

TORQUE ANGLE CONTROL OF INDUCTION MOTOR DRIVE WITHOUT SPEED SENSOR

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ABSTRACT:

A control method of induction motor fed by current regulator pulse width modulation inverter is presented to obtain fast dynamic response. This proposed method is based on the closed-loop control of the torque angle and has the merits of being simple in implementation and insensitive to rotor resistance variation. The proposed scheme utilizes the inverter frequency as the necessary system stabilizing, while the current amplitude merely adjusts the motor steady state flux level. The stabilization is achieved by regulating the phase angle between stator current and rotor flux. The design of proposed scheme is introduced. Speed controller using synchronous reference frame PI regulator is employed as an outer loop. Moreover, another synchronous reference frame PI regulator is employed as inner loop to control the tangent of torque angle. An analytical method for obtaining the rotor speed based on model reference adaptive system without using stator and rotor resistance is proposed. By using this method, speed sensor-less closed-loop torque angle control with no influence of the stator and rotor resistance variations obtained. Also, this proposed method does not require any integrators in its algorithm. In this paper, the control scheme was successfully implemented and tested in laboratory using a high-speed signal processor (DSP). The experimental results validate the theoretical predictions with different dynamic operating conditions.

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Induction motors are relatively cheap and rugged machines. Consequently much attention has been given to induction motor control. Recently, due to the development of the technology of power electronics and high performance microprocessor, the vector controlled induction machine drive has greatly been used in various industrial applications. For high performance vector controlled induction motor drive, speed information is necessary. This information is generally provided by a sensor such as a resolver or an encoder[1-4]. However, this sensor cannot be mounted in some cases such as motor drive in a hostile environment, high speed motor drive, etc. Moreover, this sensor encumbers the mechanical drive, and spoils the general characteristics of the induction motor drive [5-6]. From this view, a speed sensor-less is preferred. To estimate the rotor speed, several methods have already been presented in the literature[7-15].

The sensor-less induction motor drive has been studied for the last two decades, and some results are already applied to industrial fields. At higher stator frequency, higher than 10% of rated frequency, simple direct torque control method gives satisfactory torque control performance. However, the drive performance has still many drawbacks compared with that of the sensor-based drive. In particular, at low stator frequency, the torque controllability is still far from satisfactory[9].

In ref.[16] the design and analysis of torque angle controller for induction motor drive is made using speed sensor. In this paper, a torque and speed control system for pulse width modulated inverter fed induction motor without speed sensor is presented. The system is implemented by adding a speed calculation algorithm to the proposed torque angle control (TAC) technique. A new control method of induction motor fed by current regulator pulse width modulation inverter is presented. This control method causes the inverter firing pulses to synchronize with the motor counter electromotive force. A voltage source inverter induction motor drive incorporating the proposed control algorithm is designed. The effectiveness of the proposed system is verified by experimental and simulation results. The control strategies guarantee very good dynamic and steady state characteristics, with low sampling time and constant switching frequency. A laboratory control unit with Digital Signal Processor (DSP) scheme is presented. A simulation and experimental results are presented and they agree with each other. The simulation of the proposed speed sensor-less torque angle control system is presented, the system is verified experimentally and has the following specific features:

- It does not require any integration of sensed variables.
- It is robust to parameter thermal variations.
- It can get wider bandwidth of speed control loop.
- It can operate at low stator frequency.

CALCULATION OF MOTOR SPEED:

Vector control systems of induction motors without speed sensor have been developed to obtain a simple construction. To estimate the rotor speed, several methods have already been presented. The first is to estimate the slip angular frequency, where the rotor speed can be obtained by subtracting the slip frequency from the supply frequency [11]. The second one is to estimate the rotor linkage flux and its derivative, in which the rotor speed can be obtained by dividing the cross and dot product of the rotor current and the derivative of the rotor flux [11]. However, this calculation method is impossible under the steady state with a sinusoidal supply. Also, it is including the zero division problem. Recent researches on the speed and parameter identification of induction motors are based on the model reference adaptive system (MRAS) [10]. In these schemes, the rotor speed is obtained by adjusting the system gain to minimise the error signal between the reference model and the adjustable model.

Those schemes have a drawback; the rotor speed calculation accuracy is directly affected by the variation in the machine parameters. The main speed error signal is caused by the variation in the stator and rotor resistance. On the other hand, these schemes require pure integration of sensed variables. This leads to problems with initial conditions and drift. To avoid these problems, the pure integrator has to be replaced by a low-pass filter with high gain. However, this replacement causes instability of identification at low speeds. To overcome the above problems, a speed sensor-less torque angle control is presented by using model reference adaptive system. Also, the proposed system does not require any integrators in its reference and adjustable models.

CONVENTIONAL SPEED CALCULATION METHOD:

In this method, the rotor speed can be obtained by subtracting the slip frequency from the supply frequency. The literature uses the rotor flux estimation to estimate the slip frequency. There are two different equations to estimate the rotor flux [11].

$$\dot{\Psi}_r = \frac{L_r}{L_m} (V_s - R_s I_s - \sigma L_s i_s) \quad (1)$$

and

$$\dot{\Psi}_r = \left(\frac{-1}{T_r} I + w_r J \right) \Psi_r + \frac{L_m}{T_r} i_s \quad (2)$$

where

$$I = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \quad \text{and} \quad J = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$$

Equation (1) does not contain the rotor speed w_r ; however, (2) does. Thus, using these two equations, the rotor speed w_r can be estimated. First, the electrical angle θ of the rotor flux vector is defined as follows:

$$\theta_e = \tan^{-1} \left(\frac{\psi_{qr}}{\psi_{dr}} \right) \quad (3)$$

the derivative of the above equation gives

$$\omega_e = \dot{\theta}_e = \frac{\psi_{dr} \dot{\psi}_{qr} - \psi_{qr} \dot{\psi}_{dr}}{\psi_{dr}^2 + \psi_{qr}^2} \quad (4)$$

then, substituting for $\dot{\psi}_{dr}$ and $\dot{\psi}_{qr}$ from (2), we obtain

$$\omega_r = \omega_e - \frac{L_m}{T_r} \left[\frac{i_{qs} \psi_{dr} - i_{ds} \psi_{qr}}{\psi_{dr}^2 + \psi_{qr}^2} \right] \quad (5)$$

Equation (5) indicates that the instantaneous rotor speed ω_r can be obtained using the rotor flux estimated in (1). There are two problems related to the rotor flux estimation based on (1): There is a need of an ideal integral and its sensitivity to parameters variation, specially stator resistance R_s , which has a strong effect at very low speed.

SPEED IDENTIFICATION USING MRAS TECHNIQUES:

Figure (1) illustrates an alternative way of calculating the motor speed by means of the model reference adaptive system (MRAS) techniques[10].

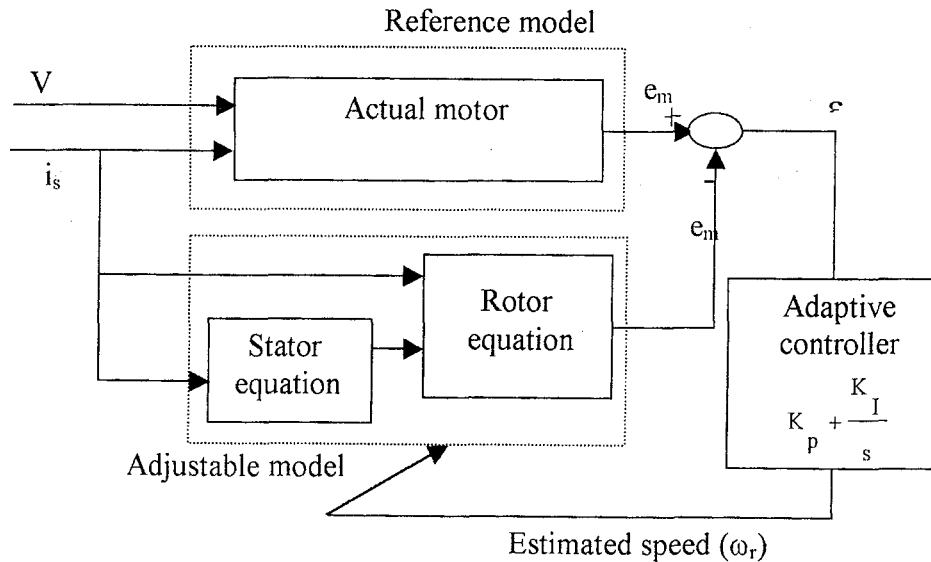


Fig.(1) Motor speed estimation based on MRAS

Two independent observers are constructed to estimate the components of the rotor flux vector, one based on the following equation [10];

$$\begin{bmatrix} \dot{\Psi}_{dr} \\ \dot{\Psi}_{qr} \end{bmatrix} = \frac{L_r}{L_m} \begin{bmatrix} V_{ds} \\ V_{qs} \end{bmatrix} - \begin{bmatrix} R_s + \sigma L_{sp} & 0 \\ 0 & R_s + \sigma L_{sp} \end{bmatrix} \begin{bmatrix} I_{ds} \\ I_{qs} \end{bmatrix} \quad (6)$$

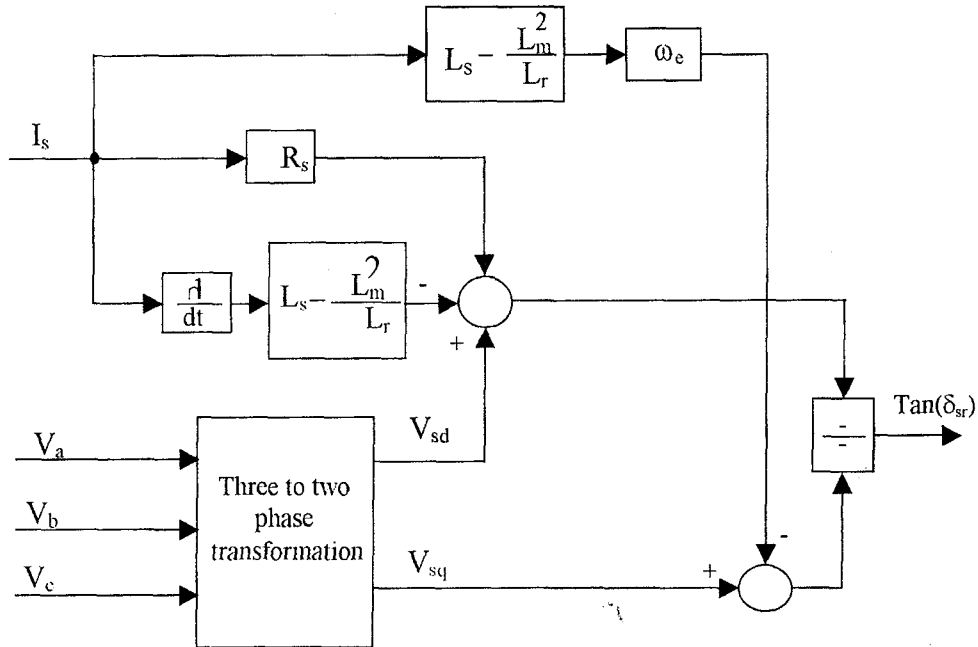
and the other based on [10];

$$\begin{bmatrix} \dot{\Psi}_{dr} \\ \dot{\Psi}_{qr} \end{bmatrix} = \begin{bmatrix} -\frac{1}{T_r} & -\omega_r \\ \omega_r & -\frac{1}{T_r} \end{bmatrix} \begin{bmatrix} \Psi_{dr} \\ \Psi_{qr} \end{bmatrix} + \frac{L_m}{L_r} \begin{bmatrix} I_{dr} \\ I_{qr} \end{bmatrix} \quad (7)$$

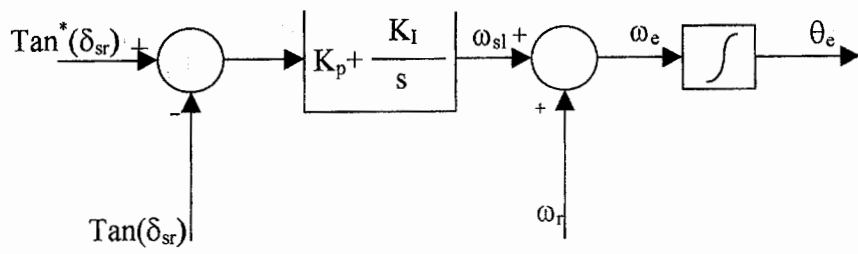
Since (6) does not involve the quantity ω_r this observer may be regarded as a reference model of the induction model, and (7) which does involve ω_r may be regarded as an adjustable model the error between the states of the two model is then used to drive a suitable adaptation mechanism which generates the estimate, ω_r , for the adjustable model.

TORQUE ANGLE CONTROL ALGORITHM DESIGN:

The torque angle is estimated by using the stator voltages and currents without any integration as shown in Fig. (2-a). The estimated torque angle can be used as a feedback variable; it is possible to force the actual torque angle to follow the desired value. The scheme of the torque angle control is shown in Fig. (2). If the estimated torque angle is less than its reference, the PI controller will immediately reduce the slip frequency so that θ_e is reduced. As a result, the torque angle increases[16].



(a) Estimated torque angle



(b) Torque angle control

Fig. (2) Estimated and control of torque angle

The rotor equation of the induction motor model is represented by;

$$0 = R_r i_r + \frac{d\psi_r}{dt} + j\omega_{sl}\psi_r \quad (8)$$

$$\psi_r = \psi_r e^{-j\delta} \quad (9)$$

$$i_r = \frac{\psi_r - L_m i_s}{L_r} \quad (10)$$

Substituting from equations (9) and (10) into equation (8), yields;

$$0 = \frac{R_r}{L_r} (\psi_r e^{-j\delta}) + \psi_r \left(-j e^{-j\delta} \frac{d\delta}{dt} \right) + j\omega_{sl} (\psi_r e^{-j\delta}) - \frac{L_m R_r i_s}{L_r} \quad (11)$$

Then by splitting the above equation into real and imaginary parts yields;

$$\cos(\delta) = \frac{\psi_r}{L_m i_s} \quad (12)$$

$$\sin(\delta) = \frac{L_r \psi_r}{L_m R_r i_s} \left(\omega_{sl} - \frac{d\delta}{dt} \right) \quad (13)$$

Then dividing equation (13) by equation(12) yields;

$$\tan^*(\delta) = \frac{L_r}{R_r} \left(\omega_{sl} - \frac{d\delta}{dt} \right) \quad (14)$$

Substituting into equation (13), and then substituting into equation (14); the reference tangent torque angle is;

$$\tan^*(\delta) = \frac{T_e^* L_r}{P \psi_r^2} \quad (15)$$

The reference stator current can be calculated by the following equation;

$$i_s^* = \frac{\psi_r}{L_m} \sqrt{1 + \frac{T_e^* L_r^2}{P^2 \psi_r^4}} \quad (16)$$

The overall of the torque angle control scheme of voltage-source PWM fed induction motor is outlined in Fig. (3).

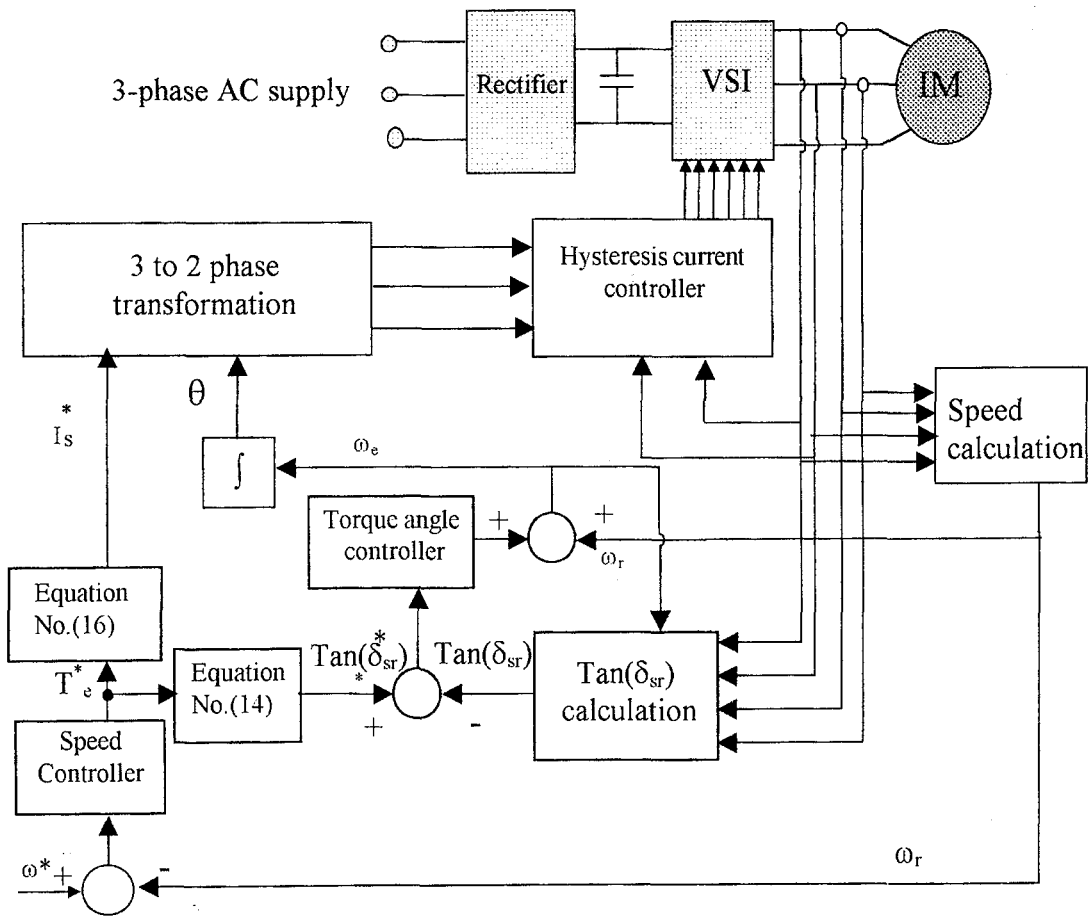


Fig. (3) Schematic diagram of proposed control system

SYSTEM IMPLEMENTATION:

The basic configuration of the drive consists of a squirrel cage induction motor fed from a voltage source inverter. The parameters of this system are given in the Appendix. The actual stator currents are measured and converted to voltage signals by using hall-effect current sensors (Type LA-NP25). The currents are fed to A/D converters on the board. Only, two phase currents need to be directly measured. The third one is determined from the sum of the other two phases. Also, an incremental encoder mounted to the motor shaft measures the motor shaft position. The output terminals of the encoder are connected to the incremental sensor interface of the board. The schematic diagram of the overall implementation system is illustrated in Fig.(4). The power circuit of the induction motor incorporates rectifier-inverter set. Six Isolated Gate Bipolar Transistor (Type MITSUBISHI IGBT CM50DY-24H) are used for the switching devices of the inverter bridge.

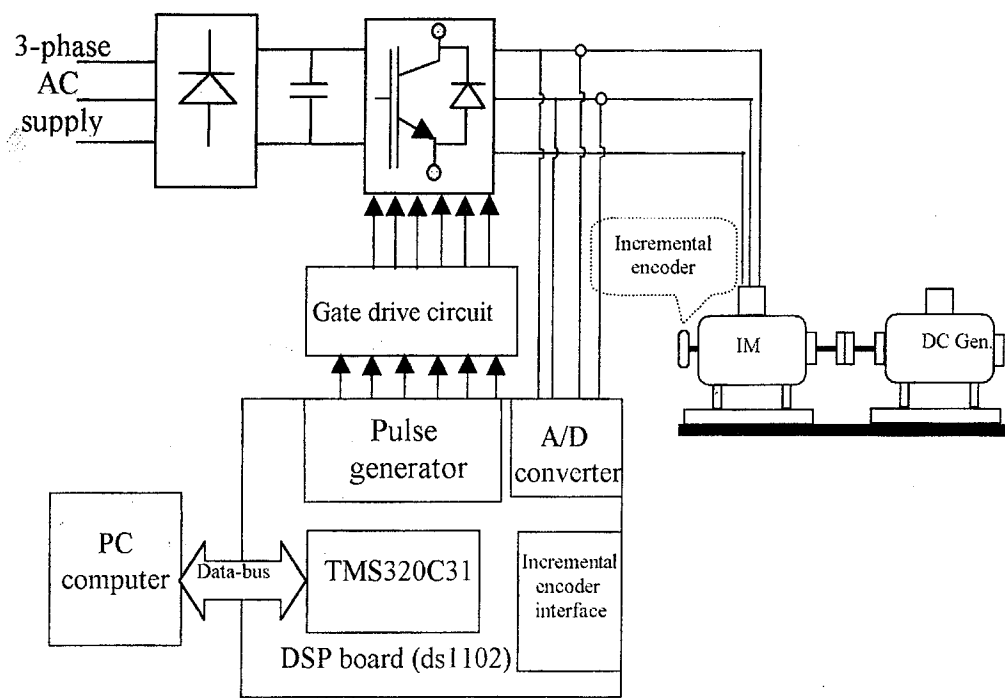


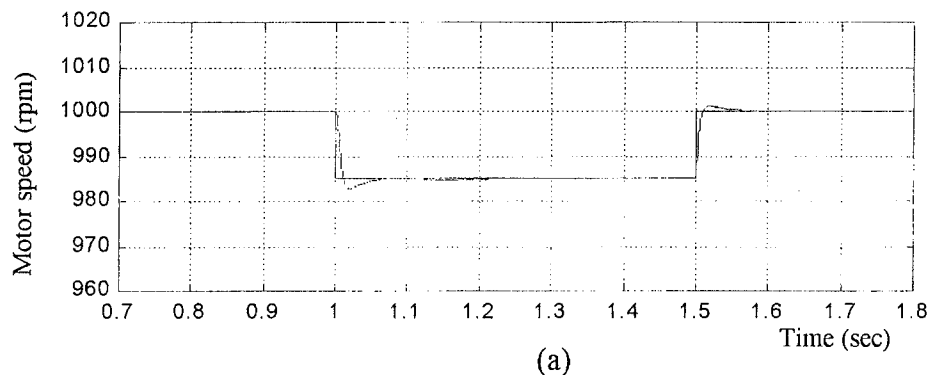
Fig. (4) Control system hardware implementation

The full digital control scheme of the system drive is implemented on the DS1102 controller board. The DSP board based on TMS320C31 as the main processor and TMS320P14 as a slave, which serves as a digital I/O subsystem. The complete DS1102 board can be installed in a Personal Computer with a capability of uninterrupted communication with the latter through the dual-port memory, which can be used by the DSP monitor on the host PC [17]. The feedback signals to the controller board are the measured two-phase currents, two-phase voltage and the motor shaft angular positions. The motor line currents are measured, and converted to voltage signals, which are then converted into digital values by the A/D sub-system module for the current control loop. An optical incremental encoder is installed at the motor shaft. The encoder generates 2048 pulses per revolution. By using a multiplier of four logic circuits, which are built in the board, the encoder output pulses are increased to 8192 pulses per revolution. A 32-bit counter is used to count the encoder pulses and is read by a calling function in the software. The counter is reset once per revolution by the index pulse that is generated from the encoder. The actual motor speed is deduced from the measured shaft position. However, the estimated motor speed is obtained by the proposed algorithm. To execute the speed control loop algorithm, a discrete transfer function of the speed controller is used. The difference equation of the system can be developed and the torque command can be computed. Then the difference between the torque

command and the calculated torque is passed through a three-level comparator. Also, the difference between the flux command and the calculated flux is passed through a two-level comparator.

SIMULATION AND EXPERIMENTAL RESULTS:

The dynamic response of the control system for step changes in the reference speed and speed reversal are studied. The responses due to a step change in the speed command are used to evaluate the control system performance in its response time, overshoot, transient or steady – state error and stability. The motor is subjected to step decrease and step increase in the reference speed under loading conditions to evaluate its performance. Figure (5-a) shows the rotor speed response with a command speed of 1000 rpm at half load. At $t = 1$ sec. and $t = 1.5$ sec., the speed reference has been changed to the speed of 985 rpm and then to the speed of 1000 rpm again, respectively. It can be seen that the rotor speed is decelerated and accelerated smoothly to track its reference value with nearly zero steady state error. Figure (5-b) shows the motor phase current and its reference, it can be seen that the motor phase current follows its reference very closely even during the transient instant due to the inherent quick response of the hysteresis current controller. The tangent of torque angle command component and the developed torque are shown in Fig.(5-c) and (5-d), respectively. Since the tangent angle component is responsible to generate the required torque, a linear relationship has been observed. Due to the sudden changes in speed reference, the tangent of torque angle command has been changed momentary and return to its value quickly. The rotor flux response is shown in Figure. (5-e). It is clear that the rotor flux is changed at the instant of changing the reference speed and fastly retrieve its steady – state value.



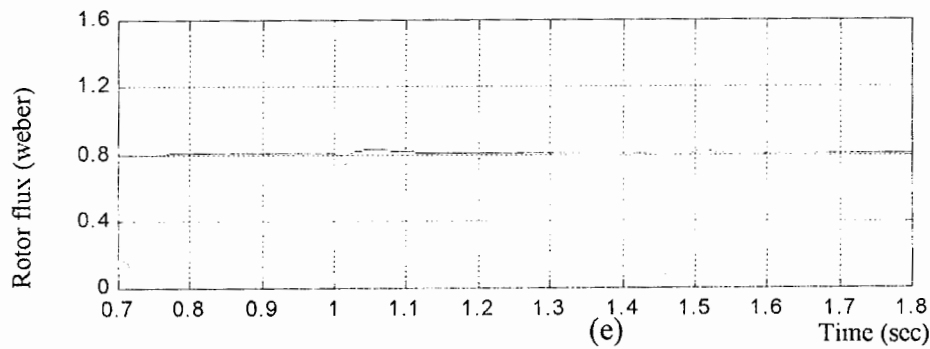
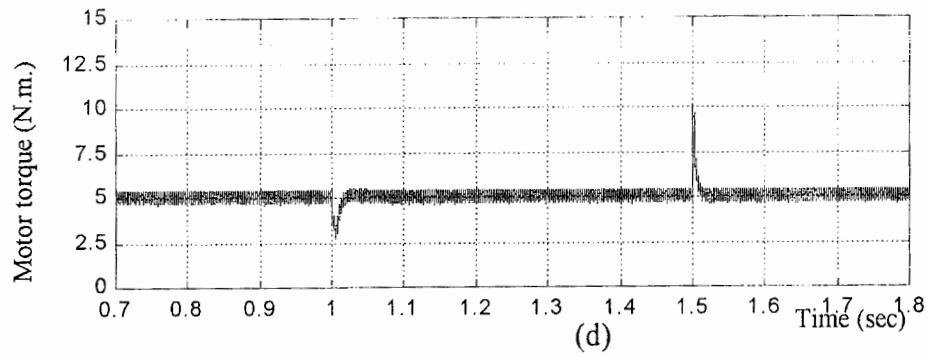
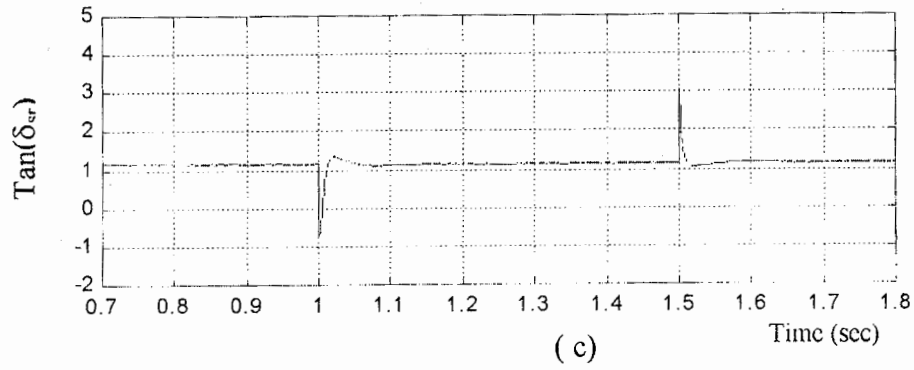
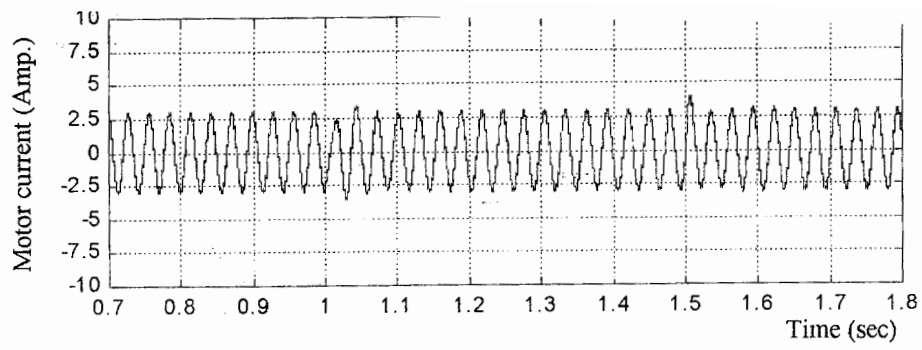


Fig.(5) Simulation results for the system response for step change in speed command from 1000 rpm to 850rpm.

A series of experimental tests have been done to verify the validity of the control scheme of the drive system. The drive response was carried out at speed command 100 rad/sec. Figure(6-a) shows the speed response at no-load. The motor started with acceptable over shoot .It is to be noticed that the motor speed follows its command with nearly zero steady-state error. As two phase currents are required only for the control scheme, the motor phase currents, i_a , i_b , i_c are displayed in Fig.(6-b).It is noted that the steady state motor currents are nearly sinusoidal and flows its Commanded value.

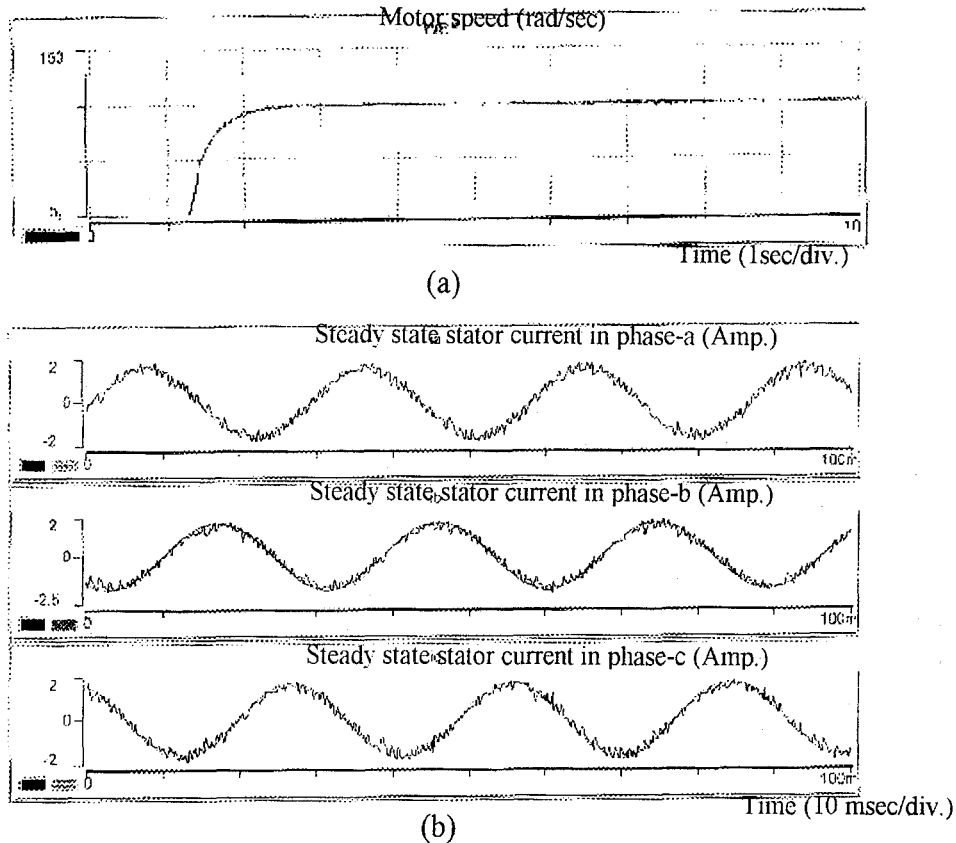


Fig.(6) Experimental results for the speed response at command speed 100 rad/sec

On the other hand, the drive is tested at very low speed condition. Figure(7) shows the speed response at starting with command 15 rad/sec. It is clear that the motor starts smoothly and reaches steady state without overshoot and with zero steady-state error. Figure(7) shows the Corresponding motor current in phase-a.

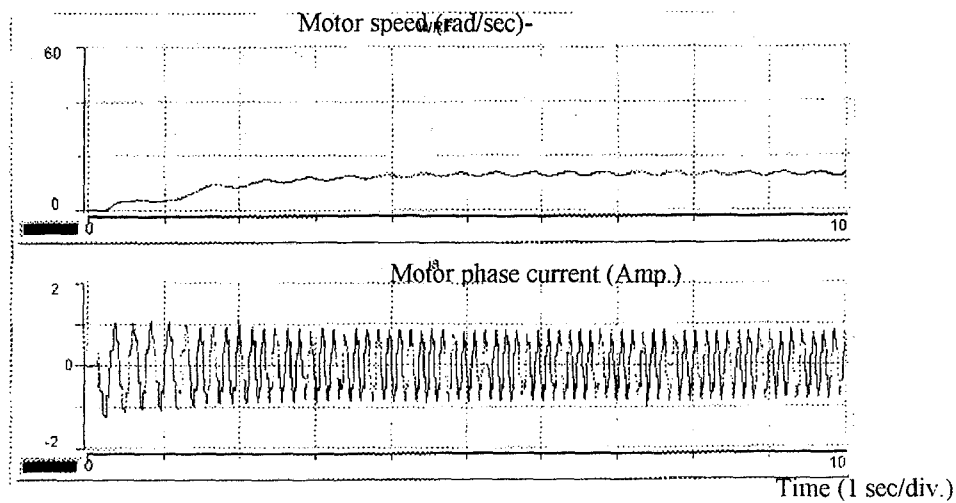


Fig.(7) Speed response at command speed 15 rad/sec.

CONCLUSION:

A system has been proposed to drive an induction motor at various speeds without a speed sensor. The proposed control scheme has been tested at run-up and steady state conditions with variable speed range. The current and torque waveforms emphasize the effectiveness of the control scheme. The simulation and experimental results confirm the advantages of the proposed control system, which has constant switching frequency, uni-polar voltage PWM, very low torque and current distortion, very fast torque and flux responses and lower sampling time. On the other hand, the presented TAC algorithm can be successfully implemented in the fast processor unit. The obtained results are acceptable and allow the proposed system to fulfil dynamic and steady state high performance characteristics

A torque angle control technique for induction motor fed by current regulator pulse width modulation has been proposed. The control technique is based on torque angle regulation. The principles associated with this particular speed control are presented and discussed. The theoretical results are verified by computer simulation. Also, experimental results are carried out to ensure the robust speed control of this proposed technique. These results ensure that the performance of the control system is effective.

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LIST OF SYMBOLS:

I_s, I_r	: Stator, rotor current.
L_s, L_r	: Self inductance of the stator and rotor per phase.
L_m	: Mutual inductance.
J	: Moment of inertia.
P	: Number of pair poles.
R_s, R_r	: Resistance of the stator and rotor per phase.
T_e	: Machine electromagnetic torque.
s, r, m	: Subscripts denoting stator, rotor and magnetizing.
d, q	: Subscripts denoting arbitrary frequency rotating axes.
*	: Subscripts denoting command value.
ω_{sl}	: Slip frequency.
ω_r	: Rotor electrical frequency.
ω_e	: Stator electrical frequency.
\otimes	: Cross product
ψ_s, ψ_r, ψ_m	: Stator, rotor, air-gap flux

APPENDIX:

The induction motor is a three-phase squirrel cage and has the following data;

Rated power	: 1.1 kw
Rated line voltage	: 380 volts
No. of pole pairs	: 2
Stator resistance	: 7.4826 ohm
Rotor resistance	: 3.6840 ohm
Mutual inductance	: 0.4114 henry
Stator leakage inductance	: 0.0221 Henry
Rotor leakage inductance	: 0.0221 Henry
Supply frequency	: 50 Hz
Motor speed	: 1400 r.p.m.
Rated load torque	: 7.5 N. m.

التحكم بزواوية العزم لتسيير آلة تأثيرية بدون إستخدام جهاز حساس للسرعة

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**الشركة العربية للصلب بمدينة السادات

ملخص البحث :

يتضمن هذا البحث طريقة التحكم بزواوية العزم لآلة تأثيرية مغذاه من مغير لتنظيم التيار وذلك بتعديل عرض النبضة وذلك بدون إستخدام جهاز حساس للسرعة والحصول على إستجابة ديناميكية سريعة.

الطريقة المقترحة مبنية على أساس التحكم بزواوية العزم بإستخدام الدائرة المغلقة وتمتاز هذه الطريقة بالبساطة العملية . ويستخدم تردد المغير فى النظام المقترح لضرورة الاتزان لنظام التحكم وتستخدم قيمة التيار لضبط مستوى التدفق فى حالة الاستقرار ويتحقق الاتزان بتنظيم زاوية الوجه بين تيار المحرك وتدفق العضو الدوار والتي تسمى بزواوية العزم. ومن مميزات هذه الطريقة أن الآلة تعمل فى أربعة إتجاهات مما يتيح عكس السرعة والتيار والجهد للآلة . تم إستخدام محكم تناسبي تكاملى للسرعة وأيضا تم إستخدام محكم تناسبي تكاملى للحساس لزواوية العزم ، وأن الطريقة التحليلية المقترحة للحصول على السرعة مبنية على اساس إستخدام نموذج ثابت لنظام يتكيف بدون إستخدام مقاومة الثابت والدوار للآلة . وبإستخدام هذه الطريقة فإن السرعة يتم حسابها بدون إستخدام جهاز حساس للسرعة وذلك فى دائرة مغلقة للتحكم فى زواوية العزم.

تم فى هذا البحث كذلك تحقيق التأثيرات المختلفة للنظام المقترح عمليا وقورنت مع النتائج النظرية ووجد أن هناك تطابقا وإتفاق كبير بينهما.