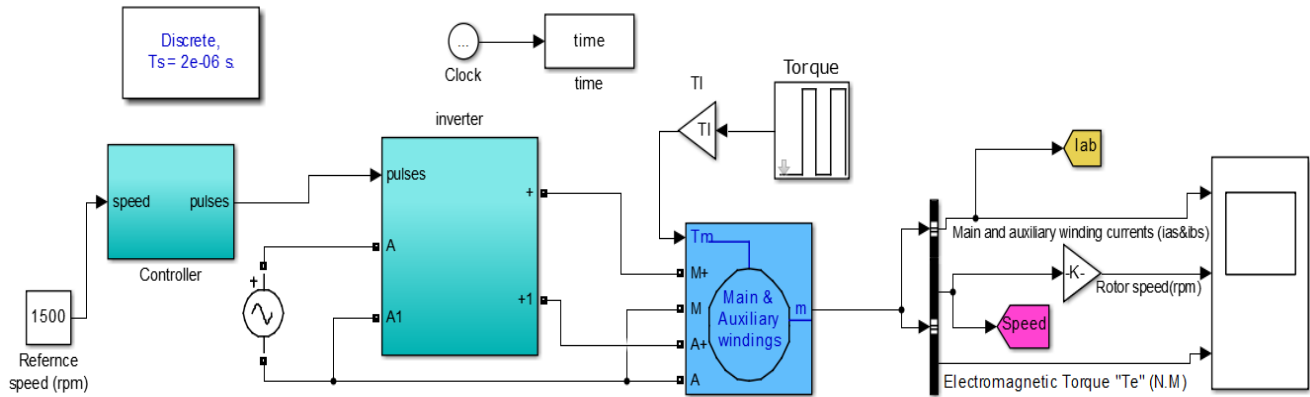
Fig. 2. Block diagram of the indirect rotor field oriented control of SPIM.
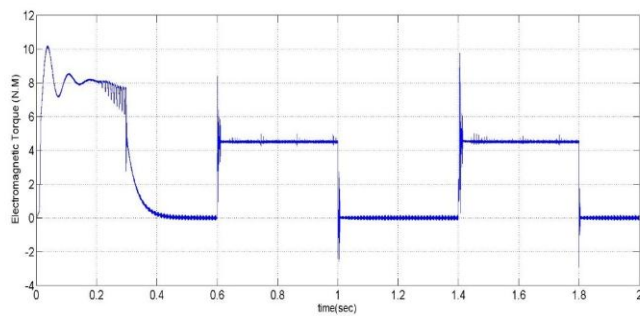
4 SIMULATION RESULTS

The speed control of the single-phase induction motor was implemented in accordance with Fig. 3.

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.
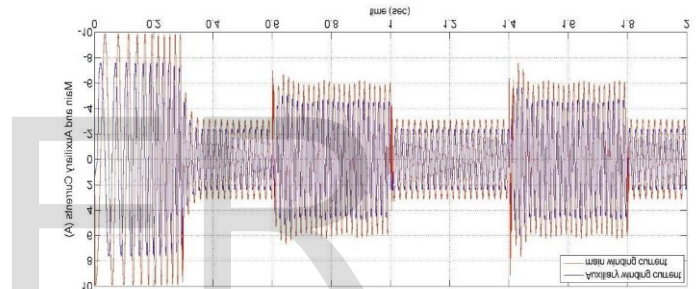
The parameters of the used machine model are given in Table 1. Selected results are presented in Figure (3).
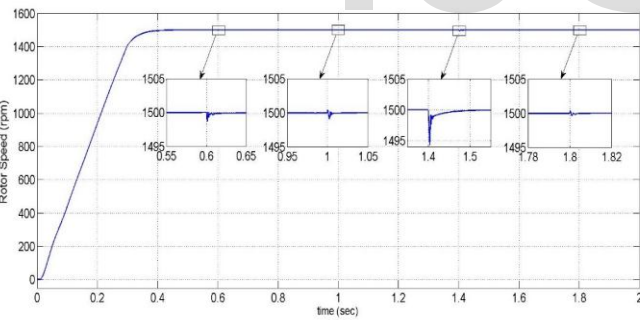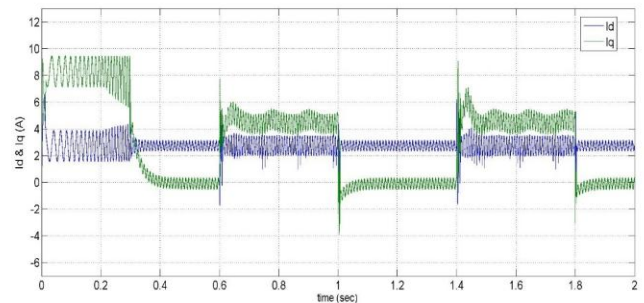

a) the actual and reference motor speed

b) electromagnetic motor torque

c) main and auxiliary currents of the motor .

d) motor currents in rotating reference frame $I_d \& I_q$

Fig. 4. Simulation results of the system under load and no-load.

Firstly, it can be seen that when the system is started, the motor was set to run with no load attached to the shaft.

Figure 3(a) shows the actual motor speed (ω_m) and reference speed (ω_m^*) under the IFOC system. The actual motor speed can track the reference speed at time less than 0.4 sec. Fig. 3(b) shows the electromagnetic-torque of the motor. Fig. 3(c) shows the motor currents I_d, and I_q in stationary reference

frame. The asymmetry of the motor can be verified by the difference in amplitude of the stator currents.

When the load (4.5 N.M) is applied at t=0.6 sec and t=1.4 sec, the actual speed sense slightly the disturbance as it is seen in Fig 3(a), then at t=1 sec and t=1.8 sec the load torque was removed. It is evident that the magnitude of stator current reduces according to electro-magnetic torque in no-load conditions.

TABLE 1
THE PARAMETERS OF SINGLE PHASE INDUCTION MACHINE.

Machine rating	Machine parameter	
Power: 730 W	$R_{sd} = 7.14\ \Omega$	$L_r = 5.6\ mH$
Voltage: 220 V	$R_{sq} = 12.02\ \Omega$	$M_{srd} = 148\ mH$
Frequency: 50 Hz	$L_{sd} = 20.5\ mH$	$M_{srq} = 181.2\ mH$
Speed: 1445 rpm	$L_{sq} = 17.4\ mH$	$J = 15.6*10\text{-}3\ Kg.m2$
Number of pole pairs: 2	$R_r = 4.22\ \Omega$	$F = 2.02.10\text{-}4$ $N.M.S.rad^{-1}$

5 CONCLUSION

This paper investigated the field oriented control for single-phase induction motor drive system with and without load. Due to the natural asymmetry of the single-phase induction motor some transformations were carried out so the IFOC method could be implemented.

For any single phase induction machine field oriented control technique is one of the best techniques for the speed control. It allows the decoupled control of the motor flux and electromagnetic torque. After decoupling, the induction motor can be controlled as a DC motor and the electromagnetic torque and current can be control independently.

In order to show the effectiveness of the control systems when driving a single-phase induction motor, tests under load condition were performed. The IFOC presented good dynamic behavior during the load transients. When the disturbance was sensed, the control systems could keep up the reference speed.

The obtained results were considered satisfactory and showed the performance of a single-phase induction motor drive under load does not differ from the performance without load.

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