AN INDIRECT ROTOR-FLUX-ORIENTED CONTROL OF A TWO-PHASE INDUCTION MOTOR DRIVE

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ABSTRACT

A vector control is proposed for a two phase induction motor drive . The motor is driven by H-bridge current-regulated pulsewidth modulated voltage source inverter. The vector control is based upon rotor field orientation concepts that have been adopted for this type of machine. Simulation results are provided to illustrate the system operation and the MATLAB/SIMULINK has been used for simulation**.**

الخلاصة

يتناول هذا البحث مقترح باستخدام سيطرة الموجه في مسوق المحرك الحثي ثنائي الطور حيث يستخدم مبدل نوع قنطرة H والمسيطر عليه بطريقة تضمين عرض النبضة نوع تنظيم التيار. سيطرة الموجه تستند على مبادئ اعتبار فيض الدوار كمحور والتي تم استخدامها لهذا النوع من المكائن.تم ايجاد نتائج المحاكاة باستخدام *MATLAB/SIMULINK* لتوضيح عمل المنظومة .

KEY WORDS

Two phase induction motor, indirect rotor-flux-oriented control.

INTRODUCTION

Control systems utilize the fractional-horsepower size electromagnetic components as motors and sensors to measure speed and position of controlled elements. A two phase induction motor is used as a control motor, and is suitable for control systems up to a few hundred watts.

The two phase induction motor has two-phase windings located in stator slots ,which are displaced from each other by 90° electrical degrees. One winding is always supplied and is called the excitation(or main) winding. The control signal is applied to the other winding (called control or auxiliary winding) , such that with no control signal the motor must be at standstill.

In order to develop a torque the two windings voltages must be shifted in time-phase. The motor operates from a single-phase supply and utilize a phase-splitting capacitor to develop a rotating field in the air gap. However , due to an elliptical rotating field, a pulsating torque that causes higher noise than a three-phase induction motor.

In recent years various schemes have been proposed for inverter-driven two phase induction motor. In references (1, 2) square voltage waveforms with quadrate phase shift are supplied to the two-phase windings of a two phase induction motor driven by an inverter. Though this drive is simple and cheap, the control range of speed is limited and the harmonic content of the output is high. In references (3, 4) phase-difference angle control of a two-phase induction motor is used which can extend the speed control range without a substantial increase in cost of the drive . However , under phase –difference angle control , the torque pulsation still exists. In reference (5) space-vector pulse width-modulation (SVPWM) inverter is proposed for constant-power operation of a two phase induction motor . Though with this scheme a smooth torque is obtained ,the drive can not suitable for constant torque with variable speed applications which are needed highly in industry. Also the dynamic response of the speed is very slow and the system has no ability to reject the disturbances in the load torque , system parameters and the dc power supply , since the system is an open loop system.

This paper introduces a variable speed drive for a two phase induction motor .A current-regulated pulsewidth modulated two phase voltage-source inverter is designed as a balanced two phase supply for the motor. A vector control method and the rotor field orientation concepts have been adopted for this type of machine to obtain closed loop speed control drive system like a separately excited dc motor drive.

Simulation results are presented to demonstrate the main characteristics of the proposed drive system, and the MATLAB/SIMULNK has been used to perform the simulation studies.

MACHINE MODEL

The simplified representation for the 2-phase machine is shown in Fig.1 .When a stator winding is distributed for the purpose of producing a sinusoidal MMF wave in space , it is convenient to consider the winding as an equivalent single coil and express the mutual coupling between it and an equivalent rotor coil as a sinusoidal function of the angular displacement between their magnetic axes.

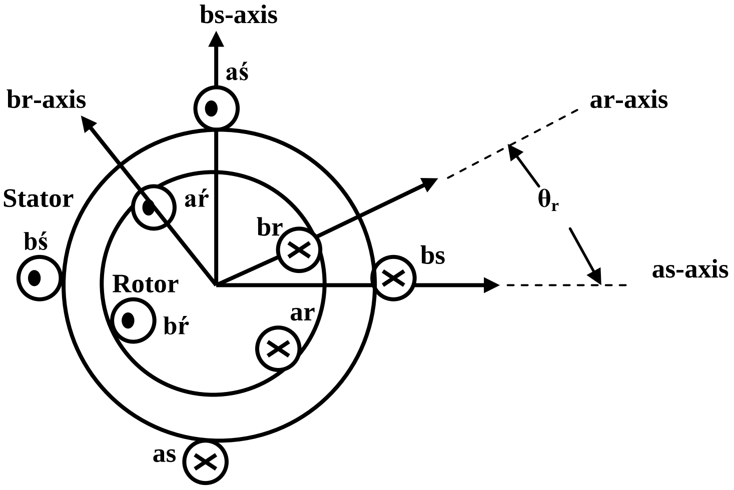


Fig.1 A 2-phase Symmetrical Machine .

If the induction machine has either a squirrel-cage rotor or a coil-wound rotor with the same number of phases as the stator, the rotor can be considered as having equivalent coils (shown in Fig.1). The stator windings are identical ,i.e. ,both windings have an identical number of effective turns N_s , identical resistance r_s ,identical leakage inductance L_{ls} ,and self inductance L_s. Similarly rotor windings are identical which have the same effective turns N_r ,resistance r_r ,leakage inductance L_{lr} , and self inductance L_r.

The voltage equations for the stator phases are written

$$v_{as} = p\lambda_{as} + r_s i_{as} \tag{1}$$

$$v_{bs} = p\lambda_{bs} + r_s i_{bs} \tag{2}$$

In the case of the rotor phases

$$v_{ar} = p\lambda_{ar} + r_r i_{ar} \tag{3}$$

$$v_{br} = p\lambda_{br} + r_r i_{br} \tag{4}$$

For induction motor with squirrel cage rotor $v_{ar}=0$,$v_{br}=0$,therefore equation 3 and equation 4 can be written

$$0 = p\lambda_{ar} + r_r i_{ar} \tag{5}$$

$$0 = p\lambda_{br} + r_r i_{br} \tag{6}$$

Where λ is the total flux-linkages of a particular winding , and p is the operator d/dt .

Figure 2 shows the angular relation of the stator and rotor axes of a 2-phase machine with the third set which is an orthogonal set (d-q axis) . It is clear that as-bs set is fixed in the stator . The ar-br set is fixed in the rotor and hence rotates at an electrical angular velocity of ω_r

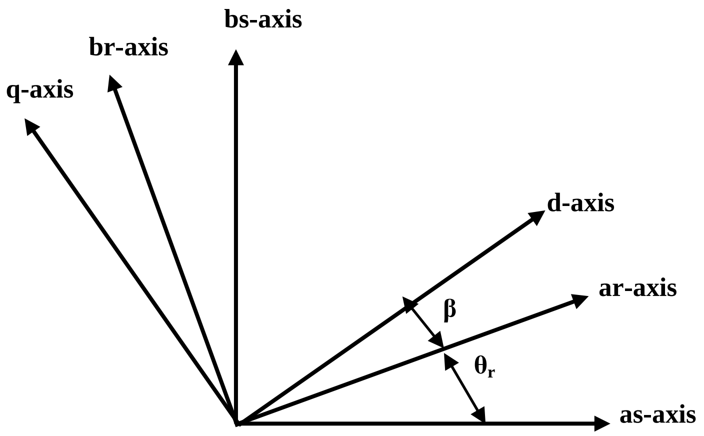


Fig.2 Axes of 2 pole 2 phase symmetrical machine

The equations of transformations which can be correlated to the angular relation of the axes in Fig.2 , are

Stator

$$f_{ds} = f_{as}\cos\theta + f_{bs}\sin\theta \tag{7}$$

$$f_{qs} = f_{bs}\cos\theta - f_{as}\sin\theta \tag{8}$$

Rotor

$$f_{dr} = f_{ar}\cos\beta + f_{br}\sin\beta \tag{9}$$

$$f_{qr} = f_{br}\cos\beta - f_{ar}\sin\beta \tag{10}$$

Where

$$\theta = \beta + \theta_r \tag{11}$$

In these equations the variable f can represent either voltage , current , or flux-linkage .If the transformation equations are used to transform the voltages , currents , and flux-linkages of both the stator and the rotor to the arbitrary reference frame (d-q axis) ,with the rotor variables are referred to the stator windings and with the self-inductances separated into leakage inductance component and a magnetizing inductance component, the following equations are obtained **(6),(7)** :

$$v_{ds} = p\lambda_{ds} - \omega\lambda_{qs} + r_s i_{ds} \tag{12}$$

$$v_{qs} = p\lambda_{qs} + \omega\lambda_{ds} + r_s i_{qs} \tag{13}$$

$$0 = p\lambda_{dr}' - (\omega - \omega_r)\lambda_{qr}' + r_r' i_{dr}' \tag{14}$$

$$0 = p\lambda_{qr}' + (\omega - \omega_r)\lambda_{dr}' + r_r' i_{qr}' \tag{15}$$

Where

$$\lambda_{ds} = L_{ls} i_{ds} + M(i_{ds} + i_{dr}') \tag{16}$$

$$\lambda_{qs} = L_{ls} i_{qs} + M(i_{qs} + i_{qr}') \tag{17}$$

$$\lambda_{dr}' = L_{lr}' i_{dr}' + M(i_{dr}' + i_{ds}) \tag{18}$$

$$\lambda_{qr}' = L_{lr}' i_{qr}' + M(i_{qr}' + i_{qs}) \tag{19}$$

$$\omega = p\theta \tag{20}$$

$$\omega - \omega_r = p\beta \tag{21}$$

For the 2-phase machine ,

$$L_{ls} = L_s - L_{ms} \tag{22}$$

$$L_{lr}' = L_r' - L_{ms} \tag{23}$$

$$M = L_{ms} \tag{24}$$

$$L_{ms} = \frac{N_s}{N_r} L_{sr} \tag{25}$$

L_{sr} is the mutual inductance between stator and rotor. N_s and N_r are the effective turns of a stator and rotor phase winding respectively. The primes are used to denote rotor quantities referred to the stator windings.

It is clear that the voltage equations (12) to (15) of the symmetrical induction machine may be expressed in any reference frame by setting the speed of the arbitrary reference frame , ω , equal to the speed of the desired reference speed. For example , the voltage equations expressed in the stationary reference frame may be obtained by setting ω to zero . For a reference frame fixed in the rotor ω is set equal to the electrical angular velocity of the rotor , ω_r . The voltage equations in the synchronously rotating reference frame are obtained by setting ω equal to the electrical angular velocity of the fundamental frequency component of the applied stator voltages ω_e .

An expression for the instantaneous electromagnetic torque can be obtained by applying the principle of virtual displacement (7) .This expression is

$$T_e = (\frac{P}{2})(\lambda_{qr}' i_{dr}' - \lambda_{dr}' i_{qr}') \tag{26}$$

Where P is the number of poles .

In order to obtain the dynamic characteristics , it is necessary to relate torque and speed , and the relation can be expressed as

$$T_e = (\frac{2}{P})Jp\omega_r + (\frac{2}{P})B\omega_r + T_l \tag{27}$$

Where T_l is load torque , J is the moment of inertia , and B is the friction constant **.**

INDIRECT ROTOR-FLUX ORIENTATION

The indirect rotor-flux oriented controller is derived from the dynamic equations of the machine in the synchronously rotating reference frame , i.e., $\omega=\omega_e$. The rotor voltage equations of the two phase induction motor in synchronously rotating reference frame are given by

$$0 = r_r' i_{dr}' - \omega_{sl}\lambda_{qr}' + p\lambda_{dr}' \tag{28}$$

$$0 = r_r' i_{qr}' + \omega_{sl}\lambda_{dr}' + p\lambda_{qr}' \tag{29}$$

Where

$$\omega_{sl} = \omega_e - \omega_r \tag{30}$$

$$\lambda_{dr}' = L_{lr}' i_{dr}' + M(i_{dr}' + i_{ds}) \tag{31}$$

$$\lambda_{qr}' = L_{lr}' i_{qr}' + M(i_{qr}' + i_{qs}) \tag{32}$$

Where ω_{sl} is the slip frequency in rad/sec .

The fluxes and currents in the above equations are represented in the synchronously rotating reference frame . In the vector control strategies , the ac motors are controlled like separately excited dc motors which have independent channels for the flux and torque control . In order to link the d-axis of the reference frame to the rotor flux vector , the q –component of this flux has to be equal to zero (8)

$$\lambda_{qr}' = 0 \tag{33}$$

$$\lambda_r' = \lambda_{dr}' \tag{34}$$

Substituting (33) ,(34) in (28) ,(29) ,(31) and (32) causes the new rotor flux and voltage equations

$$r_r' i_{dr}' + p\lambda_r' = 0 \tag{35}$$

$$r_r' i_{qr}' + \omega_{sl}\lambda_r' = 0 \tag{36}$$

$$\lambda_r' = L_r' i_{dr}' + Mi_{ds} \tag{37}$$

$$L_r' i_{qr}' + Mi_{qs} = 0 \tag{38}$$

Where

$$L_r' = L_{lr}' + M \tag{39}$$

The rotor currents in terms of the stator currents are derived from equations (37) and (38) as

$$i_{dr}' = \frac{\lambda_r' - Mi_{ds}}{L_r'} \tag{40}$$

$$i_{qr}' = -\frac{Mi_{qs}}{L_r'} \tag{41}$$

The rotor flux in term of the stator current i_{ds} can be obtained by substituting equation (40) in equation (35) as

$$\lambda_r' = \frac{Mi_{ds}}{1 + s\tau_r} \tag{42}$$

Where s is the laplace transform (s=p) and τ_r is the rotor time constant which is

$$\tau_r = \frac{L_r'}{r_r'} \tag{43}$$

Substituting (33) ,(34) and (41) in (26) cause the new electromagnetic torque equation to be

$$T_e = (\frac{P}{2})\frac{M}{L_r'}\lambda_r' i_{qs} \tag{44}$$

Equation (44) indicates that the developed torque depends on the rotor flux and quadrature-axis component of the stator current (i_{qs}) . The torque variation is proportional to the variation of I_{qs} when the rotor flux is controlled as a constant and the behavior of the two phase induction motor becomes like a separately excited dc motor . Equations (36) and (41) are used to derive a formula for slip frequency ω_{sl} in terms of i_{qs} and $\lambda_r^{/}$ as

$$\omega_{sl} = \frac{Mi_{qs}}{\tau_r \lambda_r'} \qquad (45)$$

For the indirect rotor-flux orientation , the rotor flux position required for coordinates transformation is generated from the rotor speed ω_r and the slip frequency ω_{sl} as

$$\theta_e = \int (\omega_{sl} + \omega_r) dt \qquad (46)$$

IMPLEMENTATION OF INDIRECT ROTOR- FLUX-ORIENTED CONTROL SCHEME

The block diagram that is shown in figure (3) represents the indirect rotor flux-oriented control scheme for two phase induction motor drive . The dc supply voltage is converted to balanced two phases supply through H-bridge inverter (2) , (4) which is consisted of four insulated gate bipolar transistors (IGBT) . Fig. 4 shows the H-bridge inverter and the way of connecting the two phase windings . This is a cheaper method because it uses only four semiconductor switches . Fig. 4 also shows that two capacitors are connected in series in the dc link to form a midpoint that is connected to neutral point N . In practice , two large resistors are also needed in parallel with the capacitors to balance the voltage of the capacitors.

The output of the inverter is applied to the stator windings of the motor. Motor ratings and its parameters are given in Appendix. The rotor speed ω_m is sensed and compared with the reference speed ω_m^* and the error is converted to the reference torque T_e^* using proportional-integral controller (P-I controller). The reference quadrature-axis stator current i_{qs}^*(torque current) and the slip frequency ω_{sl} are calculated in terms of the reference torque and the rotor flux using equation (44) and equation (45) respectively.

For the indirect rotor-flux-oriented control, the rotor flux position (angle) is calculated using equation (46). The stator currents i_{as} and i_{bs} are measured and converted to the direct-axis component i_{ds} and quadrature-axis component i_{qs} of the stator current using the equations (7) and (8) of transformation from stationary reference frame to the synchronously rotating reference frame (Park transformation) .

The rotor flux referred to stator (λ_r) is calculated in term of direct-axis component of stator current (i_{ds}) using equation (42) .The drive has rotor-flux control loop. The rotor flux command (λ_r^*) is constant and the drive operates in the constant-torque region. The P-I controller is used for the rotor flux loop and the output of the controller represents the reference direct-axis component of stator current (i_{ds}^*).

The currents i_{ds}^* and i_{qs}^* are reference command currents for the current-regulated pulse width modulation (CRPWM) block that will force motor stator currents to follow these reference currents .There are two P-I controllers in the CRPWM block which convert the current errors between the references and feedback into reference magnet and torque voltages .These voltages are transformed to stationary reference frame using inverse park transformation and then converted to motor terminal voltages by using sinusoidal pulsewidth modulation (9) .

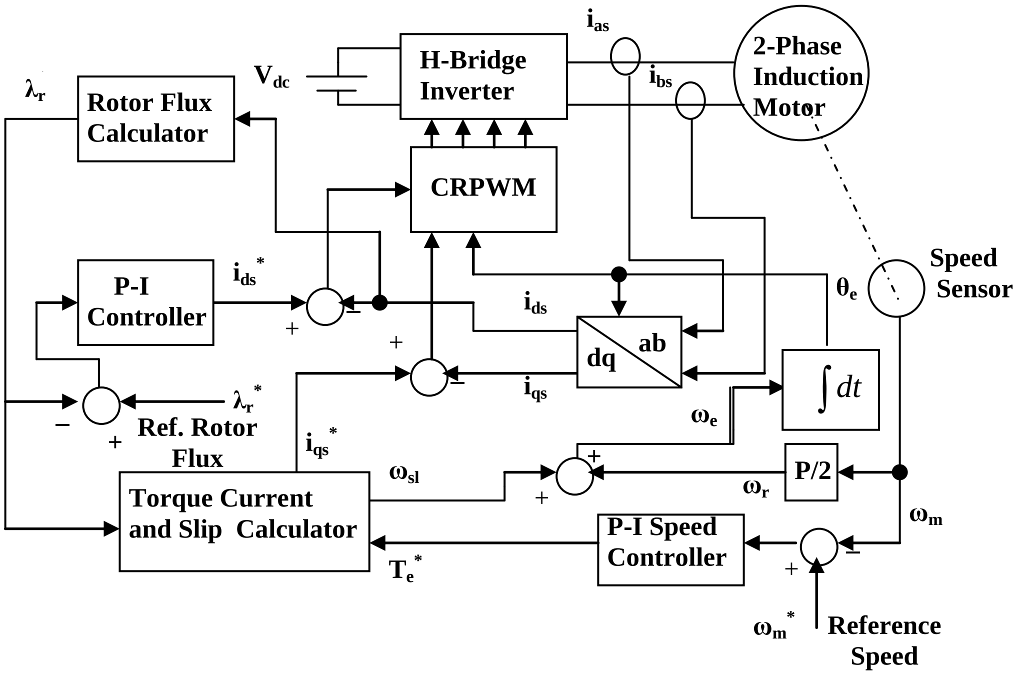


Fig.3 Block diagram of the indirect rotor- flux-oriented control of a two phase induction motor drive

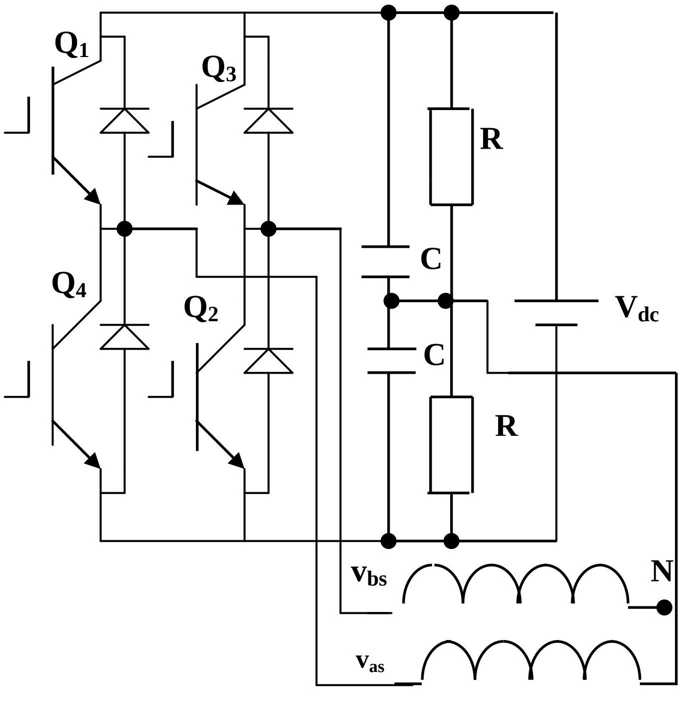


Fig.4 H-bridge inverter with phases connection

RESULTS

Digital simulations were carried out to simulate the control responses of the indirect rotor-flux-oriented control scheme using MATLAB/SIMULINK . The simulations set up such that the drive system is tested with low and high values of a step reference speed command ,also the system is tested with load and with no load for each reference speed command.

Fig.5 and Fig.6 show the simulated values of the rotor speed and the two- phase stator currents of the motor respectively. A step reference speed command of 30 rad/sec value is applied with no load torque .The rotor speed tracks the reference speed at steady state with small overshoot (approximately 1 rad/sec). The stator currents are balanced and each is limited to a maximum value of 12 A at starting in order to protect the semiconductor switching devices of the inverter from high current. The outputs of the speed controller and flux controller are provided with limiters to prevent stator currents from exceeding permissible value. The stator currents drop to a low no load of (2A) value when the speed reaches the steady state.

Fig.7 and Fig.8 represent the rotor speed and stator currents respectively for the same step reference speed command (30 rad/sec) with applied load of 4 Nm.The rotor speed response is similar with the case of no load (Fig.5).The stator currents are raised to a value of 4.5 A (maximum value) proportional to the applied load .

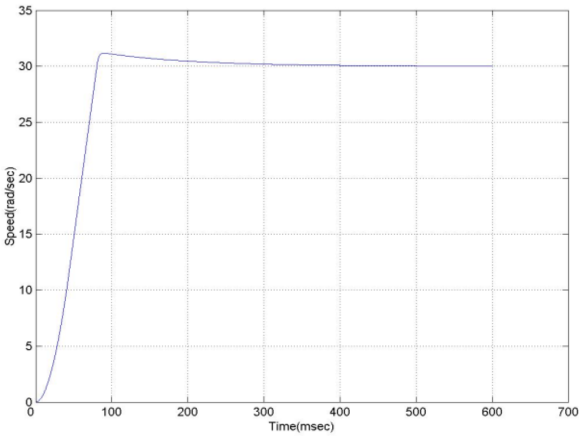


Fig.5 Rotor speed for reference value of 30 rad/sec With no load

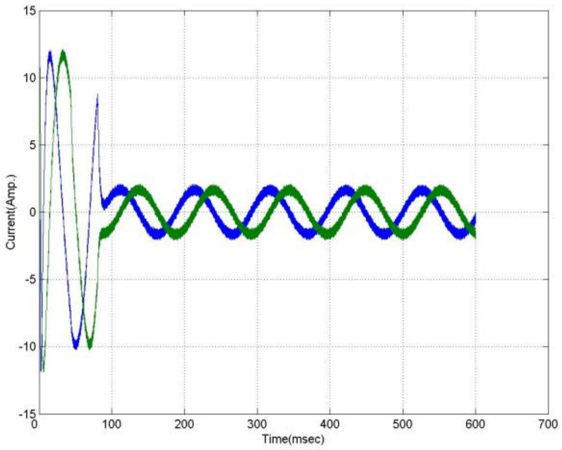


Fig.6 Two phase stator currents for reference value of 30 rad/sec With no load

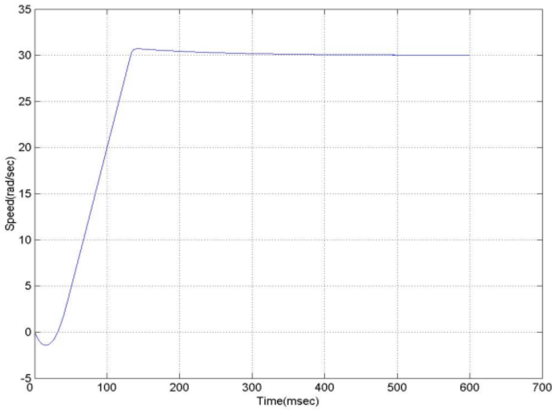


Fig.7 Rotor speed for reference value of 30 rad/sec With load value of 4 Nm

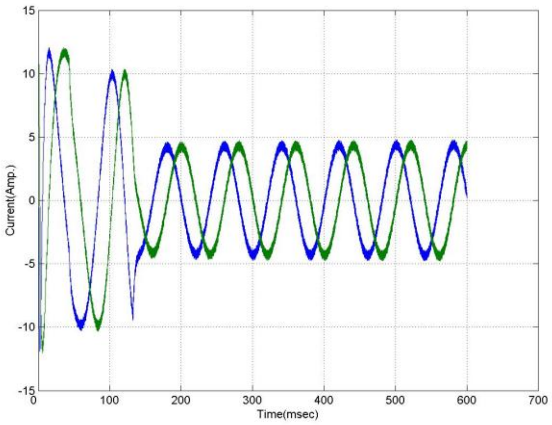


Fig.8 Two phase stator currents for reference value of 30 rad/sec with load value of 4 Nm

The drive system is tested at speed near the rated speed by applying a step reference speed command value of 130 rad/sec. Fig.9 shows the rotor speed which tracks the reference speed at steady state. Fig.10 shows the two phase stator currents with small no load value at steady state. Fig.11 and Fig.12 represent the rotor speed and stator currents for the case of 4 Nm applied load and reference speed of 130 rad/sec.

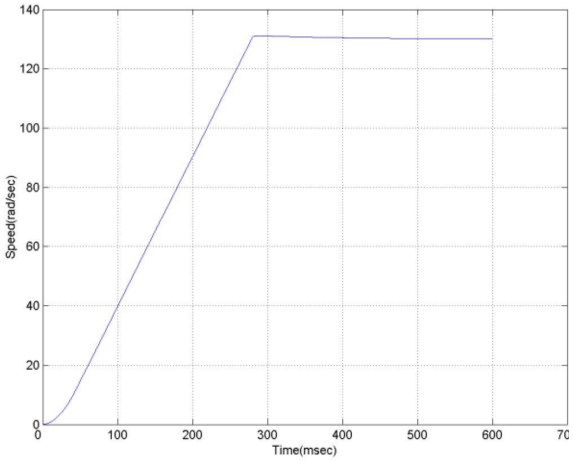


Fig.9 Rotor speed for reference value of 130 rad/sec With no load

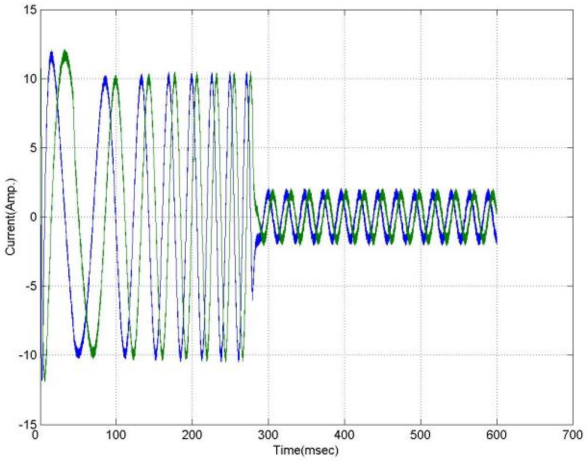
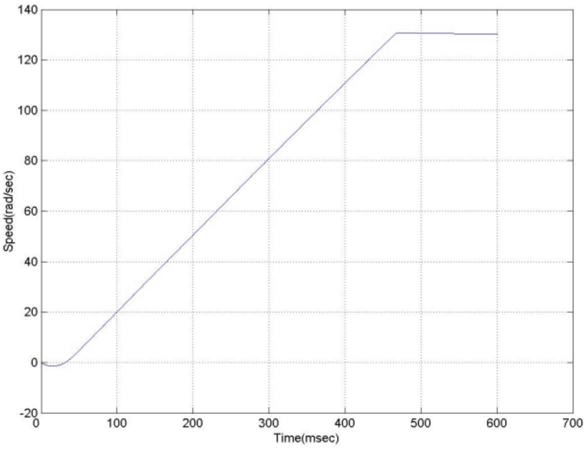


Fig.10 Two phase stator currents for reference value of 130 rad/sec with no load



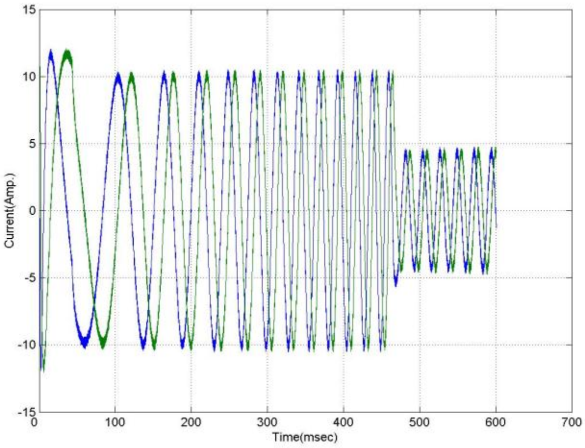


Fig.11 Rotor speed for reference value of 130 rad/sec With load value of 4 Nm

Fig.12 Two phase stator currents for reference value of 130 with load value of 4 Nm

To investigate the robustness of the proposed drive system, we analyzed the speed response and the stator currents of the motor to step change in load torque. Fig.13 and Fig.14 show the rotor speed and the stator currents when the motor is started by applying a step reference speed of 30 rad/sec with no load torque. After 0.35 sec, a step load torque of 4 Nm value is applied .Avery small dip in speed (approximately 0.5 rad/sec) occurs and the speed returns to its original value after 0.15 sec .The stator currents increases to a value of 4.5 A (maximum value) at the instant of applying the load .

Fig.15 and Fig.16 represent the rotor speed and stator currents for the case of starting the motor with applied load of 4 Nm and reference speed value of 30 rad/sec . After 0.35 sec a load is removed ,a small rise in speed occurs which decay to zero after 0.15 sec .The stator currents is reduced to its no load value at the instant of removing the load. Figs. 17-20 are similar to Figs. 13-16 but with 130 rad/sec reference value in order to verify the robustness at high speed .

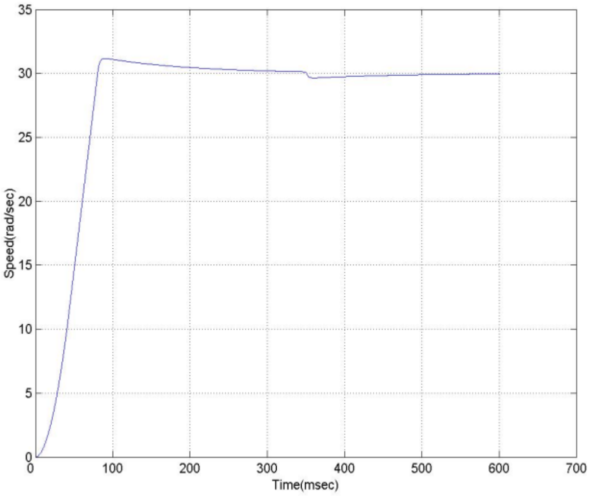


Fig.13 Rotor speed for reference value of 30 rad/sec with no load .After 0.35sec load torque of 4 Nm value is applied

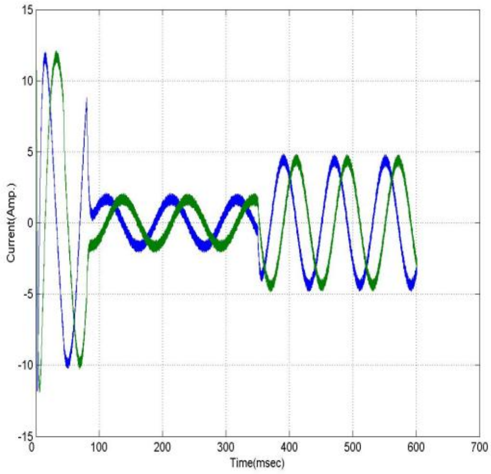


Fig.14 Stator currents for reference value of 30 rad/sec with no load.After 0.35sec load torque of 4 Nm value is applied

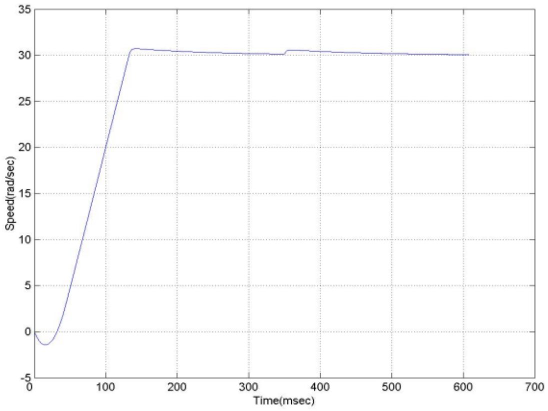


Fig.15 Rotor speed for reference value of 30 rad/sec with 4 Nm load. After 0.35 sec the load torque is removed

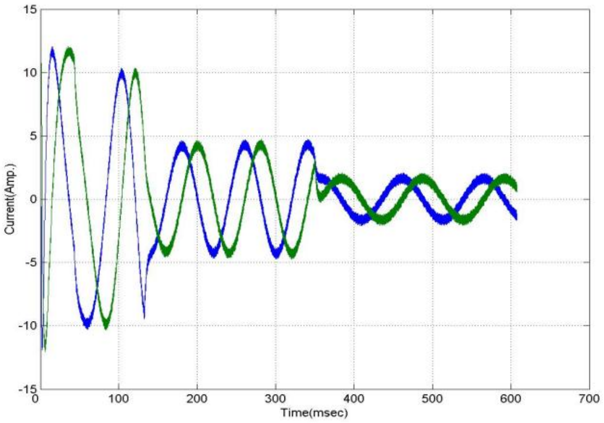
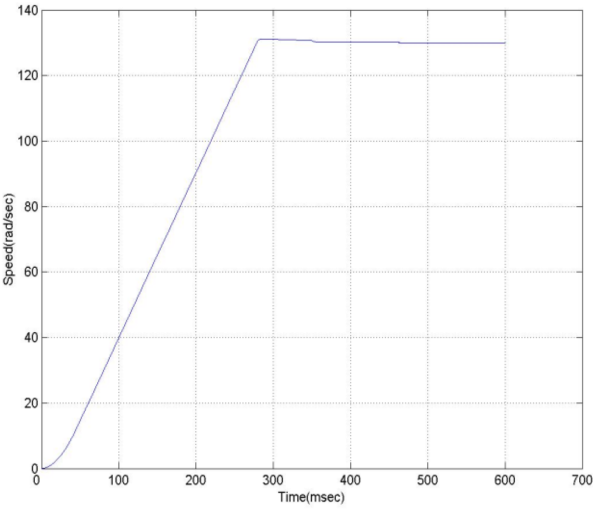


Fig.16 Stator currents for reference of 30 rad/sec with 4 Nm load. After 0.35 sec the load is removed



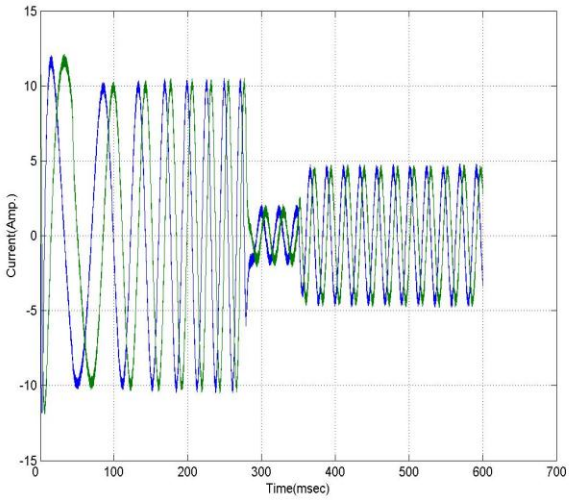
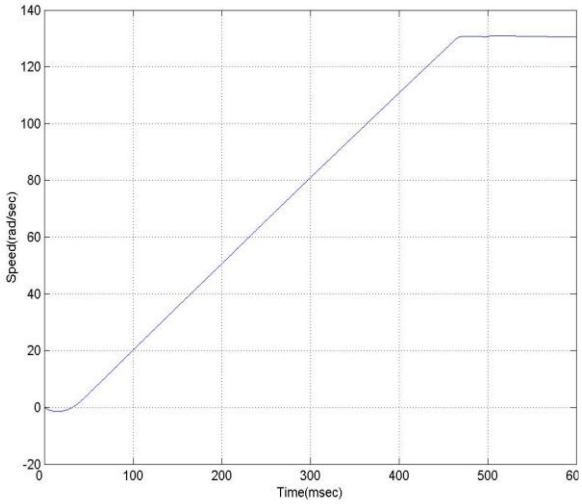


Fig.17 Rotor speed for reference value of 130 rad/sec with no load .After 0.35 sec the load torque of 4 Nm value is applied

Fig.18 Stator currents for reference value of 130 rad/sec with no load. After 0.35 sec the load torque of 4 Nm value is applied



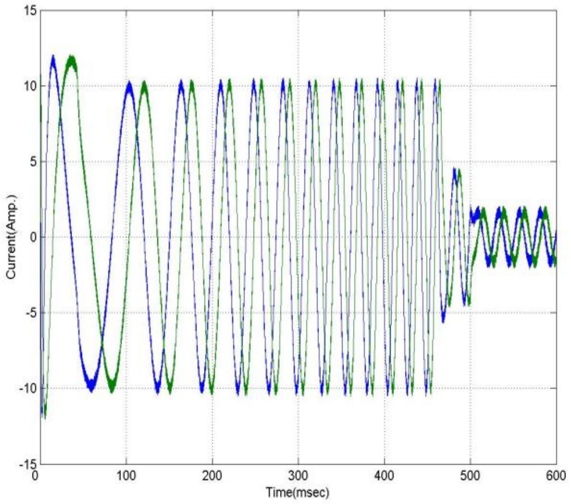


Fig.19 Rotor speed for reference value of 130 rad/sec with 4 Nm load .After 0.5 sec the load torque is removed

Fig.20 Stator currents for reference value of 130 rad/sec with 4 Nm load .After 0.5 sec the load torque is removed

Figs 21-23 show the rotor speed ,stator currents and rotor flux respectively .The motor is started with 30 rad/sec reference speed and no load torque. After 0.3 sec the reference speed is increased to 130 rad/sec. The rotor speed tracks the reference speed at steady state for each step. The rotor flux tracks the reference of 0.5 Wb value and independent upon the speed command.

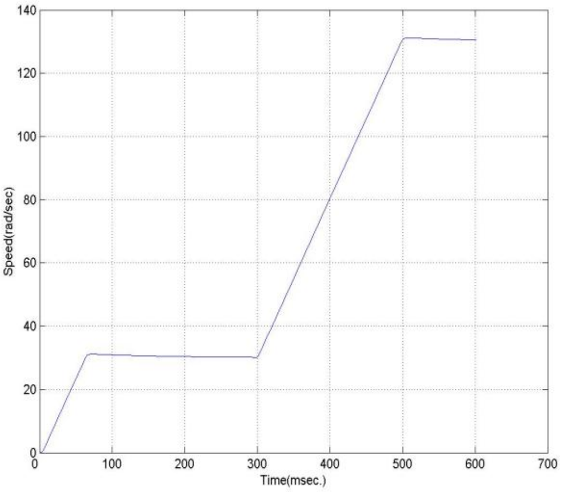


Fig.21 Rotor speed for reference value of 30 rad/sec with no load. After 0.3 sec the reference is increased to 130 rad/sec

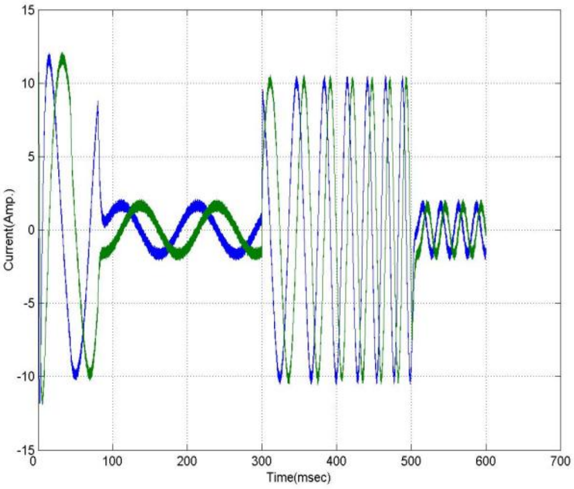


Fig.22 Stator currents for reference value of 30 rad/sec with no load. After 0.3 sec the reference is increased to 130 rad/sec

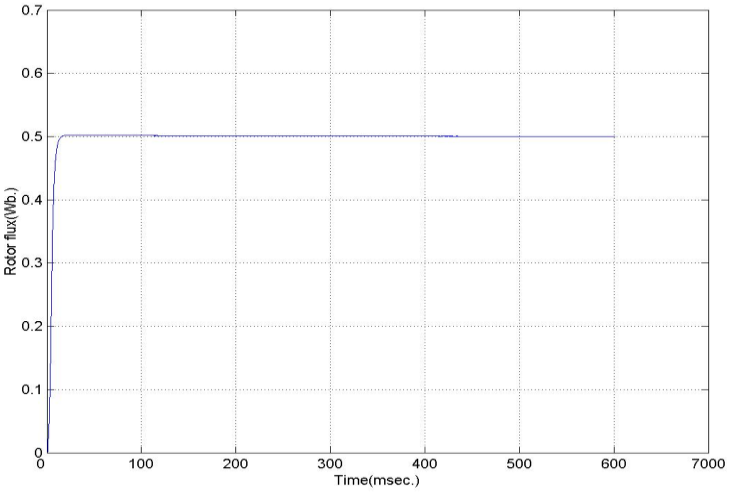


Fig.23 Rotor flux for reference flux value of 0.5 Wb

CONCLUSIONS

This paper has discussed the indirect rotor-flux-oriented control scheme for two phase induction motor. The modeling approach proposed made it possible to adapt some high performance control for use with a two phase motor drive system. Simulation tests were considered satisfactory and have confirmed the claimed features.

In spite of being more complex than other strategies, like the standard V/Hz , the use of indirect rotor-flux- oriented control may not result in additional cost in terms of data processing. This is due to the innovations of microelectronics that increase the capability of processing information and reducing cost and power consumption of the integrated circuits.

Based on simulation results , the following conclusions are made:

1. The rotor speed can be varied from zero up to rated value.
2. Balanced sinusoidal currents are obtained due to sinusoidal pulse width modulation.
3. The drive system is robust against the variation of the load torque. Small dip in speed occurs when a step of load torque is applied ,this dip decays to zero after short time (approximately 150 msec.).. Small rise in speed occurs when the load is removed .This rise decays to zero after short time (approximately 150 msec.).

The proposed drive system can be experimentally built with digital signal processing board for fast calculations of control algorithms in real time. Also the H-bridge inverter with IGBT transistors can be built to convert the dc voltage in to two phase balanced supply using sinusoidal PWM.

APPENDIX

The specifications of two phase motor that is used for simulation are: 1hp, 2Φ, 110 V, four poles and the parameters of the motor are:

$M = 308.4mH$, $L_{lr}' = 10.1mH$

$L_{ls} = 10.1mH$

$r_s = 3.2\Omega$, $r_r' = 2.4\Omega$

$J = 0.02$ kg.m^2 , $B = 2.945 \times 10^{-4}$ kg.m^2/sec

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