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Speed Control of Induction Motor Drives Using a New Robust Hybrid Model Reference Adaptive Controller

[1]K. Halbaoui, [2]D. Boukhetala and [2]F. Boudjema
[1]Power Electronics Laboratory, Nuclear Research Center of Birine, BP 180, AinOussera, 17200, Algeria
[2]Department of Automatic Control, LCP, ENSP, 10 Avenue Pasteur, Hassan Badi, BP 182, El-Harrach, 16200, Algeria

Abstract: This study presents a new robust structure for a Model Reference Adaptive Control (MRAC) using a hybrid approach to control the speed of an Induction Motor (IM). The main concept of the proposed philosophy is to ensure automatic change of the controller by means of logic-based switching so that they correspond to the current plant environment and provide an appropriate control action to improve the overall control system performance. This structure simplifies the design and implementation of the adaptive controller requiring less effort to synthesis than a standard MRAC system. The importance of the hybrid controller is demonstrated through computer simulation and by intensive experimental results. It is shown that the presented Hybrid Mode Reference Adaptive Control (HMRAC) for IM drive has fast tracking capability, less steady state error and is robust to load disturbance.

Key words: Induction motor, field oriented control, hybrid control, MRAC

INTRODUCTION

Due to the inherent advantages of induction motor as simplicity of design, high reliability, low cost and minimum maintenance, they are widely used in industrial applications. In general, the performance requirements for the induction motor drives are: (1) fast tracking of set-point changes with small overshoot and (2) steady-state step disturbance rejection. Moreover, the performance of the controller must be insensitive to the change of operating conditions. Over the past decades many control strategies have been proposed for induction motor drives to achieve better performance (Cornell *et al*., 1977; Bose, 1986; Bolognani and Giuseppe, 1985; Leonhard, 1986).

Since, the motor equations are nonlinear, a linear model obtained by linearization around an operating point is usually adopted for the controller design. However, because of the characteristics of changing loads and varying supply frequencies, the operating point of an induction motor control system will also be changed. Moreover, the machine parameters and load characteristics are not perfectly known and they can sensibly vary during motor operation. As a result, a fixed controller that is optimal under one operating condition may no longer be suitable in another status. Tuning of the parameters of the fixed controller on-line is a very difficult task.

Adaptive control is a methodology for controlling systems with large modeling uncertainties which render robust control design tools inapplicable and thus require adaptation (Ghasemi *et al*., 2009). By adaptation we usually mean a combination of on-line estimation and control, whereby a suitable controller is selected on the basis of the current estimate for the uncertain process. More precisely, we choose a parameterized family of controllers, where the parameter varies over a continuum which corresponds to the process uncertainty range in a suitable way. We then run an estimation procedure, which at each instant of time provides an estimate of the unknown process model. According to certainty equivalence, one applies a controller that is known to guarantee some desired behavior of the process model corresponding to the current estimate (Boukhetala *et al*., 2006).

This classical approach to deterministic adaptive control has some inherent limitations which have been well recognized in the literature. Most notably, if unknown parameters enter the process model in complicated ways, it may be very difficult to construct a continuously parameterized family of candidate controllers.

Estimation over a continuum may also be a challenging task. These issues become especially severe if robustness and high performance are sought. As a

Corresponding Author: K. Halbaoui, Nuclear Research Center of Birine, BP 180, AinOussera, 17200, Algeria
Tel: +213 27821154 Fax: +213 27874280

result, design of adaptive control algorithms involves a large number of specialized techniques and often depends on trial and error.

To this end, this study, proposes a Hybrid MRAC to control of IM, which seeks to overcome some of the above difficulties, while retaining the fundamental ideas on which adaptive control is based. The main feature which distinguishes this controller from conventional adaptive control is that controller selection is carried out by means of logic-based switching rather than continuous tuning. Switching among candidate controllers is orchestrated by a switching controller. The idea of using switching in an adaptive context has been around for some time and various approaches have been developed (Edoardo *et al.*, 2001; Pait and Kassab, 2001; Miller and Davison, 1991; Kosmatopoulos and Ioannou, 1999; Hocherman-Frommer *et al.*, 1998; Liberzon *et al.*, 2000; Morse, 1996; Minyue *et al.*, 1986). Validity of the proposed HMRAC technique to control the speed of IM under FOC is demonstrated by the experimental results.

FIELD ORIENTED CONTROL

Generally, the dynamic modeling of an induction motor drive is performed based on a rotating reference-frame theory and a linear technique. A system configuration of an induction motor drive is shown in Fig. 1.

This motor drive consists of an induction motor, a bang-bang current-controlled Pulse Width Modulated (PWM) inverter, a field-orientation mechanism, a coordinate translator and a speed controller. The power converter connected to the line is used as the well known 3 phase diode bridge rectifier. In this converter, the power can only flow from the utility AC side to the DC side and the line current is not continuous. Because this type of AC-DC conversion does not controlled line current harmonics, the displacement power factor is poor (Vazquez *et al.*, 2009).

The electrical dynamics of an induction motor in the synchronously rotating reference frame (d- and q-axis) can be expressed as:

$$\begin{bmatrix} R_s + L_\sigma p & \omega_e L_\sigma & \frac{L_m}{L_r} p & \omega_e \frac{L_m}{L_r} \\ -\omega_e L_\sigma & R_s + L_\sigma p & -\omega_e \frac{L_m}{L_r} & \frac{L_m}{L_r} p \\ -R_r \frac{L_m}{L_r} & 0 & \frac{R_r}{L_r} + p & (\omega_e - \omega_r) \\ 0 & -R_r \frac{L_m}{L_r} & -(\omega_e - \omega_r) & \frac{R_r}{L_r} + p \end{bmatrix} \cdot \begin{bmatrix} i_{qs} \\ i_{ds} \\ \phi_{qr} \\ \phi_{dr} \end{bmatrix} = \begin{bmatrix} v_{qs} \\ v_{ds} \\ 0 \\ 0 \end{bmatrix} \quad (1)$$

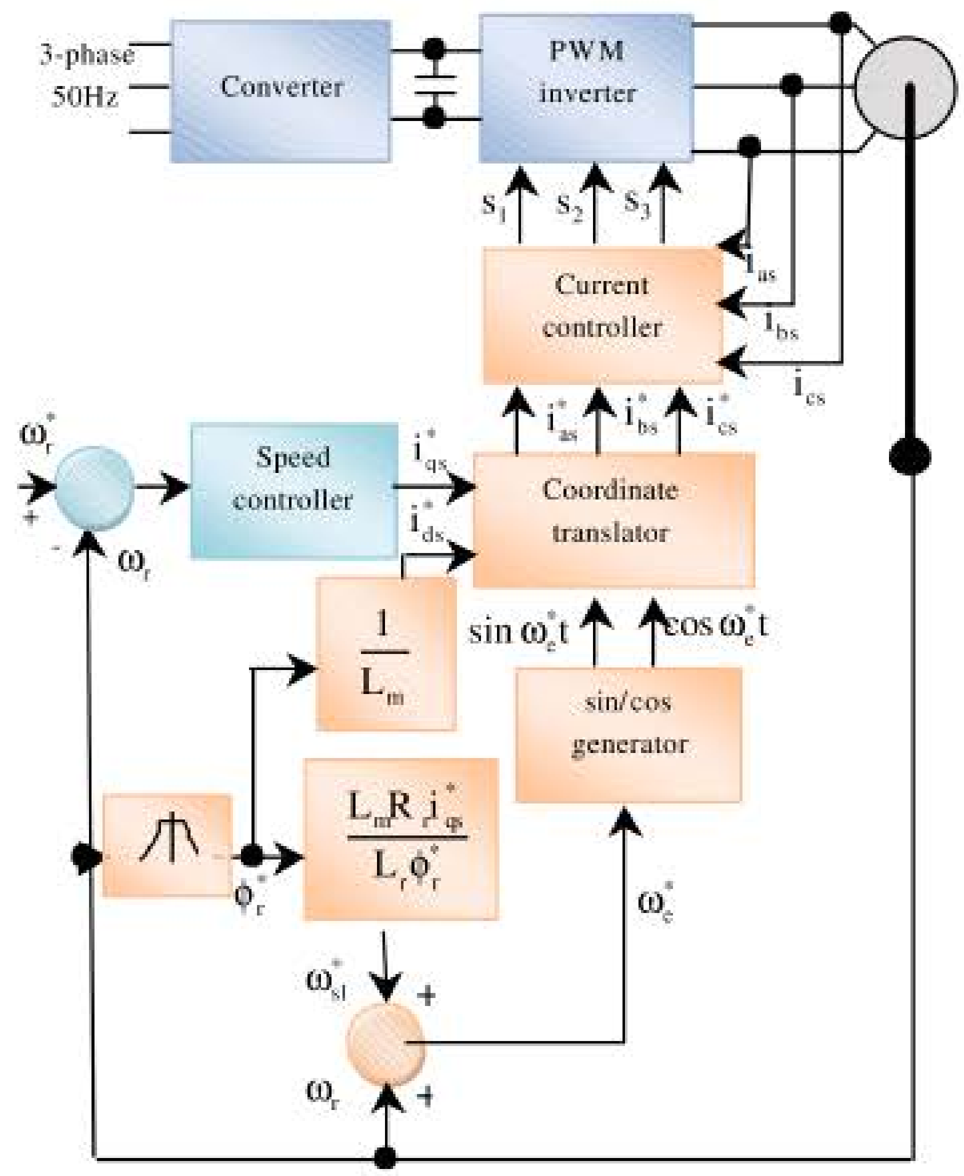

Fig. 1: The indirect field-oriented induction motor drive

The torque generated by this induction motor is:

$$T_e = \frac{3P}{4}\frac{L_m}{L_r}(\phi^e_{dr} i^e_{qs} - \phi^e_{qr} i^e_{ds}) = J\frac{d\omega_r}{dt} + B\omega_r + T_L \quad (2)$$

Where:

v_{qs}, v_{ds}	: d- and q-axis stator voltages
i_{Qs}, i_{ds}	: d- and q-axis stator currents
ϕ_{qr}, ϕ_{dr}	: d- and q-axis rotor fluxes
R_s, R_r	: Stator and rotor resistances
L_s, L_r and L_m	: Stator, rotor and mutual inductances
L_σ	: Leakage inductance
p	: Differential operator
p	: Pole number
ω_e, ω_r and ω_{sl}	: Synchronous, rotor and slip angular speeds
J	: Rotor inertia
B	: Viscous friction
T_L	: Load torque

For field-oriented control (Ustun, 2007; Marino *et al.*, 1999; Barambones and Garrido, 2004; Huang *et al.*, 1999), the instantaneous speed of the rotor flux vector is selected to revolve at a synchronous speed and the d-axis is aligned to the rotor flux direction. The q-axis component of the rotor flux vanishes and the rotor flux is entirely in the d-axis, i.e.,

$$\phi_{qr} = p\phi_{qr} = 0 \tag{3}$$

and

$$\phi_{dr} = \phi r \text{ constant} \tag{4}$$

where, ϕ_r denotes the rotor flux. Substituting Eq. 3 and 4 into Eq. 1 and 2 yields:ω

$$\omega_{s1}^{*} = \frac{R_r L_m}{\phi_r^{*} L_r} i_{qs}^{*} \tag{5}$$

$$i_{ds}^{*} = \frac{\phi_r^{*}}{L_m} \tag{6}$$

and

$$i_{qs}^{*} = \frac{4L_r}{3PL_m\phi_r^{*}} T_e^{*} \tag{7}$$

where, the subscript * represents the command. Equation 7 indicates that if the rotor flux ϕ_r is constant for a constant torque operation, the electromagnetic torque T_e^{*} can be linearly varied by adjusting i_{qs}^{*}. Therefore, a field-oriented control method controls the induction machine as if it were a separately excited dc machine.

CONTROLLER DESIGN

The design of HMRAC controller had as motivation to get a controller more robust that, only making the available information of the reference model and output measures of the plant, it turned the system in robust shut mesh in relationship with uncertainties in the parameters, external disturbances and non modeled dynamics, besides a good transitory acting (Halbaoui *et al*., 2008).

Case 1: Assuming the IFOC-IM as a dc equivalent machine, as it sees in Fig. 2, the plant can represent as a first order differential equation.

The algorithm will be explained to Hybrid controller as first order plant:

$$T.\frac{d\omega_r(t)}{dt} + \omega_r(t) = K.u(t) \tag{8}$$

The two integral controllers in Fig. 2 will be used as the analog controller C_1 and C_2 in the switched controller. Then the controlled signal $u_i(t)$ is calculated as follows:

$$u_i(t) = \int_0^t g_i.S_i(\tau).\varepsilon(\tau).d\tau \tag{9}$$

where, g_i is a constant gain of analog controller C_i, $\varepsilon(t)$ is the error signal and $S_i(t)$ is two values (1 or 0) function and determined by switching controller as following equation:

$$S_i(t) = \begin{cases} 1; & C_i \text{ is being connected} \\ 0; & C_i \text{ is being disconnected} \end{cases}$$

Thus $S_i(t)$ can be considered as a pulse train function. If $\delta_i(t)$ and $\lambda_i(t)$ denotes its pulse width and period, respectively then the duty rate of pulse is $\delta_i(t)/\lambda_i(t)$. Let $h_i(t)$ denotes the duty rate. Since the switch is tuned around in order shown as Fig. 2 so then the summation of duty rate of each switch will be equal 1, i.e., $h_1(t)+h_2(t) = 1$.

Since, the control signal of plant u(t) is the sum of each analog controller then it can be calculated by next equation:

$$u(t) = u_1(t)+u_2(t) \tag{10}$$

Substituting in Eq. 9 to 10, the following equation is obtained:

$$u(t) = \int_0^t k_1.S_1(\tau).\varepsilon(\tau).d\tau + \int_0^t k_2.S_2(\tau).\varepsilon(\tau).d\tau \tag{11}$$

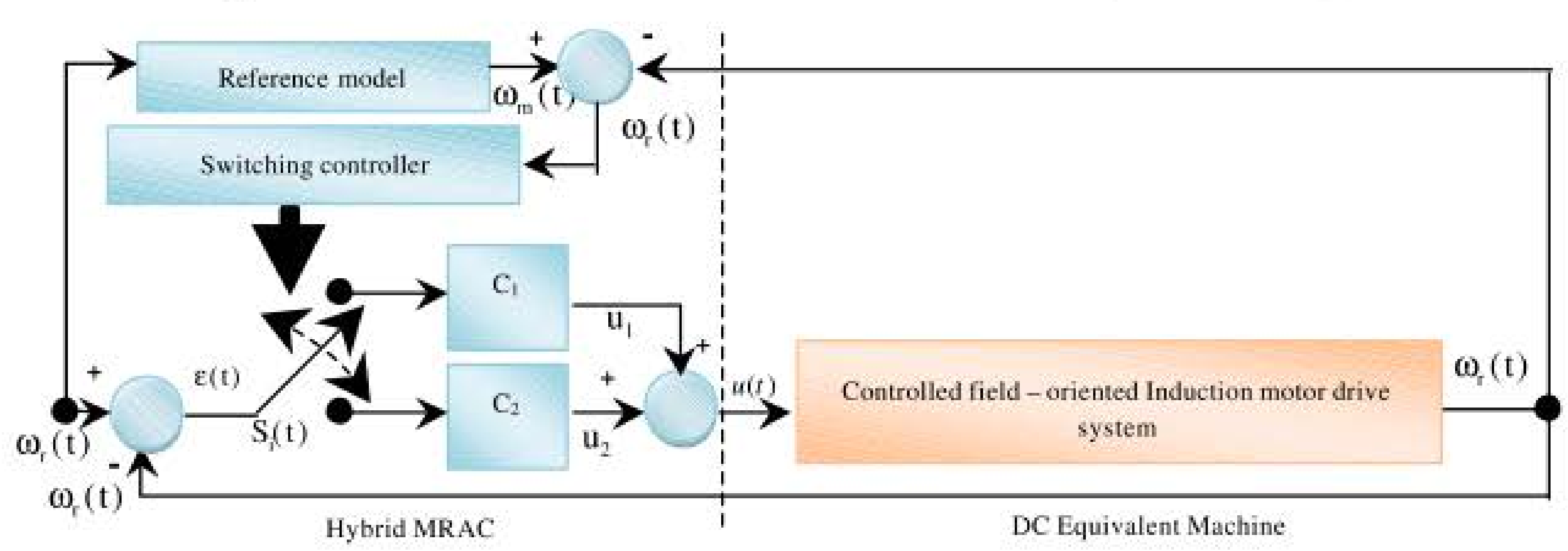

Fig. 2: The field-oriened induction motor drive with speed controller of HMRAC

If frequency of switching is higher than the frequency of reference signal enough Eq. 11 can be approximated as follows:

$$u(t) \approx \int_0^t (h_1 g_1 + h_2 g_2).\varepsilon(\tau).d\tau \tag{12}$$

where, h_1 and h_2 are the duty rate of switch $S_1(t)$ and $S_1(t)$ mentioned above, respectively. Using this control signal in Eq. 12 to the plant in Eq. 8, the closed loop adaptive control system can be described as below:

$$T\frac{d^2\omega_r(t)}{dt^2} + \frac{d\omega_r(t)}{dt} + (h_1 g_1 + h_2 g_2)K\omega_r(t) = (h_1 g_1 + h_2 g_2)K\omega_r^*(t) \tag{13}$$

As above closed loop system that consists of 1st order plant and the integrator, the reference model should be 2nd order system described as follows:

$$T.\frac{d^2\omega_m(t)}{dt^2} + \frac{d\omega_m(t)}{dt} + L_m\omega_m(t) = L_m\omega_r^*(t) \tag{14}$$

Comparing Eq. 14 to 13, we can show that the error signal e(t) between the output of plant and reference model will be converged to zero asymptotically if the coefficient of both equations are the same or Eq. 15 is satisfied:

$$(h_1 g_1 + h_2 g_2).K = L_m \tag{15}$$

To satisfy Eq. 15 the switching controller will turn the switch to connect an analog controller to the closed loop path and disconnected the behind one from the loop logically by the following switching law. However, the limitation of switch bandwidth frequency and the excitation of the analog controller so then the considerable small boundary region of error $\omega\Delta_r$ will be applied to the switching law as the hysteresis width. Δt is the sampling time of switching controller. The switching law of the hybrid controller is shown in Table 1.

To investigate the above adaptive scheme a study case of simulation is performed. The following parameters condition is used for simulation.

- Model: T = 0.35, Lm = 1.5
- Plant : T = 0.35, k = 0.5
- Hybrid analog controller: C_1 = 10/s, C_2 = -10/s

The simulation results, the step response of both model and plant are shown in Fig. 3 and 4, respectively. Furthermore, the control signal is shown in Fig. 5.

These results verify that the two analog controllers C_1 and C_2 are switched by the switching controller suitably.

Table 1: Switching law of switched controller

	$\lvert e(t)\rvert > \Delta\omega_r$		$\lvert e(t)\rvert \le \Delta\omega_r$
Variables	$e(t).\varepsilon(t)>0$	$e(t).\varepsilon(t)<0$	X
$S_1(t)$	1	0	$S_1(t-\Delta t)$
$S_1(t)$	0	1	$S_1(t-\Delta t)$

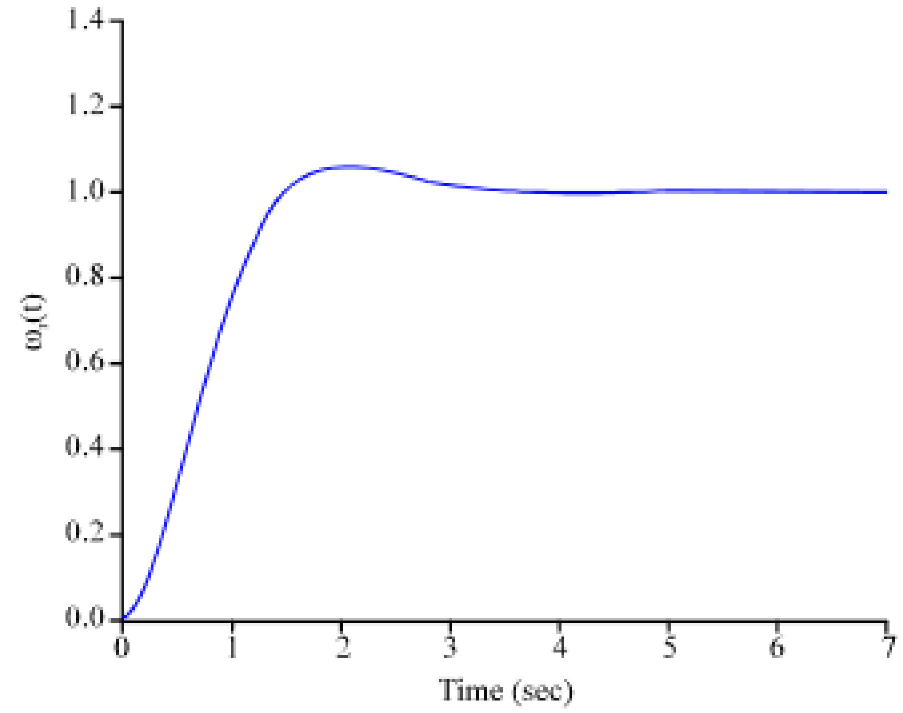

Fig. 3: A step response of the plant

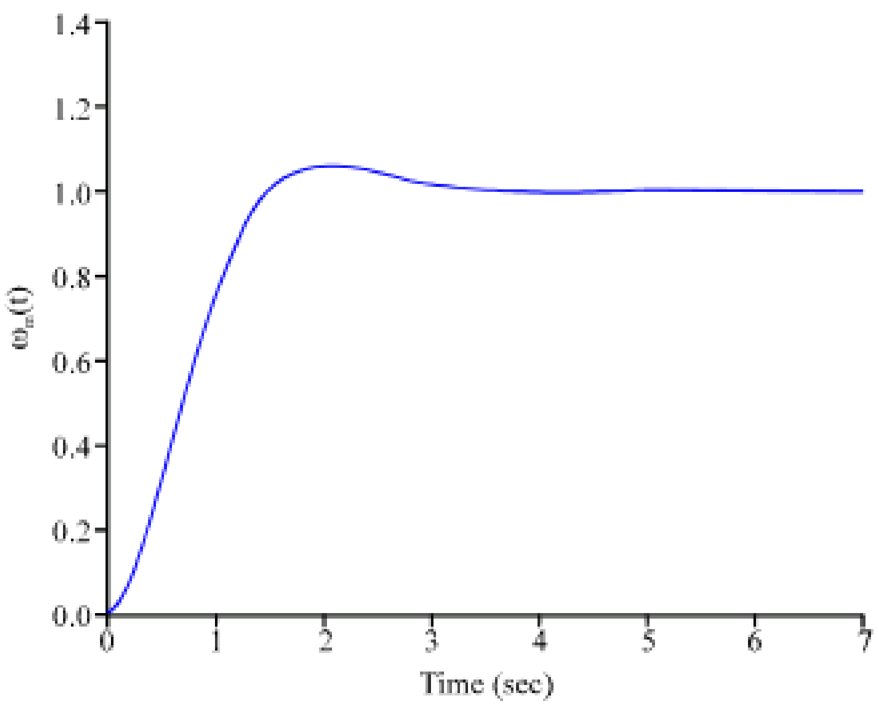

Fig. 4: A step response of the model reference

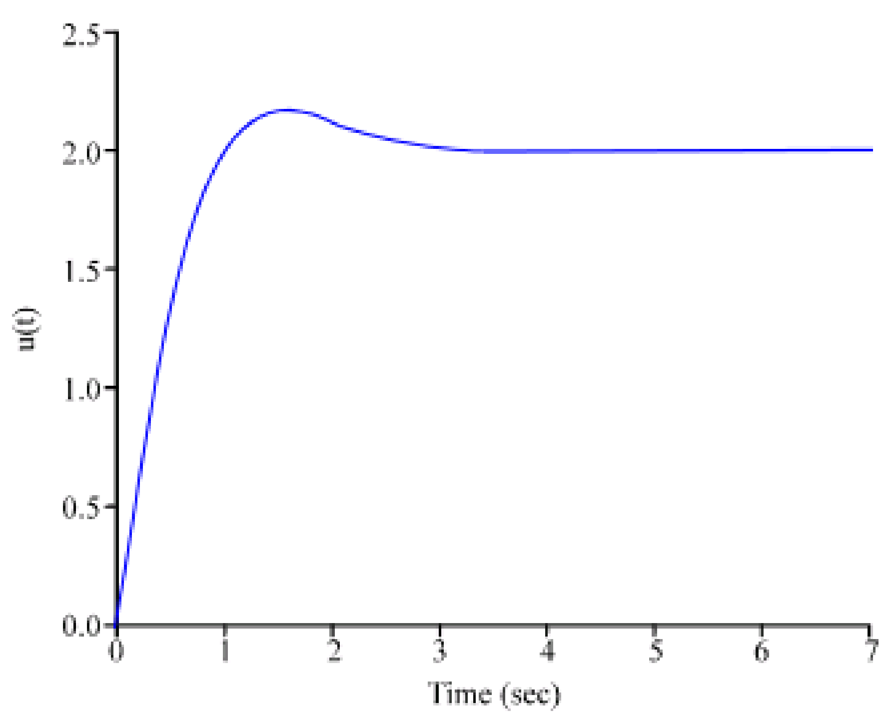

Fig. 5: A control signal of the plant

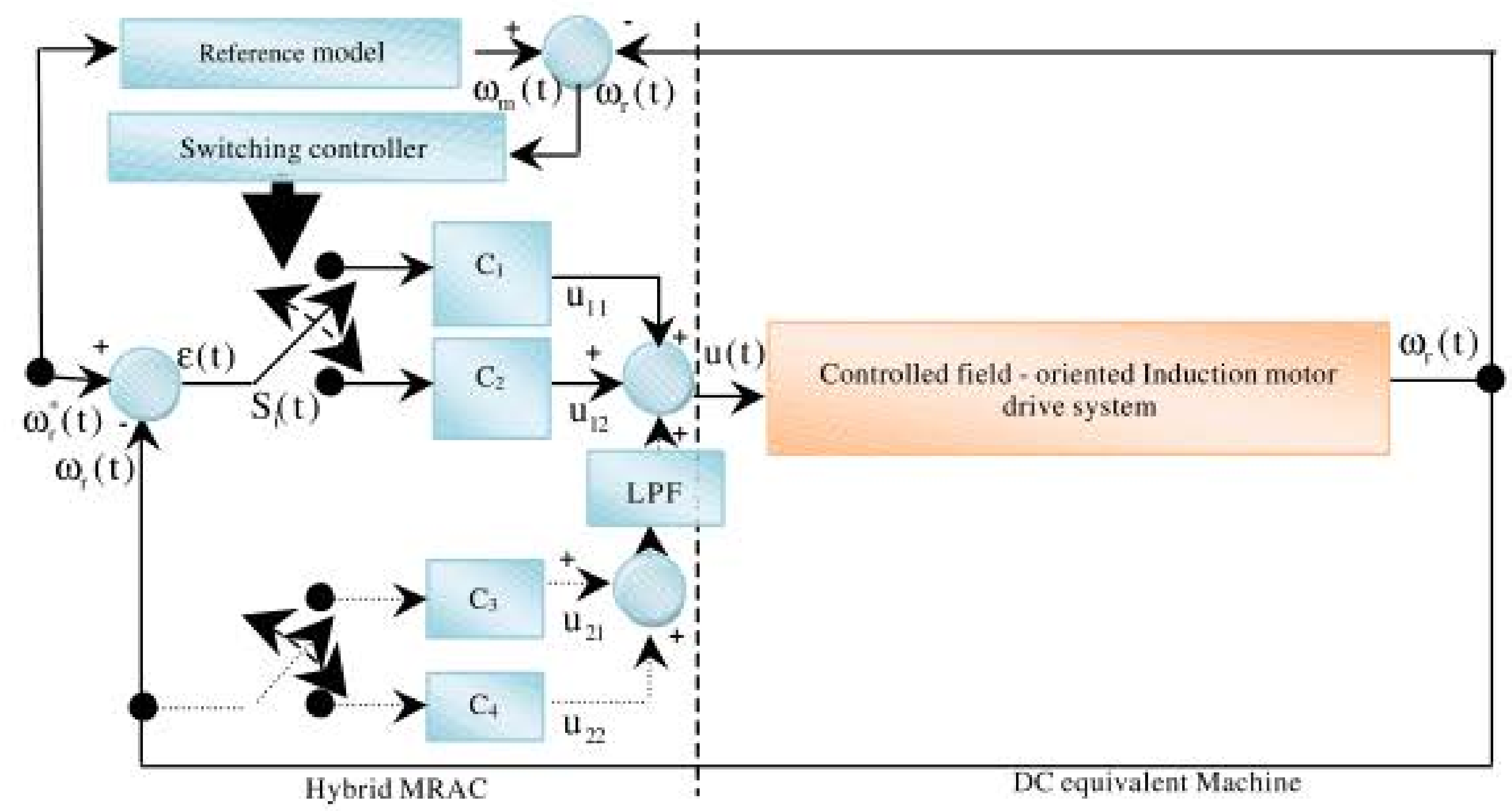

Fig. 6: The field-oriented indiduction motor drive with speed controller of HMRAC

Table 2: Switching law of switched controller

Variables	$\lvert e(t)\rvert > \Delta\omega_r$		$\lvert e(t)\rvert \le \Delta\omega_r$
	$e(t).\omega_r(t)>0$	$e(t).\omega_r(t)<0$	X
$S_3(t)$	1	0	$S_3(t-\Delta t)$
$S_4(t)$	0	1	$S_4(t-\Delta t)$

In the case 2 mentioned below will extend the use of hybrid analog controller to the plant with two varying parameters.

Case 2: For better consideration of the parametric variation T and k of the induction motor and keeping the response that coincides with the response of 2nd order model described in Eq. 14, the adaptation of the closed inner loop is needed. So, then a hybrid adaptive controller is added to the adaptive control system as shown in Fig. 6.

As Fig. 6, the C_3 and C_4 are the proportional analog controller with constant gain g_3 and g_4, respectively. Low pass filter LPF that rejects the high frequency signal occurred from switching.

The switching law of the hybrid controller in the inner loop is shown in Table 2.

The simulation is performed by the following conditions:

- Model: T = 0.35, Lm = 1.5
- Plant: T = 0.5, k = 0.4
- Hybrid analog controller: C_1 = 10/s, C_2 = -10/s
- LPF: 1/(0.01s+1)

In this case, the adaptation mechanism may generate additional control signal $u_2(t)$ (Fig. 6) which minimize the difference between reference model (Fig. 8) and system output $\omega_r(t)$ (Fig. 7). Such a control system is known as

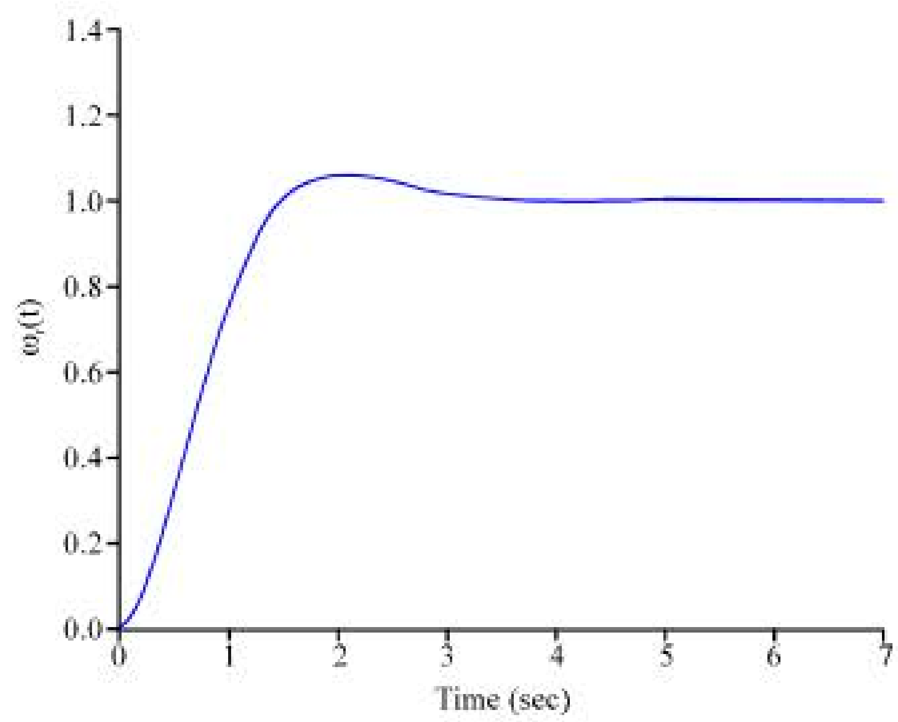

Fig. 7: A step response of the plant

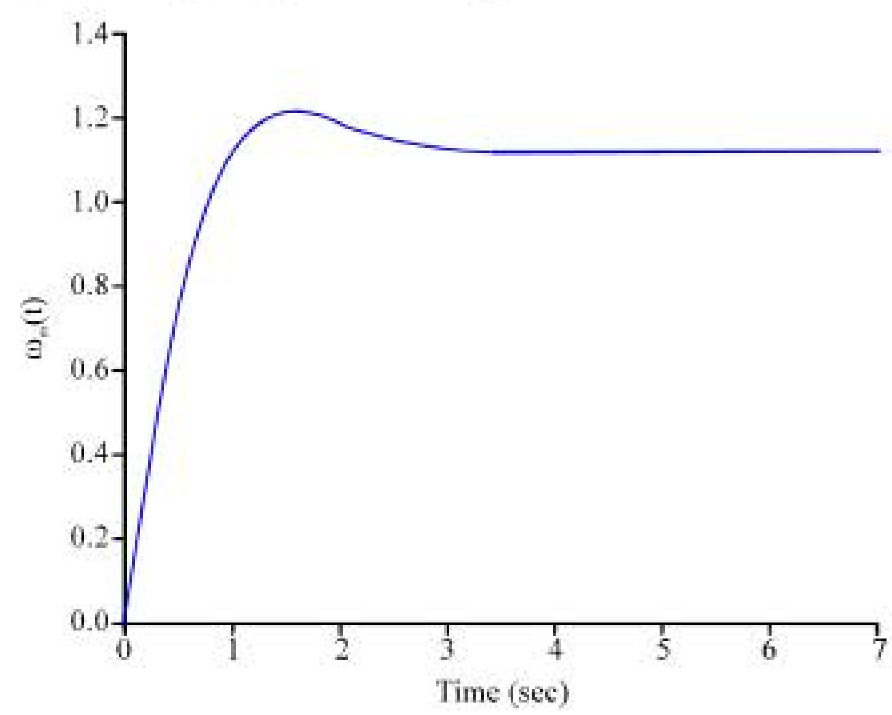

Fig. 8: A step response of the model reference

Model Reference Adaptive Control (MRAC) with signal adaptation. The signal adaptation algorithm generates the

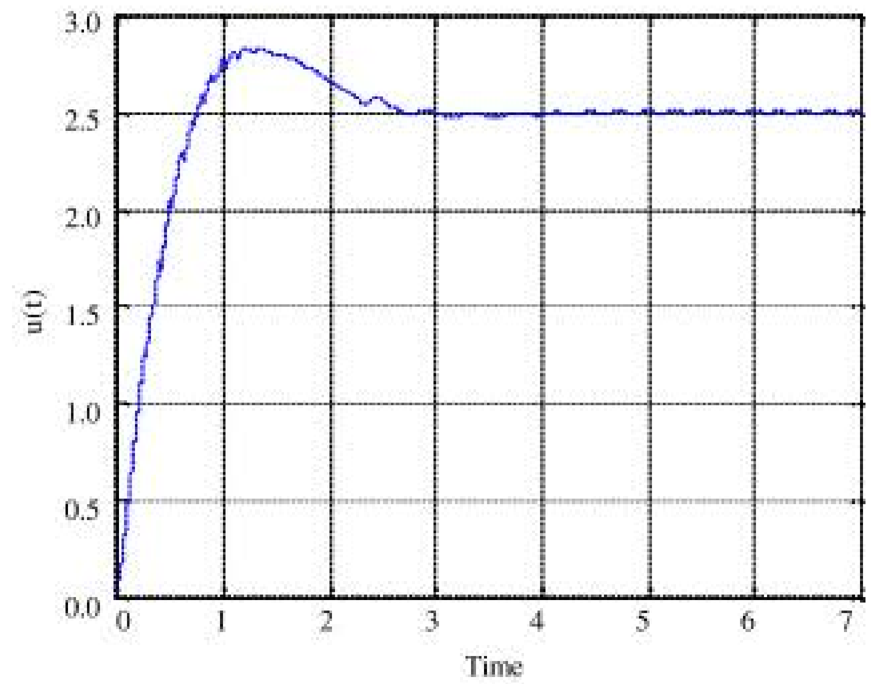

Fig. 9: A control signal of the plant

adaptation signal $u_2(t)$, which compensates for the errors, i.e., the difference between reference model behavior $\omega_m(t)$ and the behavior of system with changed parameter value $\omega_r(t)$.

EXPERIMENTAL RESULTS

In order to assess the validity of the proposed controller, the hybrid speed controller of induction motor is shown in Table 3. The proposed control was tested on a 1.5 kW four-pole squirrel-cage induction motor of LEROY SOMER. Figure 10 shows the electric drive system during test.

The parameters of the proposed HMRAC are chosen as:

$$\Delta\omega_r = 0.001,\ \ \Delta t = 200\,\mu\text{sec},\ \ C_1 = -C_2 = 20.5/\text{s},\ \ C_3 = -C_4 = 20$$

$$\text{and } G_{\text{Model}} = \frac{6.7}{0.0086\ s^2 + 0.366\ s + 6.7}$$

Some experimental results are provided to demonstrate the effectiveness of the proposed hybrid controller. The measured responses of the reference model and rotor speed due to step commands are given in Fig. 11a and b, where, the step commands are (1) 60 rpm in Fig. 11a, (2) 500 rpm in Fig. 11a, (3) 800 rpm in Fig. 11a and (4) 1000 rpm in Fig. 11a. From the experimental results, good model-following control performance is yielded by the proposed hybrid controller under various operating conditions.

To show the control performance of the proposed hybrid controller to step command and step load disturbance, the step command of 60, 500, 800 and 1000 rpm and a step load torque of 4.7 Nm is applied to the motor shaft after the motor reaches the steady state

Fig. 10: Electric drive system test

Table 3: Motor parameters

Rated power	1.5 kW
Rated stator voltage	220/380 V
Rated stator current	6.1/3.4 A
Stator resistance	4.58 Ω
Rotor resistance	4.468 Ω
Stator inductance	0.253 H
Rotor inductance	0.253 H
Mutual inductance	0.11 3 H
Motor inertia	0.023 Nm sec^2/rad
Viscous coefficient friction	0.0026 Nm sec^2/rad

at 2 sec, the measured dynamic responses of the proposed hybrid controller are shown in Fig. 12a and b. There is no overshoot in the position response before the load torque is applied and the settling time is about 0.4 sec. When the step load torque is engaged, there is a small position dip about -0.025 ω_r^* rpm and the response time is about 0.2 sec. The motor torque is then removed at time 3 sec which results in a 0.02 ω_r^* rpm transient. The control can be seen to drive the motor to the correct steady state speed in the case of the load torques and in fact can be used to operate the motor in overloaded conditions for short periods of time.

In the experiments, a sinusoidal-triangular position command is used to evaluate the position tracking capability of the proposed hybrid controller.

Under the condition of no load, the measured dynamic responses of the proposed approach to the smooth start sinusoidal-triangular position command are shown in Fig. 13a and b. The performance index and speed tracking error are very small, as seen from the experimental results. These results verify that the analog controllers C_1, C_2, C_3 and C_1 are switched by the switching controller suitably. Namely the duty rate satisfying are obtained.

Figure 14a and b shows the responses of the rotor speed before and after the stator resistance Rs have

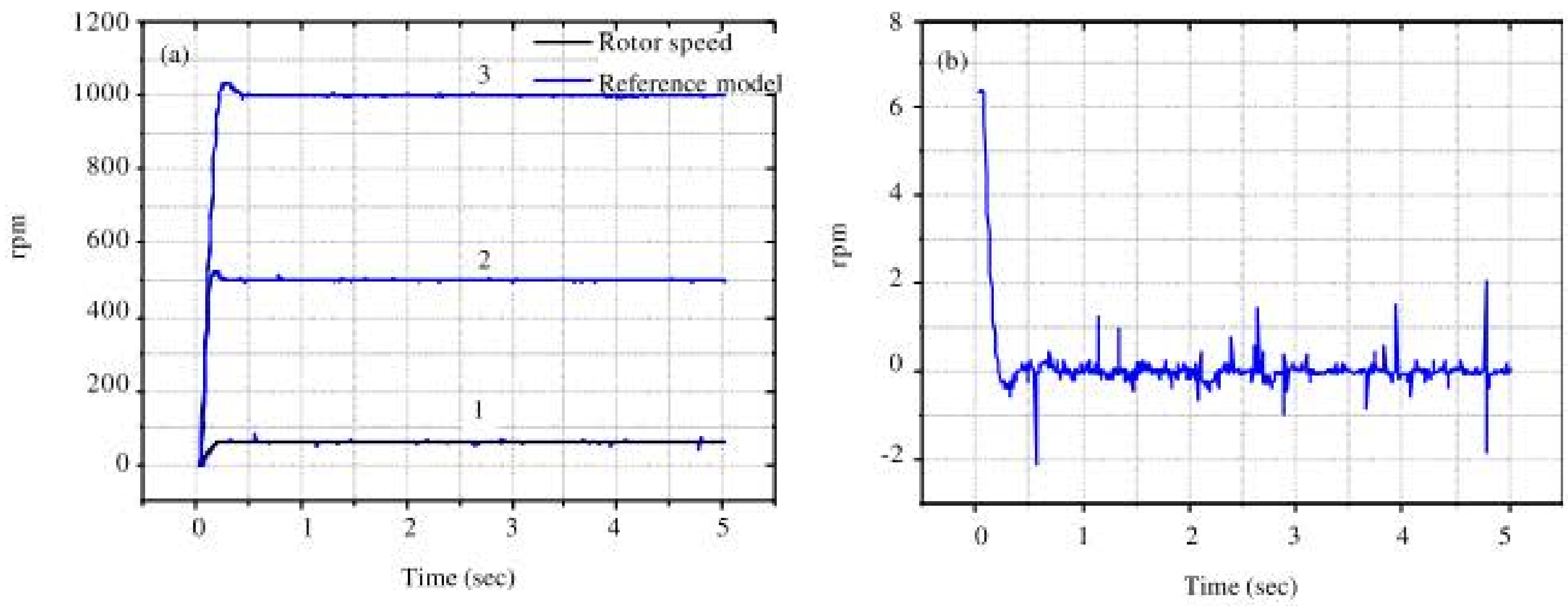

Fig. 11: Experimental results of hybrid speed controller due to step command: (1) 60 rpm, (2) 500 rpm, (3) 800 rpm and (4) 1000 rpm. (a) Rotor speed and reference model response; (b) Error between the command and the rotor speed (for $\omega_r^* = 60$ rpm)

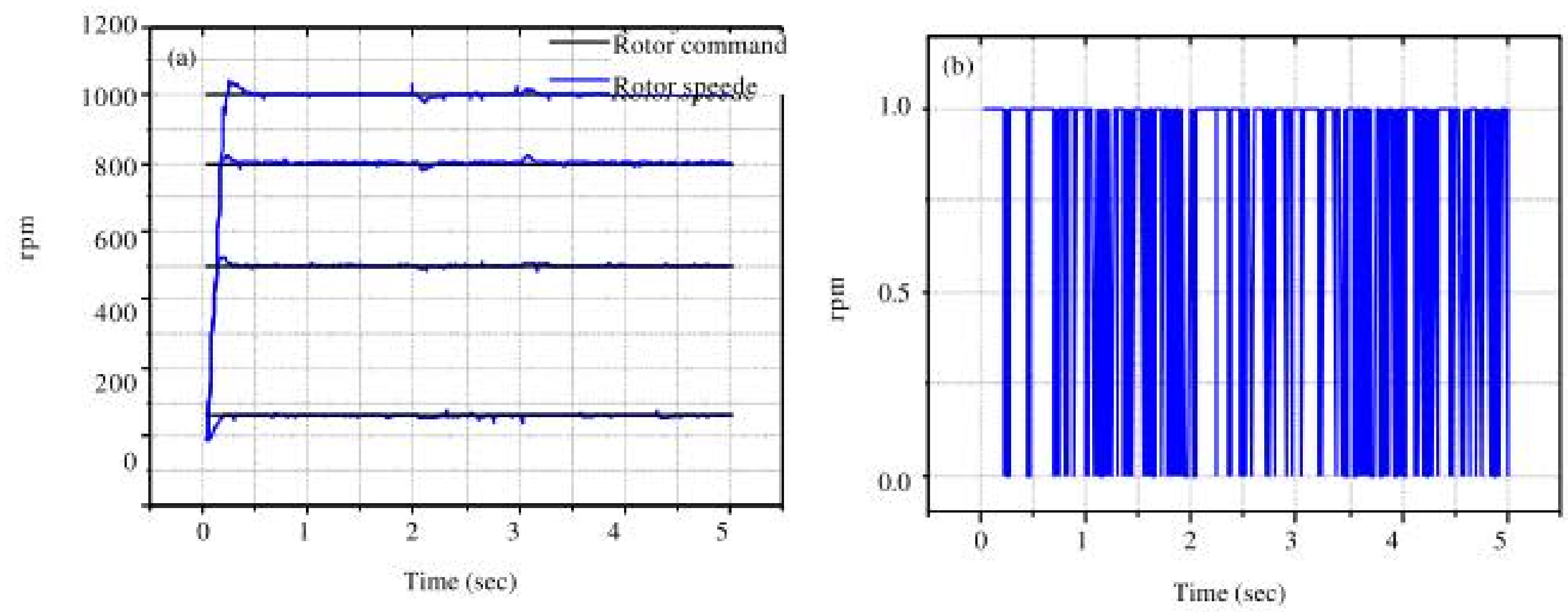

Fig. 12: Response of induction motor to application of 4.7 Nm torque at 2 sec and removal of torque at 3 sec (steady state speed of 60, 500, 800 and 1000 rpm). (a) Speed command and speed response and (b) Switching controller S1 (for $\omega_r^* = 60$ rpm)

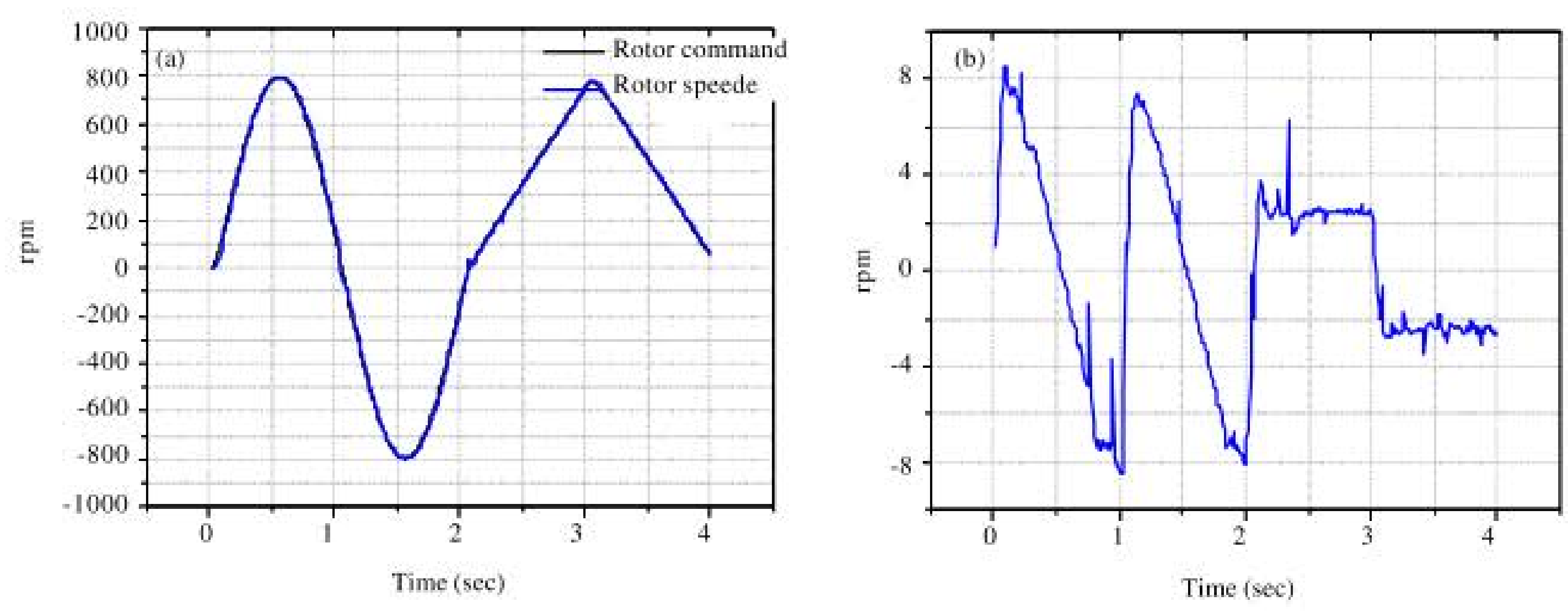

Fig. 13: Measured dynamic responses of hybrid controller wit sinusoidal-triangular position command and no load. (a) Speed command and speed response and (b) Error between the reference model response and the rotor speed (performance index)

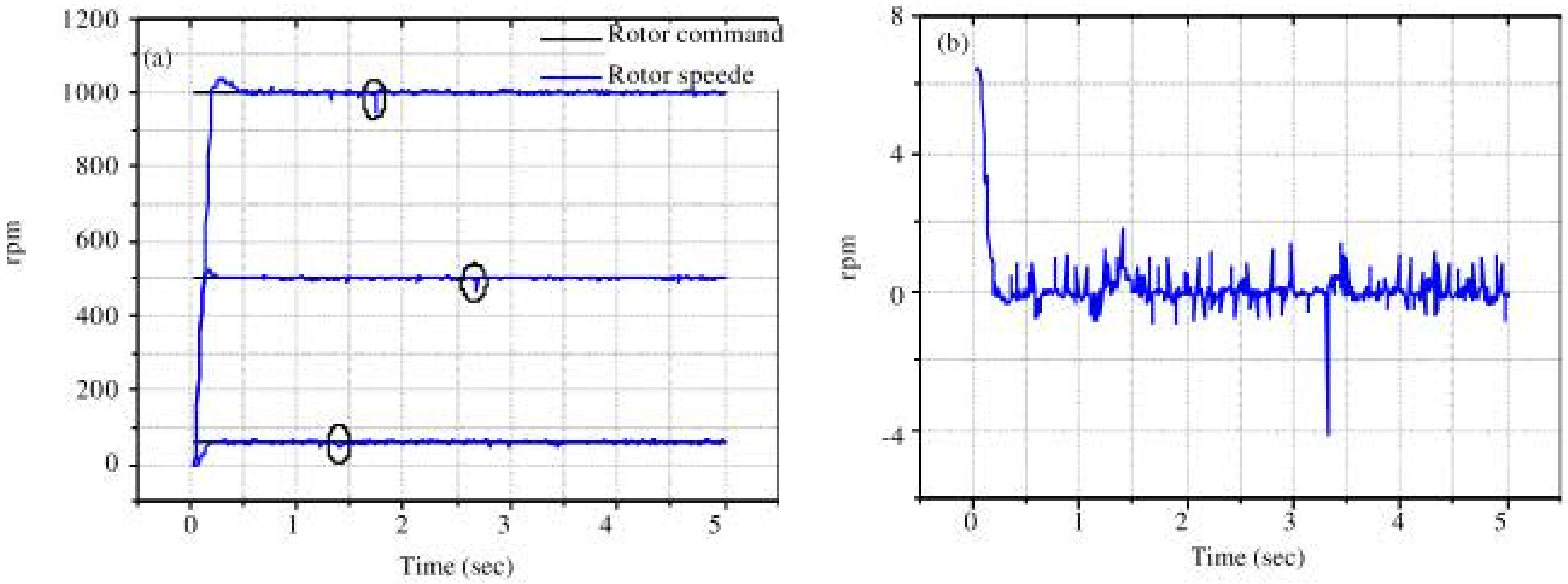

Fig. 14: Stator resistance compensation (load torque = Const = 4.7 Nm. ω_r^* = 60, 500, 800 and 1000 rpm and Rs = 2.5*Rs). (a) Speed command and speed response and (b) Error between the command and the rotor speed (for ω_r^* 60 rpm)

changed in which the load torque is constant and the preset stator resistance is 250% larger then Rs.

CONCLUSION

A speed hybrid adaptive controller for induction motor has been introduced. For taking care of the variations of load and machine parameters, no on-line model identification is required. Only the information of the reference model states and output as well as the plant output is required.

Hence, the proposed controller is easy to implement practically. Experimental results are provided to demonstrate the effectiveness of the presented strategy.

REFERENCES

Barambones, O. and A.J. Garrido, 2004. A sensorless variable structure control of induction motor drives. Electric Power Syst. Res., 72: 21-32.

Bolognani, S. and S.B. Giuseppe, 1985. Control system design of a current inverter induction motor drive. IEEE Trans. Indust. Appli., 1A-21: 1145-1153.

Bose, B.K., 1986. Power Electronics and AC Drives. Prentice-Hall, Englewood Cliffs, New Jeresy.

Boukhetala, D., K. Halbaoui and F. Boudjema, 2006. Design and implementation of a self-tuning adaptive controller for induction motor drives. Int. Rev. Electrical Eng., 1: 260-269.

Cornell, E., P. Lipo and A. Thomas, 1977. Modeling and design of controlled current induction motor drive systems. IEEE Trans. Indust. Appli., IA-13: 321-330.

Edoardo, M., C. Francesco and C. Alessandro, 2001. Designing predictors for MIMO switching supervisory control. Int. J. Adaptive Control Signal Process., 15: 265-286.

Ghasemi, R., M.B. Menhaj and A. Afshar, 2009. A Decentralized stable fuzzy adaptive controller for large scale nonlinear systems. J. Applied Sci., 9: 892-900.

Halbaoui, K., D. Boukhetala and F. Boudjema, 2008. A New Robust Model Reference Adaptive Control for Induction Motor Drives Using a Hybrid Controller. Proceedings of the International Symposium on Power Electronics, Electrical Drives, Jun. 11-13, Automation and Motion, Italy, pp: 1109-1113.

Hocherman-Frommer, J., S.R. Kulkarni and P.J. Ramadge, 1998. Controller switching based on output prediction errors. IEEE Trans. Automatic Control, 43: 596-607.

Huang, C.Y., T.C. Chen and C.L. Huang, 1999. A microcomputer-based induction motor drives with current and torque control. IEEE Trans. Energy Conversion, 14: 874-880.

Kosmatopoulos, E.B. and P.A. Ioannou, 1999. A switching adaptive controller for feedback linearizable systems. IEEE Trans. Automatic Control, 44: 742-750.

Leonhard, W., 1986. Microcomputer control of high dynamic performance AC drives-A survey. Automatica, 22: 1-20.

Liberzon, D., J.P. Hespanha and A.S. Morse, 2000. Hierarchical hysteresis switching. Proceedings of the 39th IEEE Conference on Decision and Control, Dec. 12-15, Sydney, Australia, pp: 484-489.

Marino, P., M. Milano and F. Vasca, 1999. Linear quadratic state feedback and robust neural network estimator for field-oriented-controlled induction motors. IEEE Trans. Indust. Elect., 46: 150-161.

Miller, D.E. and E.J. Davison, 1991. An adaptive controller, which provides an arbitrary good transient and steady state response. IEEE Trans. Automatic Control, 36: 68-81.

Minyue, F., B. Barmish, F. Minyue and B. Barmish, 1986. Adaptive stabilization of linear systems via switching control. Proceedings of the 25th IEEE Conference on Decision and Control, Dec. 1986, IEEE, USA., pp: 819-825.

Morse, A.S., 1996. Supervisory control of families of linear set-point controllers Part 1: Exact matching. IEEE Trans. Automatic Control, 41: 1413-1431.

Pait, F.M. and Jr. F. Kassab, 2001. On a class of switched, robustly stable, adaptive systems. Int. J. Adaptive Control Signal Process., 15: 213-238.

Ustun, S.V., 2007. GA-based optimization of PI speed controller coefficients for ANN-modelled vector controlled induction motor. J. Applied Sci., 7: 4001-4006.

Vazquez, N., H. Rodriguez, C. Hernandez, E. Rodriguez and J. Arau, 2009. Three-phase rectifier with active current injection and high efficiency. IEEE Trans. Indust. Electron., 56: 110-119.