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MRAS Speed Observer for Direct Torque Control of Sensorless Induction Motor Drives Sensitivity Study

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Abstract: To avoid the use of mechanical speed sensor in Direct Torque Control of induction motors, it was agreed to estimate by an estimator using electrical measurements and machine parameters. This study presents a speed sensorless drive of induction motors. The proposed speed estimator is based on the Model Reference Adaptive Scheme (MRAS) and uses based the comparison of estimated and measured stator current. The reduction error is achieved by an appropriate unity transfer function as reference model. The estimator formulation is defined and developed in the discrete case. The proposed algorithm requires neither matrix calculation nor approximation on Taylor series of matrix exponential. The effect of variation parameters on the estimated speed is presented. Some simulation results are shown, in order to valid the theoretical development.

Key words: Sensorless drives, induction motors, field-oriented control, adaptive control, MRAS, hyperstability concept

INTRODUCTION

The induction motor drive system is a high nonlinear plant and many parameters vary with the time and temperature. DTC of induction motor is a popular method for its fast dynamic response, lower sensitivity to motor parameter and relatively lower switch harmonics in the inverter. For high performance system, the speed sensor is necessary, but in some cases, it is impossible to use sensors for speed measurement, perhaps because it is either technically impossible or extremely expensive. In such situation as speed sensorless, an observer or a filter is needed for speed estimation. In addition, the estimation of stator flux isn't accurate in the low-speed range. There are many methods proposed to control the induction motor drive system without speed sensor, but in these methods selection of pole or gain, which gives reasonable estimation both in the steady state and transient states, is very difficult. So in the noisy environment, the methods may fail to find the stable position and estimate the speed especially in the low speed region. For this reason, the measuring noise must be considered. The MRAS is a suitable solution for the system with measuring and system noise (Maurizio and Marcello, 2005; Kyo-Beum *et al*., 2005).

This study is organized as follows. In the first part, the discrete equations of DTC of induction motor are presented.

In the next study, the proposed speed estimator based on digital MRAS structure is developed. The use of the hyperstability concept permits us to establish the stability domain and the adaptation mechanism to guarantee the stability.

Finally, the estimated speed is used in the feedback loop of the speed controller to show:

- The applicability of the algorithm is validated by simulation of the sensorless DTC.
- The behavior speed during of the variation of the parameter motor.

DTC MODELLING

The Direct Torque Control (DTC) technique was developed in the mid 1980, initially applied to the asynchronous machines. It is characterised by the simplicity of its structure, decreasing the parameter sensibility of the machine, raising the dynamic performances and requiring no speed or position sensors. A simple switching logic table allows a flux and torque decoupling. This table is based on a flux and torque hysteresis comparator, a flux detection zone and a machine model. The basic idea of the DTC method consists in the definition of a look up table which specifies the switching pattern, in order to maintain stator

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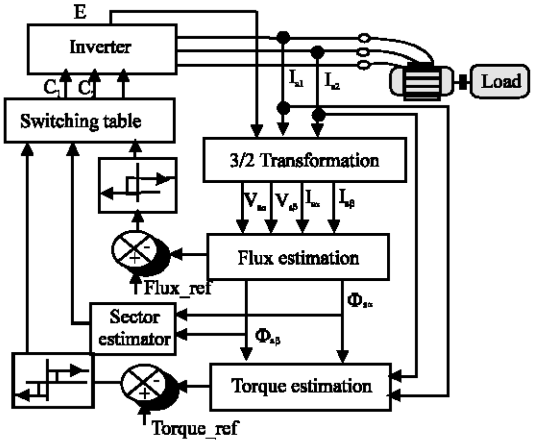

Fig. 1: Block diagram of the DTC

flux and electromagnetic torque inside a hysteresis band and close to their references.

Figure 1 shows the whole control system of an asynchronous motor. Control variables are directly estimated from stator currents (I_{s1}, I_{s2}), DC voltage E and switching logic control (C1,C2,C3).

The basic idea of the DTC control is to calculate the instantaneous values of flux and torque in the machine. These values are directly estimated from stator voltages determined with the DC voltage E and the Boolean switching controls C2, C2, C3. Triphased-diphased Concordia transformation is used to compute stator voltage vectors and current vectors on perpendicular (α,β) axis as exposed with the following expressions:

$$V_{s\alpha} = \sqrt{\frac{2}{3}}E \quad (C_1 - 0.5 * C_2 - 0.5 * C_3) \tag{1}$$

$$V_{s\beta} = \frac{E}{\sqrt{2}}(C_2 - C_3) \tag{2}$$

$$i_{s\alpha}(k) = \sqrt{\frac{3}{2}} i_{s1}(k) \tag{3}$$

$$i_{s\beta}(k) = \frac{1}{\sqrt{2}}(i_{s1}(k) + 2i_{s2}(k)) \tag{4}$$

The calculation of the constituents of the flux is assured by a system of equations according to:

$$\phi_{S\alpha} = \int (V_{S\alpha} - R_S . I_{S\alpha})dt \tag{5}$$

$$\phi_{S\beta} = \int (V_{S\beta} - R_S . I_{S\beta})dt \tag{6}$$

where, R_s is the stator resistance.

The estimated field is calculated from the following relations:

$$\phi_{S\_est}(k) = \sqrt{(\phi_{S\alpha}(k))^2 + (\phi_{S\beta}(k))^2} \tag{7}$$

$$Cem_{est}(k) = P\begin{pmatrix} \phi_{s\beta}(k) I_{s\beta}(k) \\ -\phi_{s\alpha}(k) I_{s\alpha}(k) \end{pmatrix} \tag{8}$$

where, P is the number of pole pairs.

SPEED MRAS TECHNIQUE

Structure of MRAS speed estimator: The proposed MRAS estimator, use the equations for induction motor expressed in the stationary α-β frame, is:

$$\frac{di_m}{dt} = \frac{1}{L} e_m \tag{9}$$

$$e_m = L\begin{bmatrix} -\frac{1}{T_r} & -\hat{\omega} \\ \hat{\omega} & -\frac{1}{T_r} \end{bmatrix} i_m + \frac{L}{T_r} i_s \tag{10}$$

$$\frac{d\hat{i}_s}{dt} = -\frac{R_s}{\sigma L_s}\hat{i}_s - \frac{1}{\sigma L_s}(v_s - e_m) \tag{11}$$

where, $L = M^2/L_r$ and $\hat{i}_s$ is the estimated current.

i_s and v_s are the measured current and voltage, respectively.

The structure of the MRAS speed estimator is based on the comparison of measured and estimated currents. According to the theory of MRAS, Eq. (9-11) are used as the adjustable model and the reference model is chosen as a unity transfer function. This leads to eliminate computation errors due to reference model (Oulaha, 2001).

Discrete MRAS speed estimator: The discretization of Eq. (9-11) gives:

$$i_s(k+1) = \lambda . i_s(k) + \frac{1}{R_s}(1-\lambda) \left[v_s(k) - e_m(k)\right] \tag{12}$$

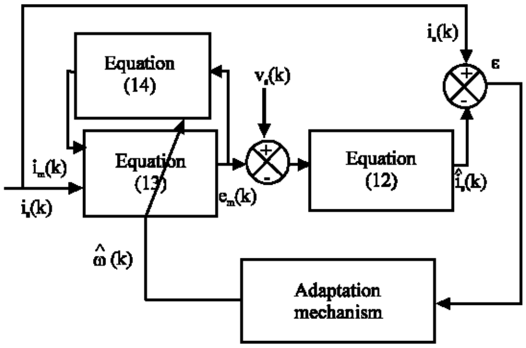

Fig. 2: The speed estimation scheme based upon MRAS technique

$$e_m(k) = L\begin{bmatrix} -\frac{1}{T_r} & -\omega \\ \omega & -\frac{1}{T_r} \end{bmatrix} i_m(k) + \frac{L}{T_r} i_{s0}(k) \quad (13)$$

$$i_m(k+1) = i_m(k) + \frac{T}{L}\left(\frac{3}{2}e_m(k) - \frac{1}{2}e_m(k-1)\right) \quad (14)$$

Where,

$$\lambda = e^{-\frac{T}{\sigma T_s}}$$

The Eq. (12) describes two decoupled discrete models in terms of currents $i_{s\alpha}$ and $i_{s\beta}$. The Eq. (14) uses the ADAMS method limited to a second order.

The proposed speed estimator provides only the current and the voltage measurements.

The Eq. (12-14) constitute the adjustable model with the variable in the speed ω in MRAS structure.

The proposed estimator can be easily implemented because the adjustable model is limited to a second order. We note that the equations require neither matrix calculation nor approximation on Taylor series of matrix exponential.

The proposed sensorless induction motor drive block diagram is shown in Fig. 2.

The stability study and the establishment of the appropriate adapted laws appeared in the feedback path in order to satisfy the Popov integral inequality (Kyo-Beum and Frede, 2005; Khoucha *et al*., 2004).

The adaptation law expressed by Eq. (15) guaranties the hyperstability of MRAS estimator.

$$\omega(k+1) = \omega(k) + \Gamma\begin{pmatrix} i_{m\beta}(k)\varepsilon_{s\alpha}(k) \\ -i_{m\alpha}(k)\varepsilon_{s\beta}(k) \end{pmatrix} \quad (15)$$

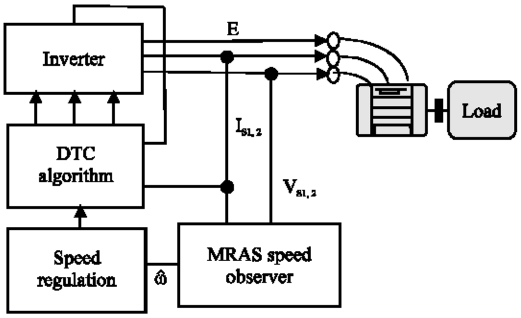

Fig. 3: The DTC control strategy with sensorless

where,Γ is a constant positive,

$$\varepsilon_{s\alpha}(k) = i_{s\alpha}(k) - \hat{i}_{s\alpha}(k)$$
$$\text{and}\,\varepsilon_{s\beta}(k) = i_{s\beta}(k) - \hat{i}_{s\beta}(k)$$

The Fig. 3 presents the DTC strategy with speed estimator. The speed controller is a classical PI regulator which produces the reference torque.

Only the dc-link voltage and two line currents are measured.

SIMULATION RESULTS

In the following simulation, the digital speed estimator under study is integrated in the DTC control system. The simulations have been performed by employing the Matlab-Simulink environment. The parameters of machine are given in appendix. The sampling time is 30 µs. The method is tested for a wide speed variation domain including low speed. The method doesn't require any variation on the adaptation gain for different loaded case (open circuit trial, constant load torque).

The simulations have been executed for low and high speed operation for unloaded machine. The reference speed is applied at 0.1 sec and inverted value is operated at 2 sec.

Simulation results presented in Fig. 4-6 illustrate the nominal speed operation (1440 rpm). The stator flux evolution is illustrated in Fig. 4. After a fast transient response, the estimated flux is regulated around 0.87 Wb and it follows its reference suitably. Its value is affected by the hysteresis; so that, it presents some fluctuations in its permanent regime. The tolerance band was fixed to 10% of the nominal flux. The Fig. 5 shows that the torque is correctly controlled and it follows its reference after a fast transient regime. It is also affected by the hysteresis and presents many fluctuations around the torque

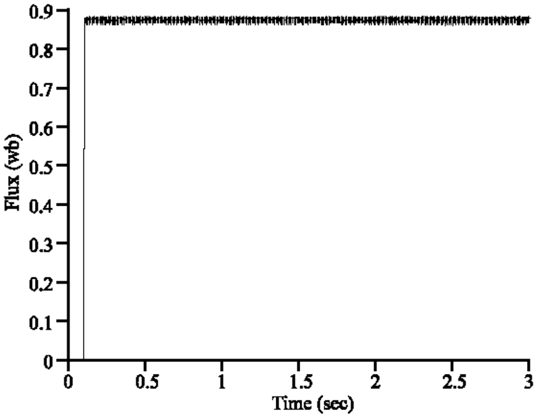

Fig. 4: The flux simulation for nominal speed

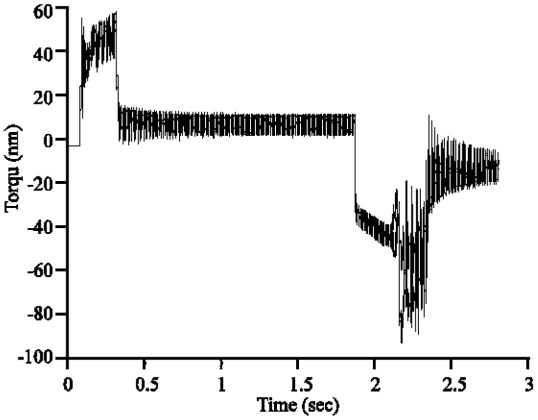

Fig. 5: The torque simulation for nominal speed

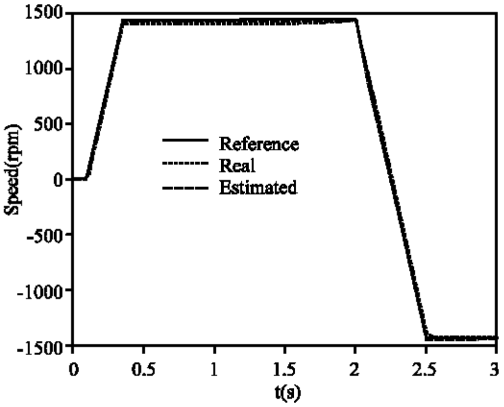

Fig. 6: The evolution of the speeds for nominal speed

reference. Figure 6 shows the effectiveness of the developed structure observer and proves that the speed is well estimated either for a positive or negative reference.

It is noted that estimated speed follows the reference suitably. Thus, we can say that the observer MRAS structure can replace a speed sensor effectively.

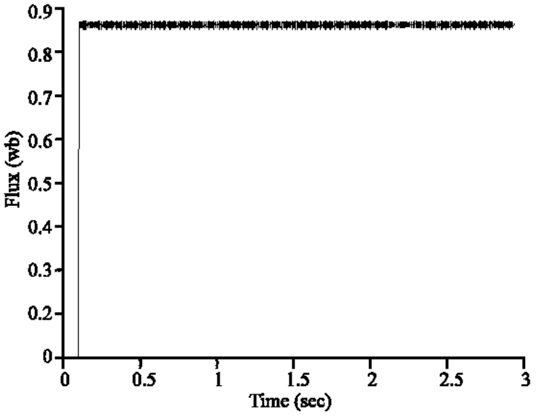

Fig. 7: The flux simulation for low speed

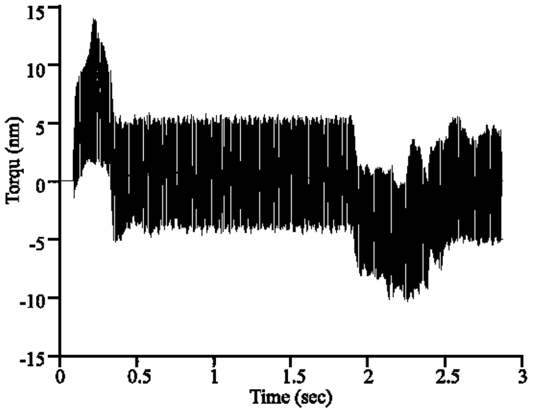

Fig. 8: The torque simulation for low speed

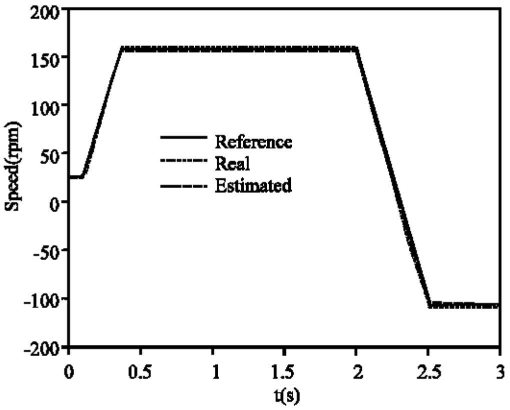

Fig. 9: The speed simulation for low speed

In the case of low speed (150 rpm) the same simulations are realised. Figure 7-9, respectively present flux, torque and speeds of the system.

The torque present significant undulations but it always follows correctly its reference.

This speed MRAS observer is also tested for very low speed (14 rpm) under the same conditions.

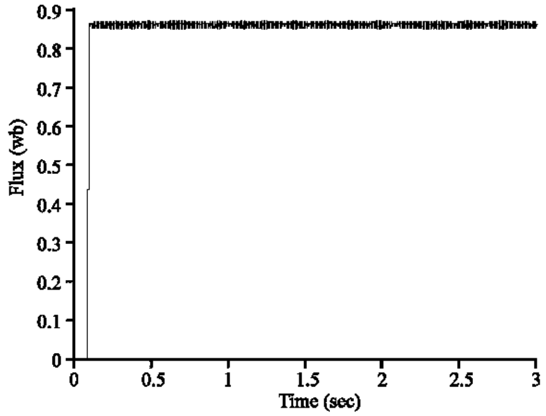

Fig. 10: The flux simulation for very low speed

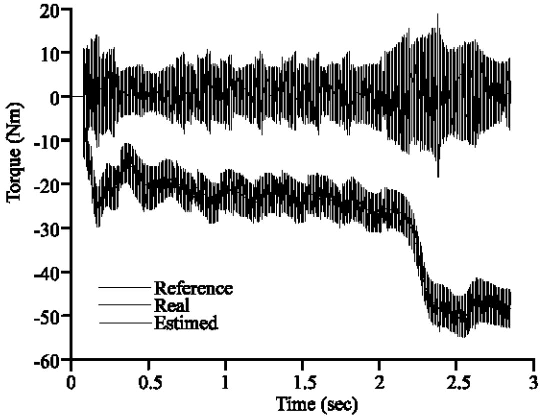

Fig. 11: The torque simulation for very low speed

Figure 10-12 show, respectively the flux, torque and speeds.

It is noted that the observed speed suitably follows the actual speed of the machine and both not following the reference. In fact, this is due to the structure of the DTC algorithm. In deed, if we test this MRAS observer for another control like Field Oriented Control, we obtain excellent behaviour at low, average and high speed (Oulaha, 2001).

EFFECT OF THE PARAMETRIC VARIATION

In the following paragraph we will study the influence of the parametric variation on the system.

The MRAS structure depends on several parameters of the machine. Several studies (Murat *et al*., 2005; Landau, 1979; Popov, 1973; Ebehard and Voges, 1984) made in evidence the sensitivity of induction machine parameters to many factors like saturation and especially the temperature variation that's affect the stator and rotor resistances.

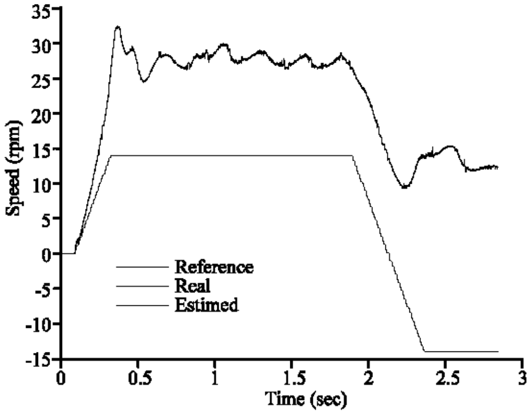

Fig. 12: The speed simulation for very speed

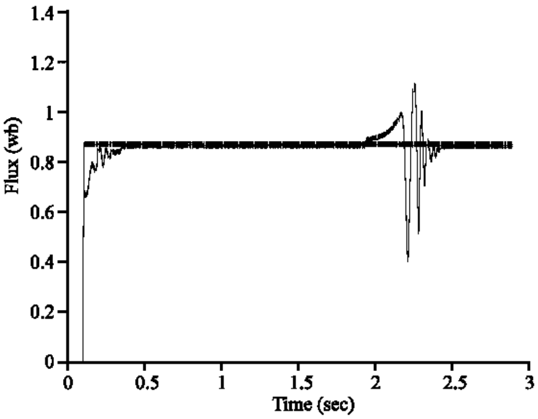

Fig. 13: The flux evolution with R_s and R_r variation

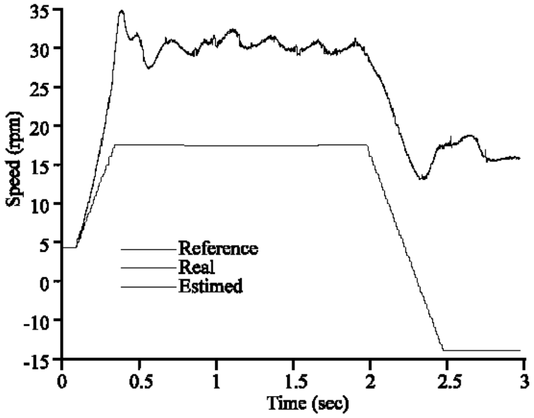

Fig. 14: The torque evolution with R_s and R_r variation

The rise in temperature causes an increase of resistances. So, in this research we could notice that a variation of R_s and R_r, which exceeds 60% of true values, generates adverse effects on the speed observer.

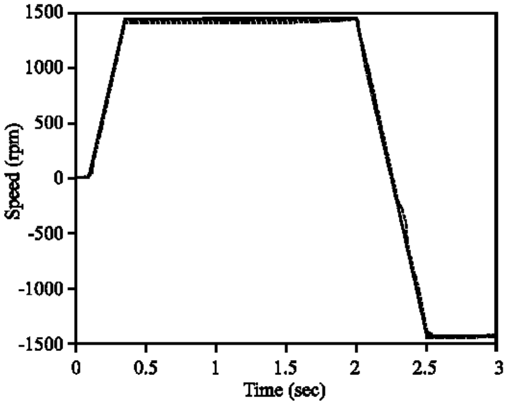

Fig. 15: The speed evolution with R_s and R_r variation

We simulated the behaviour of the system without speed estimator during an increase of the temperature which generates an increase of 60% of R_s and R_r. The results are given in Fig. 13-15.

Figure 15 shows that the observed speed follows suitably the reference and presents very negligible fluctuations. Thus we can consider that speed MRAS observer is robust via the parametric variations Rs and Rr.

CONCLUSION

In this study, a digital sensorless controller based on Model Reference Adaptive System (MRAS) for induction motor drives is presented. The proposed scheme is based on the comparison of measured and estimated stator current. The simulation results have been performed to validate the theoretical analysis. The robustness of speed estimator is observed in context of DTC Control. The drive for such a system has a quick response and simple configuration. A suitable control strategy having the above mentioned features for the electrical drive is the DTC technique. The major drawback of this technique is the dependency on motor parameters. This research showed the performances of an adaptive speed observer at low and nominal speed and its robustness with stator and rotor resistances tuning. The simulation is performed in Matlab-Simulink software. The results illustrate that the analysis focuses both on transient and static characteristics Basic-DTC. Its prove the effectiveness of the adaptive observer in association with the DTC strategy. Also, it's mentioned that the variation of the stator and rotor resistances not affect significantly the dynamic of the behaviour.

Appendix: The induction machine used for test is 220V/380V three-phase, 50 Hz, 11 kW, four-pole. Motor with the following parameters in the per phase steady-state equivalent circuit is presented in Table 1.

Table 1: Motor parameters

Parameters	Values
Stator resistance $R_s(\Omega)$	0.5
Rotor resistance $R_r(\Omega)$	0.5
Stator inductance L_s(H)	0.069
Rotor inductance L_r(H)	0.069
Mutual inductance M(H)	0.067

Nomenclature

$\hat{i}_s$: Estimated current.
i_s : Measured current.
v_s : Measured voltage.
v_{ds}, v_{qs} : Measured stator voltages in d-q components.
$v_{s\alpha}, v_{s\beta}$: Measured stator voltages in α-β components.
$i_{ds}, _{IQs}$: Measured stator currents in d-q components.
$i_{s\alpha}, i_{s\beta}$: Measured stator currents in α-β components.
ϕ_{dr}, ϕ_{qr} : Rotor fluxes in d-q components.
R_s, R_r : Stator and rotor resistances.
L_s, L_r : Stator and rotor self-inductances.
M : Mutual inductance.
P : Number of pole pairs.
ω_s : Synchronous speed.
ω : Rotor speed.
T : Sampling period.
$\sigma = 1\text{-}M^2/L_sL_r$: Total leakage factor.
$Ts = L_s/R_s$: Stator time constant.
$Tr = L_r/R_r$: Rotor time constant.
$i_m = \phi_{dr}/M$: Magnetizing current.

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