

## A Cost Effective sensorless vector control of 4-Switch 3-Phase Inverter Fed IM using MRAS

Z. M. El-Barbary<sup>1</sup>, M. K. Metwally<sup>2</sup>, H. Z. Azazi<sup>3</sup>

<sup>1</sup>Department of electrical Engineering, Kafrelsheikh University- Egypt, King Khalid university-KSA

<sup>2</sup>Department of electrical Engineering, Menoufiya University, Menoufiya, Egypt

<sup>3</sup>Department of electrical Engineering, Menoufiya University, Menoufiya, Egypt

e-mail: z\_elbarbary@yahoo.com, mohkamel2007@yahoo.com, Dr\_hn1984@yahoo.com

### Abstract

*This paper investigates performance of a Model reference adaptive system (MRAS) based cost-effective drive system of an induction motor (IM) for low-cost applications. In this paper, the MRAS is used as a speed estimator and the motor is fed from a four-switch three-phase (FSTP) inverter instead of a conventional six-switch three-phase (SSTP) inverter. This configuration reduces the cost of the inverter, the switching losses, and the complexity of the control algorithms. The robustness of the proposed MRAS-based FSTP inverter fed IM drive is verified by Experimental results at different operating conditions. A comparison of the proposed FSTP inverter fed IM drive with a conventional SSTP inverter system is also made in terms of the performance analysis. The proposed FSTP inverter fed IM drive is found quite acceptable considering its performance, cost reduction and other advantages.*

**Keywords:** induction motor, four switch inverter, six switch inverter, sensorless control, vector control, MRAS

### 1. Introduction

Over the years induction motor has been utilized as a workhorse in the industry due to its easy build, high robustness, and generally satisfactory efficiency. With the invent of high speed power semiconductor devices three-phase inverters play the key role for variable speed AC motor drives [1]. Induction motor drives have been thoroughly studied in the past few decades and many vector control strategies have been proposed, ranging from low cost to high performance applications. Traditionally, 6-switch, 3-phase (SSTP) inverters have been widely utilized for variable speed IM drives. This involves the losses of the six switches as well as the complexity of the control algorithms and interface circuits to generate six PWM logic signals [2].

In the past, researchers mainly concentrated on the development of the efficient control algorithms for high performance variable speed IM drives. However, the cost, simplicity and flexibility of the overall drive system which become some of the most important factors did not get that much attention to the researchers. That's why, despite tremendous research in this area most of the developed control system failed to attract the industry. Most of the reported works on 4-switch, 3-phase (FSTP) inverter for machine drives did not consider the closed loop vector control scheme, which is essential for high performance drives.

Usually, high performance motor drives used in robotics, rolling mills, machine tools, etc. require fast and accurate response, quick recovery of speed from any disturbances and insensitivity to parameter variations. The dynamic behavior of an AC motor can be significantly improved using vector control theory where motor variables are transformed into an orthogonal set of d-q axes such that speed and torque can be controlled separately. This gives the IM machine the highly desirable dynamic performance capabilities of a separately excited DC machine, while retaining the general advantages of the ac over DC motors [3].

In this paper, a cost effective FSTP inverter fed sensorless IM drive is developed. The four switches makes the inverter less cost, less switching losses, less chances of destroying the switches due to lesser interaction among switches, less complexity of control algorithms and interface circuits as compared to the conventional SSTP inverter, the proposed control approach reduces the computation for real time implementations. Furthermore, the use of speed sensorless for induction motor drives besides being reduce bulky and increase the robustness, it reduce additional electronics, extra wiring, extra space. And reduce extra cost to the drive system, Speed sensor, also, implies and careful mounting which detracts from the inherent robustness of the drive.

The proposed sensorless control method verifies the validity of an MRAS-based FSTP inverter fed IM drive system for cost reduction and other advantages such as reduced switching losses, reduced number of interface circuits to supply logic signals for the switches, easier control algorithms to generate logic signals. Thus, the main issue of this paper is to develop a cost effective, simple and efficient high performance IM drive.

A closed-loop vector control scheme of the proposed FSTP inverter fed IM drive incorporating the MRAS is implemented using digital signal processing DSP1104 interfaced with the MATLAB/SIMULINK soft ware. A comparison of the proposed FSTP inverter fed IM drive with a conventional SSTP inverter system is also made in terms of performance analysis.

## 2. The Proposed Inverter

The proposed FSTP inverter is configured as shown in Fig. 1. The inverter converts the DC-voltage to a balanced three-phase output with adjustable voltage and frequency.

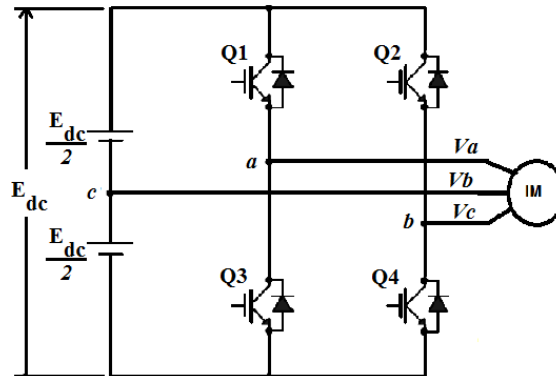


Fig.1 Four switch three- phase inverter with IM

This inverter is configured with four switches  $Q_1$ ,  $Q_2$ ,  $Q_3$  and  $Q_4$ , respectively. Two output phases are taken from the inverter legs directly where the third output is taken from the midpoint of the two capacitors. A detailed comparison of the four-switch inverter with the conventional six-switch inverter configuration is given in [5]. [6].

Two control possibilities exist to control the four-switch bridge inverter, i.e., two-level current control to force the two controlled phases currents to sinusoidal, or using PWM to control the voltages applied to the three-phase quasi-sinusoidally. The two-level current control of the four-switch bridge inverter used to control the load current by forcing it to follow a reference one. This is achieved by the switching action of the inverter to keep the current within the hysteresis band. The load currents are sensed and compared with respective command currents using two independent hysteresis comparators. The output signals of the comparators are used to activate the inverter power switches. This controller is simple and provides excellent dynamic performance. The modulated phase voltages of four switch inverter are introduced as a function of switching logic  $NA$ ,  $NA1$ ,  $NB$  and  $NB1$  of power switches by the following relations [7].

$$V_a = \frac{E_{dc}}{3}(4NA + 2NB - 1). \quad (1)$$

$$V_b = \frac{E_{dc}}{3}(-2NA + 4NB - 1). \quad (2)$$

$$V_c = \frac{E_{dc}}{3}(-2NA - 2NB + 2). \quad (3)$$

where,  $NA1$  and  $NB1$  are complementary of  $NA$  and  $NB$ ,

## 3. MRAS Model for Sensorless Control of IM

Model Reference Adaptive Systems (MRAS) techniques applied in order to estimate rotor speed. This technique is based on the comparison between the outputs of two estimators. The outputs of two estimators may be (the rotor flux, back emf, or motor reactive power). The estimator that does not involve the quantity to be estimated (The rotor speed  $\omega_r$ ) is considered as the induction motor voltage model. This model considered to be the reference model (RM). The other model is the current model, derived from the rotor equation, this model considered to be the adjustable model (AM). The error between the estimated quantities by the two models is used to drive a suitable adaptation mechanism which generates the estimated rotor speed [4].

In this paper, the observer depends on the MRAS technique. The speed observer is based on stator current and rotor flux as state variables. The speed estimating procedures from the stator current error are as follows: First, the rotor flux is expressed as in Eqs. (7) and (8) from the induction motor equation the stator current is represented as:

$$\begin{aligned}
 i_{ds} &= \frac{1}{Lm} [\lambda_{dr} + \omega_r T_r \lambda_{qr} + T_r p \lambda_{dr}] \\
 i_{qs} &= \frac{1}{Lm} [\lambda_{qr} - \omega_r T_r \lambda_{qr} + T_r p \lambda_{qr}]
 \end{aligned} \tag{4}$$

Using Equation (4), and estimated instead of measured speed, the stator current is estimated as

$$\begin{aligned}
 \hat{i}_{ds} &= \frac{1}{Lm} [\lambda_{dr} + \hat{\omega}_r T_r \lambda_{qr} + T_r p \lambda_{dr}] \\
 \hat{i}_{qs} &= \frac{1}{Lm} [\lambda_{qr} - \hat{\omega}_r T_r \lambda_{qr} + T_r p \lambda_{qr}]
 \end{aligned} \tag{5}$$

Form the relationship between the real stator current and the estimated stator current, the difference in the stator current is obtained as

$$\begin{aligned}
 i_{ds} - \hat{i}_{ds} &= \frac{T_r}{Lm} \lambda_{qr} [\omega_r - \hat{\omega}_r] \\
 \hat{i}_{qs} - i_{qs} &= \frac{T_r}{Lm} \lambda_{dr} [\omega_r - \hat{\omega}_r]
 \end{aligned} \tag{6}$$

In Equation (6), the difference of stator current is sinusoidal value because it is the function of rotor flux. Multiplying by the rotor flux and adding them together;

$$\begin{aligned}
 (i_{ds} - \hat{i}_{ds}) \lambda_{qr} &= \frac{T_r}{Lm} \lambda_{qr}^2 [\omega_r - \hat{\omega}_r] \\
 (\hat{i}_{qs} - i_{qs}) \lambda_{dr} &= \frac{T_r}{Lm} \lambda_{dr}^2 [\omega_r - \hat{\omega}_r]
 \end{aligned} \tag{7}$$

By summing the above two equations.

$$(i_{ds} - \hat{i}_{ds}) \lambda_{qr} + (\hat{i}_{qs} - i_{qs}) \lambda_{dr} = \frac{T_r}{Lm} (\lambda_{qr}^2 + \lambda_{dr}^2) [\omega_r - \hat{\omega}_r] \tag{8}$$

Hence, the error of the rotor speed is obtained as follows:

$$\begin{aligned}
 \omega_r - \hat{\omega}_r &= [(i_{ds} - \hat{i}_{ds}) \lambda_{qr} - (\hat{i}_{qs} - i_{qs}) \lambda_{dr}] / K \\
 \text{Where } K &= \frac{T_r}{Lm} (\lambda_{qr}^2 + \lambda_{dr}^2)
 \end{aligned} \tag{9}$$

The right hand term seems as the term of speed calculation from adaptive observer, so the speed can be calculated from the following equation [8]:

$$\begin{aligned}
 \hat{\omega}_r &= \frac{1}{K} [(K_p (i_{ds} - \hat{i}_{ds}) \lambda_{qr} - (i_{qs} - \hat{i}_{qs}) \lambda_{dr}) + \\
 &\quad (K_I \int (i_{ds} - \hat{i}_{ds}) \lambda_{qr} - (i_{qs} - \hat{i}_{qs}) \lambda_{dr})]
 \end{aligned} \tag{10}$$

Fig. 2 shows The MRAS system.

#### 4. Drive System

The control scheme of low cost induction motor drive is shown in Fig. 3. It incorporates the speed controller which receives the error signal between the preset speed and the actual observed speed of the motor shaft and then generates the torque command ( $T_e^*$ ) through a proportional integral (PI) speed controller. This torque command produces the quadrature current command  $I_{qs}^*$  in the synchronous reference frame (SYRF). The direct

current  $I_{ds}^{*e}$  is sets by the rotor flux level  $\lambda_{dr}^{*e}$ . This flux level is calculated according to the method described in [6]. The two current commands are then transformed to the stationary reference frame (STRF) with the aid of the calculated command angle ( $\theta_e^*$ ). This command angle is calculated in such way that aligns the direct-axis of SYRF with the rotor flux axis. The two stator current commands,  $I_{qs}^{*e}$  and  $I_{ds}^{*e}$  in the SYRF are then transformed to STRF and then transformed to three phase references current  $i_{ar}, i_{br}$  and  $i_{cr}$ . Only, two currents reference  $i_{ar}$  and  $i_{br}$  required for the hysteresis current controller that generates the switching function for the pulse width modulated voltage source inverter.

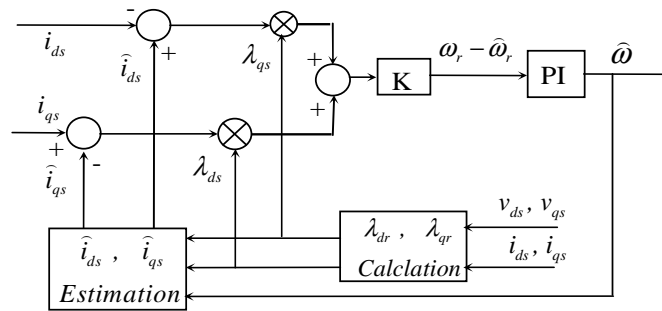


Fig. 2 MRAS speed estimation

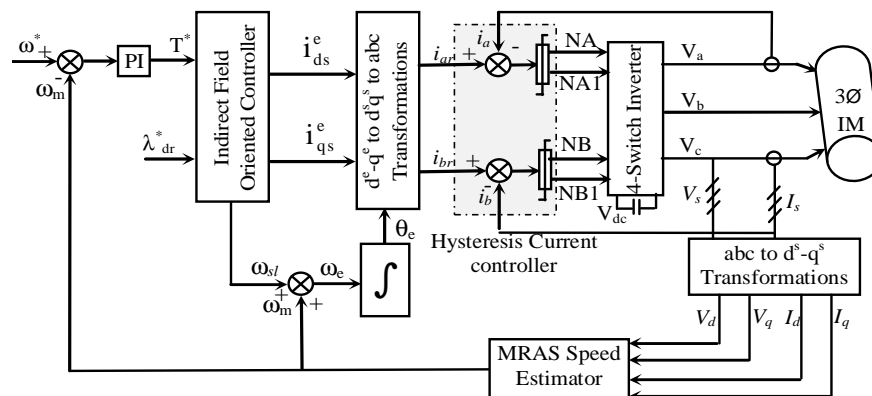


Fig 3. Block diagram for a vector-controlled induction motor based on speed estimation

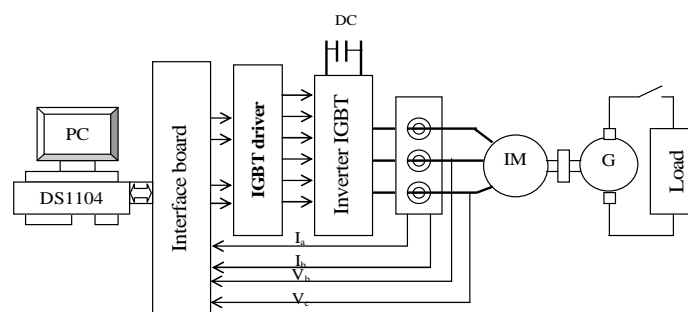


Fig 4 Experimental set-up for DSP-based control of induction motor

### 5. Experimental Results

To verify the validity of the proposed system, an induction motor vector control system was constructed. Fig. 4 shows a block diagram of the experimental system, which was composed of a DSP board DSP 1104 which is based on 32-bit floating point DSP TI TMS320C31. The board is also equipped with a fixed point 16 bit TMS320P14 DSP which is used as a slave processor [9]. Two phases currents and voltages  $I_a, I_b$  and  $V_a, V_b$  are sensed by Hall-effect current and voltage sensors.

These signals are fed to the DSP through the signal conditioning circuit. Also the speed of the rotor is sensed by 2048 PPR incremental encoder for detecting the motor speed and fed to the encoder interface on the DSP board. The control algorithm is executed by 'simulink' and downloaded to the board through host computer. The outputs of the board are four logic signals, which are fed to the proposed 4-switch, 3-phase inverter through driver isolation circuits. The sampling time for experimental implementation is chosen as 100  $\mu$ sec. The performance of the conventional six switch inverter based sensorless IM drive system and proposed system is compared at different operating conditions.

The performances of the proposed MRAS-based FSTP inverter fed IM have been investigated experimentally. The response due to a step change in the speed command is used to evaluate the performance in terms of steady state errors and stability. The motor is subjected to step increase in the reference speed at no load to evaluate the performance.

Fig. 5.a shows the estimate and measured speed response with a command speed of 90 rad/sec at no load at  $t=0.9$  second, the speed reference has been changed to 120 rad/sec. It can be seen that the rotor speed is accelerated smoothly to follow its reference value with nearly zero steady state error. Fig. 5.b shows the motor phase current and its reference. The motor current increases with increasing speed and return back to its normal value. These results show a good correlation between the estimated speed signal and its corresponding measured as well as reference speed signals.

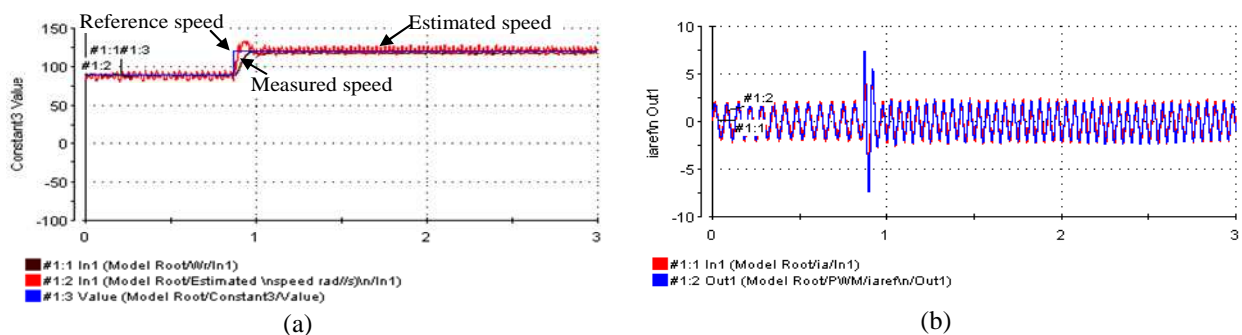


Fig. 5 Experimental results of FSTP Drive at no load, (a) Speed; (b) Phase current and its reference

In order to provide a fair comparison, the speed responses of the conventional SSTP inverter fed IM drive at identical conditions are shown in Fig.6. It is seen in Figs 6.a that the estimated and measured speed follows the reference speed. Fig. 6.b shows the motor phase current and its reference for the step change in speed command.

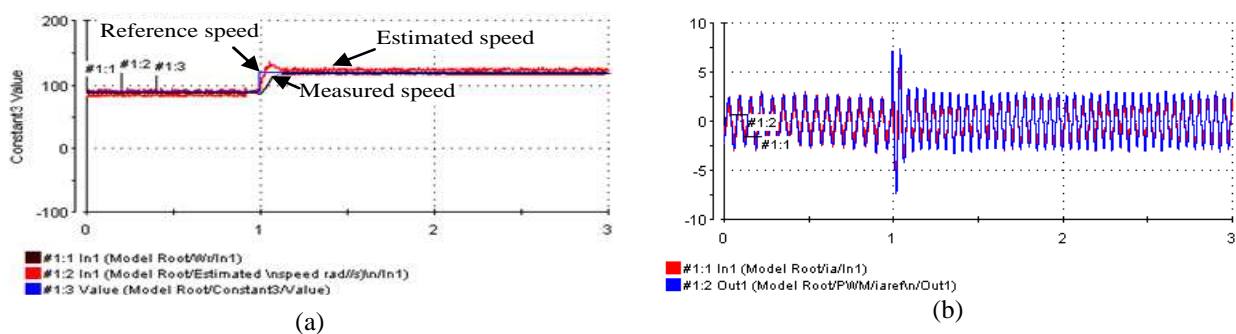


Fig. 6 Experimental results of SSTP Drive at no load, (a) Motor Speed; (b) Phase current and its reference

Fig. 7 shows the drive response when motor fed from FSTP inverter. The drive is subjected to step change in the speed reference at full load. The motor is running at 90 rad/sec, At  $t=0.9$  second, the speed reference has been changed to 120 rad/sec. it shows that perfect speed tracking with zero steady state error. The response indicates how well the controller succeeds in forcing the actual rotor speed to follow the desired reference trajectory. With nearly zero steady-state error. Fig. 7.b shows motor phase current with its reference, it increases with step up of speed reference and back to its normal value.

Also, Fig. 8.shows the drive response when the motor is fed from SSTP conventional inverter at identical conditions. Fig. 8a shows that the estimated and measured speed follows the reference speed with nearly zero steady state error. Fig. 6.b shows the motor phase current and its reference for the step change in speed command.

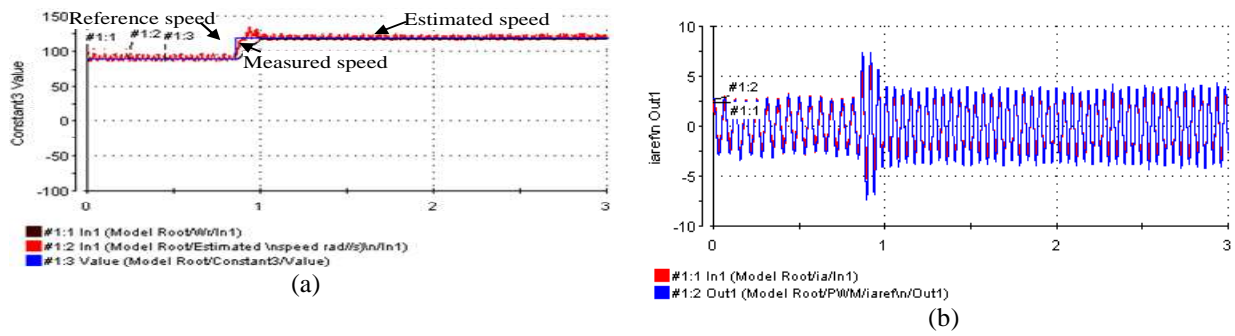


Fig. 7 Experimental results of FSTP Drive at full load, (a) Speed; (b) Phase current and its reference

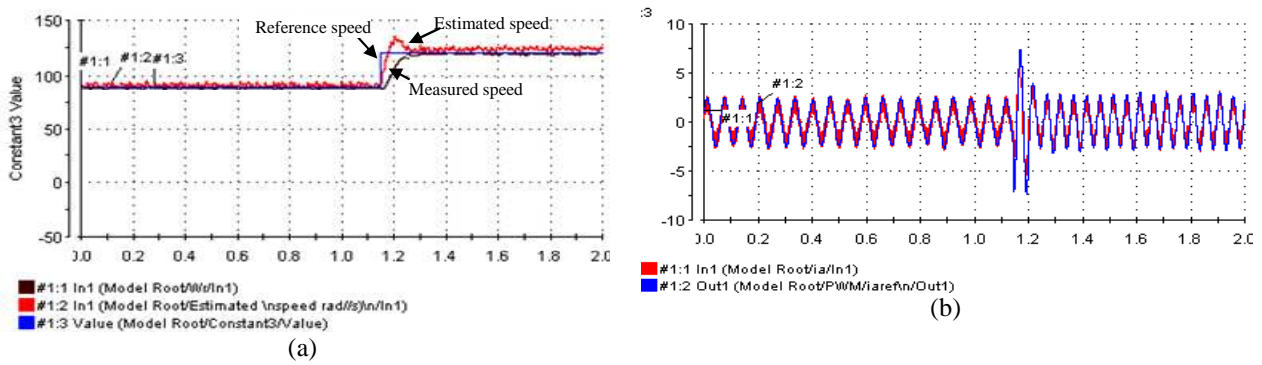


Fig. 8 Experimental results of SSTP Drive at full load (a) Speed; (b) Phase current and its reference

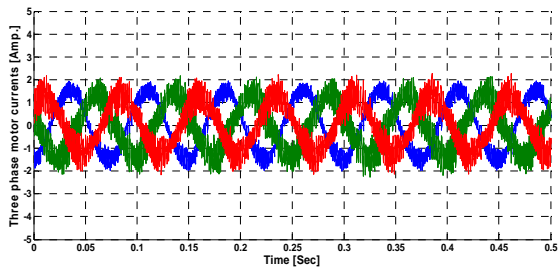


Fig. 9 Three phase motor currents of FSTP Drive at no load

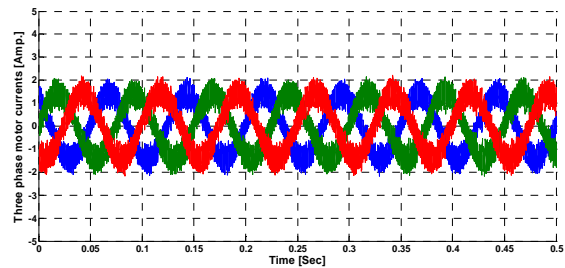


Fig. 10 Three phase motor currents of SSTP Drive at no load

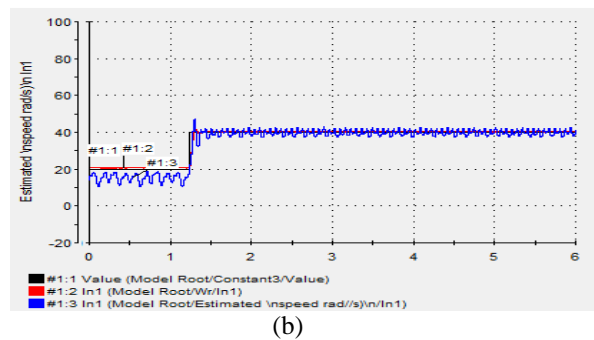
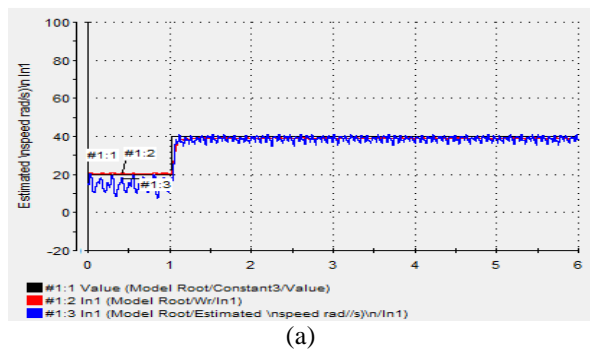


Fig. (12) Estimate, measured and reference motor speed at no load

Fig. 9 shows the steady-state three phase motor currents of FSTP Drive at no load with a command speed of 90 rad/sec. the steady-state three phase motor currents indicates almost balanced operation of the 4-switch, 3-phase inverter, which is also verified by conventional 6-switch, 3-phase inverter response shown in Fig. 10. Figs 11, 12 show the estimate and measured speed response when motor fed from FSTP and SSIP inverter at low speed respectively, with a step change in command speed from 20 to 40 rad/sec at load. It is observed that the actual speed

of the proposed drive is following the command speed without steady-state error. However, after considering all the results, the proposed system can successfully perform sensorless control.

## 6. Conclusion

A cost-effective FSTP inverter fed IM drive using an MRAS has been implemented. The proposed MRAS-based FSTP inverter fed IM drive system reduces the cost of the inverter, the switching losses and the complexity of the control algorithms as compared with the conventional SSTP inverter based drive. The vector control scheme has been incorporated in the integrated drive system to achieve high performance. The MRAS as a speed estimator verified the robustness of the proposed approach. The performances of the proposed MRAS-based FSTP inverter fed IM drive has been investigated. A comparison of performances for the proposed FSTP inverter fed IM drive with a conventional SSTP inverter fed IM drive has also been made in terms of the speed under identical operating conditions. The proposed FSTP inverter fed IM drive has been found robust and acceptable for low-cost applications such as automotive and home appliance.

## References

- [1] Jin-Su Jang, Byoung-Gun Park, Tae-Sung Kim, Dong Myung Lee, Dong-Seok Hyun, "Sensorless Control of Four-Switch Three-Phase PMSM Drive Using Extended Kalman Filter" IEEE, pp.1368-1372, June 2008.
- [2] M. N. Uddin, T. S. Radwana, and M. A. Rahman, "Performance analysis of a 4-switch, 3-phase inverter based cost effective IM motor drives," Electrical and Computer Engineering, Canadian Conference, pp. 85–88, 2004
- [3] C. B. Jacobina, E. R. C. da Silva, A. M. N. Lima, and R. L. A. Ribeiro, "Vector and scalar control of a four switch three phase inverter," in Conf. Rec., IEEE-IAS Annu. Meeting, pp. 2422–2429, 1995.
- [4] J.Holtz, "Sensorless Control of Induction Motor Drives" proceedings of IEEE, Vol.90. No.8, pp.1359-1394, 2002.
- [5] C. B. Jacobina, M.B. de Rossiter Correa, E. R. C. da Silva, and A. M. N. Lima, "A General PWM Strategy for Four-Switch Three-Phase Inverters," IEEE Trans. Energy Conversion, vol. 21, no. 4, pp. 832-838, Dec. 2006.
- [6] J. Klima, "Analytical Investigation of an Induction Motor Fed From Four-Switch VSI With a New Space Vector Modulation Strategy," IEEE Trans. Power Electron., vol. 21, no. 6, pp. 1618-1617, Nov. 2006.
- [7] Nalin Kant Mohanty, Ranganath Muthu, Microcontroller Based PWM Controlled Four Switch Three Phase Inverter Fed Induction Motor Drive" SERBIAN JOURNAL OF ELECTRICAL ENGINEERING Vol. 7, No. 2, pp. 195-204, November 2010.
- [8] Chul-Woo Park, Woo-Hyen Kwon "Simple and robust speed sensorless vector control of induction motor using stator current based MRAC" Electric Power Systems Research 71, pp. 257–266, 2004.
- [9] dSPdCE."Digital Signal Processing and Control Engineering. Manual Guide. GmhH. Paderhom~ Germany, 1996".
- [10] Matlab/Simulink Toolbox User's Guide, The Mathworks Inc., Natick, MA, USA, May 1998.

## Appendix

### Machine parameters of the applied induction machine

Rated power	1.1 kw
Rated load torque	7.5 N.m.
No. of poles	4
Stator resistance	7.4826 ohm
Rotor resistance	3.6840 ohm
Rotor leakage inductance	0.0221 H
Stator leakage inductance	0.0221 H
Mutual inductance	0.4114 H
Supply frequency	50 Hz
Motor speed	1500 r.p.m.
Supply voltage	380 volts
Inertia	0.02 kg.m <sup>2</sup>

### List of Symbols;

$$L_{\sigma} = L_s - \frac{L_m^2}{L_r}, T_r = \frac{L_r}{R_r}, \sigma = 1 - \frac{L_m^2}{L_s L_r}$$

$V_{qse}, V_{dse}$	qe-de –axis stator voltage
$I_{qse}, I_{dse}$	qe-de –axis stator current
$\lambda_{qse}, \lambda_{dse}$	qe-de –axis stator flux linkage
$R_s, R_r$	stator and rotor resistances
J, B	moment of inertia and viscous friction coefficients
$L_s, L_r, L_m$	stator, rotor and mutual inductances

**Bibliography of authors**

**Dr. Z. M. Elbarbary** was born in Kaferelsheikh, Egypt, in 1971. He received the B.Sc., M.Sc., and Ph.D. degrees in electrical engineering from Menoufiya University, Shebin El-Kom, Egypt, in 1994, 2002, and 2007, respectively. In 2009, he joined Kaferelsheikh University as an Assistant Professor. His fields of interests are ac motor drives ; power electronics and Solar energy.



**Dr. M. K. Metwally** received his doctoral degree in electrical engineering from Vienna University of Technology, Austria in March 2009. He is a lecturer in the Department of Electrical Engineering, Minoufiya University, Egypt. Presently he is working as Assistant Professor in Electrical Engineering department, Taif University, Kingdom of Saudi Arabia. His research interests cover AC machines control, the transient excitation of AC machines, sensorless control techniques, and signals processing.



**Dr Haitham Z. Azazi** was born in Sharkia, Egypt in 1979. He received his BSc, MSc and PhD degrees in electrical engineering from the Faculty of Engineering, Menoufiya University in 2003, 2008 and 2011, respectively. He joined the Department of Electrical Engineering, Faculty of Engineering, Menoufiya University as a demonstrator in 2003. Then, he became an assistant lecturer in 2008 and was appointed as an assistant professor in 2011. His current interests are power electronics, Control of electrical machines, DSP control and power factor correction.