

ADAPTATION OF THE ROTOR TIME CONSTANT OF INDUCTION MACHINES WITH FIELD ORIENTED CONTROL

S. REHAHLA* and Kh. DERAFA**

ABSTRACT

Procedures for on-line adaptation of rotor time constant are always based on error models considering two or more machine parameters. A mismatch between the parameters in the models and in the machine has strong influence on the adaptation quality and therefore on the result of field oriented control method. The parameter sensitivity of the adaptation method is analysed theoretically and investigated by means of simulation studies. A new approach to improve the parameter robustness by using a reactive power method. is shown.

KEY WORDS

Induction motor_ Field oriented control _ On-line adaptation procedure_ Sensitivity

NOMENCLATURE

d-q : suffixes denoting axes rotating synchronously with supply frequency.

F : coefficient of friction.

J : rotor inertia

L_r, L_s : apparent self inductance per phase of rotor and stator, respectively

M : apparent mutual inductance

P : differential operator d/dt (or Laplace operator).

p : number of pole pairs

r, s : suffixes denoting rotor and stator, respectively

R_r, R_s : resistance of rotor and stator coils per phase

T_e : Electromagnetic torque

T_L : load torque

T_r : rotor time constant ($T_r=L_r/R_r$).

α - β : suffixes denoting stator-fixed axes

θ_s : stator electrical angle

σ : leakage factor ($1-M^2 / L_s L_r$).

Ω_r : mechanical speed.

ω_r : rotor electrical frequency

ω_s : stator electrical frequency

ω_{sl} : slip frequency.

ψ : flux

* Dir. Labo. Power Electronics, EMP, Bordj-El-Bahri, Algiers, Algeria. Fax.+213 2 81 60 97

** Post-graduate Student, EMP, BP17, Bordj-El-Bahri, Algiers, Algeria. Fax.+213 2 86 32 04

1. INTRODUCTION

The principle of field oriented control, first established by Blaschke [1], has become one of the most frequently applied control techniques for high performance induction motor drives. It offers the possibility of a decoupled control of torque and rotor flux linkage immediately by their corresponding current components. However, the direct proportionality between torque current and motor torque can be guaranteed only if the rotor flux is known and the slip is computed correctly. With the presumption that the rotor flux is not measured directly, the fulfilment of both conditions requires the knowledge of the rotor time constant T_r , and therefore of rotor inductance and rotor resistance. While the nonlinear dependency of the rotor inductance on the magnetising current can be considered by a feed forward compensation, the non predictable dependency of rotor resistance on temperature changes requires the implementation of an on-line adaptation for high performance drive.

Many solutions have been published in the last few years [2]. The best changes for a practical realisation can be awarded to procedures which are easy to implement without additional hardware components (sensors, coils), use terminal currents and voltages as inputs only. Such methods are often based on the calculation of an error signal as equivalent to the rotor resistance detuning driving a readjusting controller for T_r or the rotor resistance, respectively.

In principle, the error equation contains at least two machine parameters, for instance, stator resistance, leakage inductance or stator inductance. Hence, accuracy and stability of the T_r adaptation are essentially influenced by the accuracy of the knowledge of these parameters and their working point dependencies (main and leakage field saturation, temperature).

2. MATHEMATICAL MODEL OF THE INDUCTION MOTOR

The basic equation of induction machine in the d-q axis which synchronously rotates with an angular velocity ω_s are expressed as follows :

2.1. Electrical Equations

$$\begin{bmatrix} V_{qs} \\ V_{ds} \end{bmatrix} = \begin{bmatrix} R_s & 0 \\ 0 & R_s \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \Psi_{qs} \\ \Psi_{ds} \end{bmatrix} + \begin{bmatrix} 0 & \omega_s \\ -\omega_s & 0 \end{bmatrix} \begin{bmatrix} \Psi_{qs} \\ \Psi_{ds} \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_r & 0 \\ 0 & R_r \end{bmatrix} \begin{bmatrix} i_{qr} \\ i_{dr} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \Psi_{qr} \\ \Psi_{dr} \end{bmatrix} + \begin{bmatrix} 0 & \omega_{sl} \\ -\omega_{sl} & 0 \end{bmatrix} \begin{bmatrix} \Psi_{qr} \\ \Psi_{dr} \end{bmatrix}$$

with: $\omega_{sl} = \omega_s - p\Omega_r$

Considering the rotor flux (Ψ_{dr} , Ψ_{qr}), the mechanical speed (Ω_r) as state variables, the stator currents (i_{ds} , i_{qs}), the slip frequency (ω_{sl}) as control variables and the load torque as disturbance [3] we obtain the equations (2), (3) and (4).

2.2. Field Equations

The flux linkage vectors are related to the stator and rotor currents by the following relationship [4]:

$$\begin{aligned}
 \Psi_{ds} &= L_s i_{ds} + M i_{dr} \\
 \Psi_{qs} &= L_s i_{qs} + M i_{qr} \\
 \Psi_{qr} &= L_r i_{qr} + M i_{qs} \\
 \Psi_{dr} &= L_r i_{dr} + M i_{ds}
 \end{aligned} \tag{2}$$

In practice, rotor currents are inaccessible quantities in a squirrel cage motor. Therefore, the rotor current in equation (2) is eliminated by the corresponding flux vector and stator current vector.

$$\frac{d}{dt} \begin{bmatrix} \Psi_{dr} \\ \Psi_{qr} \end{bmatrix} = \begin{bmatrix} -\frac{1}{T_r} & \omega_{sl} \\ -\omega_{sl} & -\frac{1}{T_r} \end{bmatrix} \begin{bmatrix} \Psi_{dr} \\ \Psi_{qr} \end{bmatrix} + \begin{bmatrix} \frac{M}{T_r} & 0 \\ 0 & \frac{M}{T_r} \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} \tag{3}$$

2.3. Mechanical Equation

$$\begin{aligned}
 T_e - T_L &= J \frac{d\Omega_r}{dt} + F\Omega_r \\
 \text{with } T_e &= \frac{3pM}{2L_r} (\Psi_{dr} i_{qs} - \Psi_{qr} i_{ds})
 \end{aligned} \tag{4}$$

From the equations (3), (4) we establish the following machine model fed by current:

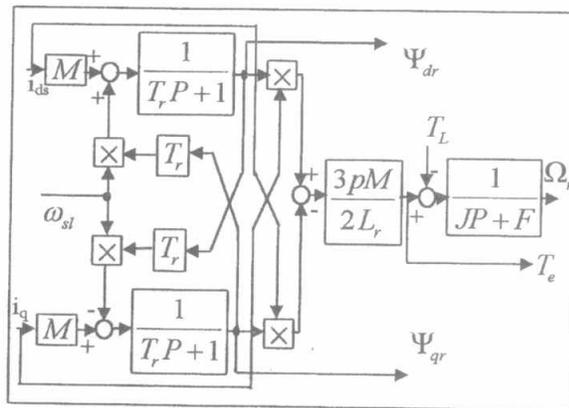


Fig.1 Induction machine model

3. FIELD ORIENTATION

The flux models contain field coordinates (i.e. d-q quantities) that are dc quantities in the steady state. This greatly simplifies the control approach when dc quantities are dealt with. Also, it is expedient to align the rotor flux (ψ_r), along the d-axis, we obtain:

$$\Psi_{dr} = \Psi_r, \Psi_{qr} = 0 \tag{5}$$

3.1. Machine Model with Rotor Flux Orientation

Substituting the flux equation (5) into equations (2), (3) and (4) and considering the stator currents (i_{ds}, i_{qs}) as control input: the machine flux model can be formulated as following

$$\begin{aligned} T_r \frac{d\Psi_r}{dt} + \Psi_r &= M i_{ds} \\ \omega_{sl} &= \frac{M i_{qs}}{T_r \Psi_r} \\ T_e &= \frac{3pM}{2L_r} \Psi_r i_{qs} \end{aligned} \tag{6}$$

3.2. Structure Control of the Rotor Flux Model

Considering the rotor flux (ψ_r^*) and the torque (T_e^*) as reference control, the equations system (6) gives the structure (fig.2) with the following relationship:

$$\begin{aligned} \frac{1}{M} (T_r \frac{d\Psi_r^*}{dt} + \Psi_r^*) &= i_{ds} \\ \omega_{sl} &= \frac{M i_{qs}}{T_r \Psi_r^*} \\ \frac{2L_r T_e^*}{3pM \Psi_r^*} &= i_{qs} \end{aligned} \tag{7}$$

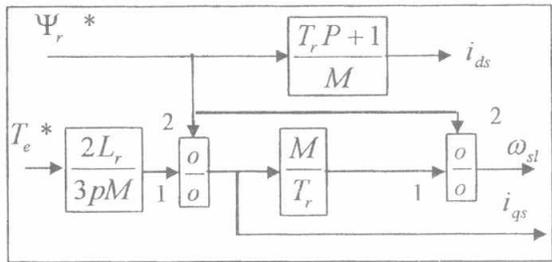


Fig.2 :Field oriented control structure (FOC)

4. SPEED CONTROL

The speed is controlled with a classical (PI) controller that generates the reference torque (T_e^*) to be applied to the open loop structure (FOC).

The rotor flux reference (ψ_r^*) estimated from the nominal voltage and frequency values of the machine, is controlled simply by the block "flux function", which is defined by the following relationship:

$$\Psi_r^* = \begin{cases} \Psi_{r0} & \text{if } |\Omega_r| \leq \Omega_{r0} \\ \frac{\Psi_{r0} \cdot \Omega_{r0}}{|\Omega_r|} & \text{if } |\Omega_r| > \Omega_{r0} \end{cases} \quad (8)$$

The rotor flux reference (ψ_r^*) is constant in the constant-torque region, but it is weakened as inversely proportional to speed in the constant-power region [4].

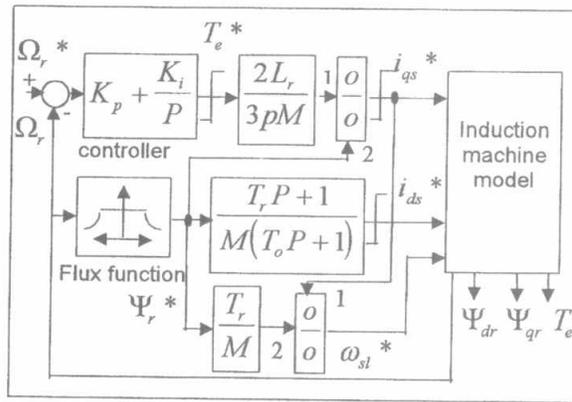


Fig.3. Speed control structure with rotor flux orientation

5. ADAPTATION PROCEDURE

5.1. Stationary Frame Model

The dynamic machine model in the stationary reference frame in α - β notation is shown in fig.4, where L_{TH} is the equivalent leakage inductance of the stator and rotor transferred to the input [4].

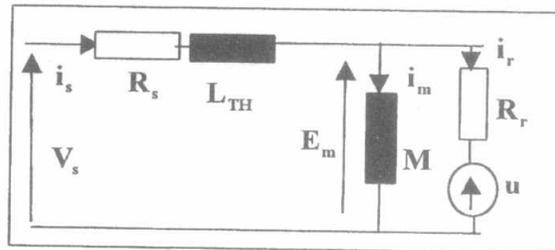


Fig.4 : Equivalent circuit of the induction machine

The emf can be derived immediately from fig.4 as:

$$\mathbf{E}_m = \mathbf{V}_s - \mathbf{R}_s \mathbf{i}_s - (\mathbf{L}_{TH}) \frac{d\mathbf{i}_s}{dt} \quad (9)$$

The reactive power is given by

$$\mathbf{Q}_m = \mathbf{E}_{m\beta} \mathbf{i}_{s\alpha} - \mathbf{E}_{m\alpha} \mathbf{i}_{s\beta} \quad (10)$$

The reactive power is consumed only in the main inductance L_m then:

$$\mathbf{Q}_m = \omega_s \mathbf{M} \mathbf{I}_m^2 \quad (11)$$

The stored energy F_m in the main inductance may be formulated as following [5]

$$\mathbf{F}_m = \frac{\mathbf{Q}_m}{\omega_s} = \frac{(\mathbf{i}_{s\alpha} \mathbf{E}_{m\beta} - \mathbf{i}_{s\beta} \mathbf{E}_{m\alpha})}{\omega_r + \frac{1}{T_r} \frac{\mathbf{i}_{qs}^*}{\mathbf{i}_{ds}^*}} \quad (12)$$

$$\mathbf{F}_m^* = \frac{\mathbf{Q}_m^*}{\omega_s} = \mathbf{M} \mathbf{I}_m^{*2} \quad (13)$$

Substituting equation (9) in (12) yields

$$\mathbf{F}_m = \frac{\left| \mathbf{i}_{s\alpha} \mathbf{V}_{s\beta} - \mathbf{L}_{TH} \mathbf{i}_{s\alpha} \frac{d\mathbf{i}_{s\beta}}{dt} - \mathbf{i}_{s\beta} \mathbf{V}_{s\alpha} + \mathbf{L}_{TH} \mathbf{i}_{s\beta} \frac{d\mathbf{i}_{s\alpha}}{dt} \right|}{\omega_r + \frac{1}{T_r} \frac{\mathbf{i}_{qs}^*}{\mathbf{i}_{ds}^*}} \quad (14)$$

\mathbf{I}_m^* : magnetisation current without load, it is initially measured on 50 Hz, under nominal voltage.

5.2. Application

The block diagram of the considered field oriented control system is shown in fig.5. Reference values are marked with a superscript*. The special configuration of the current controller is not of interest for the studies proposed in this paper; only it must be able to fulfil the condition $i_{qs} = i_{qs}^*$, $i_{ds} = i_{ds}^*$ in steady state.

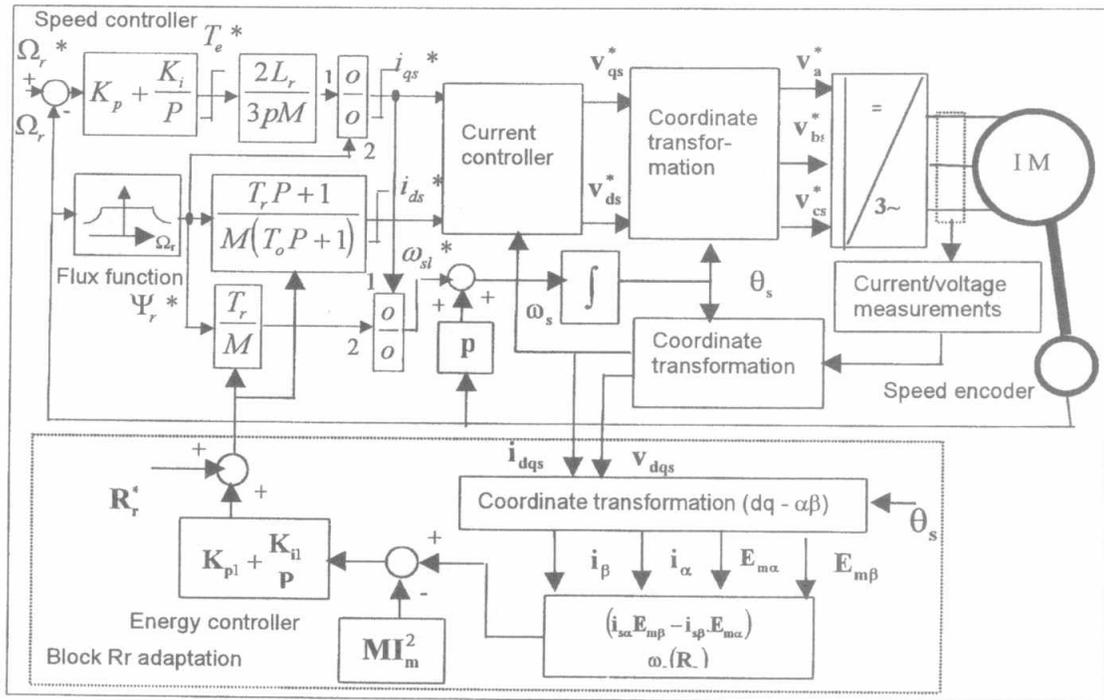


Fig.5. Field oriented control system with rotor resistance adaptation

The error of the speed control loop generates the reference torque (T_e^*) through a PI controller and limiter, obtained with an analytical method [6], which is divided by the flux (Ψ_r^*) to generate the command current (i_{qs}^*) (equation 7).

A step change in command flux or torque will cause the generation of σ function (due to $P\Psi_r^*$, in Fig.5). In practice, the rate of rise of machine currents are limited by the stator leakage inductance, therefore a very small first order time delay is incorporated in the flux input path to ensure a smooth function of i_{ds}^* with a pole location of $-1/T_0$.

The P.I parameters of the energy controllers are obtained by Ziegler and Nichols method [7].

The equation (14) which includes the rotor resistance R_r gives the tuning model. The equation (13) gives the reference model. In both models all parameters are influenced by the saturation effects in the machine.

However the used adaptation procedure is to cancel the error signal between the reference model and the tuning model by minimizing the saturation effects; so in the block R_r adaptation (Fig.5): the starting-point for the power balance method is the reactive power (equation 14).

The vector rotator angle θ_s which is influenced by the actualised rotor time constant (T_r) is defined by :

$$\theta_s = \int (\omega_{sl} + p\Omega_r) dt \quad (15)$$

The inverter being used is a three-phase bridge employing I.G.B.T. transistors.

The instantaneous inverter current/voltage are fed back to perform the current control and the adaptation procedure used

6. SIMULATION RESULTS

To verify analytical key results and the validity of the proposed control scheme, the aforementioned structure of field oriented control system with rotor resistance adaptation was tested by simulation on pentium personal computer. Computer simulation was carried out using Matlab environment.

The fig.6 shows the simulated results under a nominal torque and a rotor flux (ψ_r^*) of 1 Wb. At the moment t_1 (2 sec, fig.6-b) we put a linear variation of +50 % between the rotor resistance used in machine model and the rotor resistance ($T_r=L_r/R_r$) used in the speed control structure (fig.3): consequence the ψ_{qr} is not equal to zero (fig.6-e) and ψ_r comes different of the reference value ($\psi_r^*=1$ Wb.) fig.6-d), the electromagnetic torque T_e decrease lightly (fig.6-g), therefore the decoupling control is not effective on 'd axis'. At the moment t_2 (3.5 sec., fig.6-b) we introduce the adaptation procedure proposed and the parameters (ψ_{qr} , ψ_{dr} , ψ_r and T_e) come to their initial values, so the decoupling or oriented control is now effective.

The speed response Ω_r (fig.6-a), is not affected by the dynamic of the decoupling control, due to its controller.

7. CONCLUSION

It has been shown that the accuracy of the motor parameters in the rotor time constant adaptation error model has an important effect on the adaptation accuracy and therefore the quality of the field orientation. Relatively small deviations can already result in instability of the control system. Hence the parameter sensitivity becomes an important criterion for the choice of an adaptation procedure for application.

Simulation studies are necessary because an analytical analysis does not yield statements of the stability of the problem.

The reactive power method turns out to yield the best results independent of stator resistance deviations and with an acceptable sensitivity to the inductances.

8. MACHINE PARAMETERS

$P_n=1$ (kW), $U_n=220/380$ (V), $N_n=2830$ (rpm), $f=50$ (Hz) $I_{ny}=2.7$ (A), $I_{nV}=4.7$ (A),
 $p=1$, $R_s=5.06$ (Ω), $R_r=3.1$ (Ω), $L_s=0.386=L_r$, $M=0.374$ (H), $F=0.0011$ (Nm/rad/s),
 $J=0.006$ (kg.m²), $I^*_m=3.12$ (A),

$K_p=4*2J/T_r$, $K_i=J*\omega_0^2$, $T_0=0.025$ (sec), $\omega_0^2=\omega_{sl}^2+1/T_r$, $k_{p1}=0.0012$, $k_{i1}=0.00012$.

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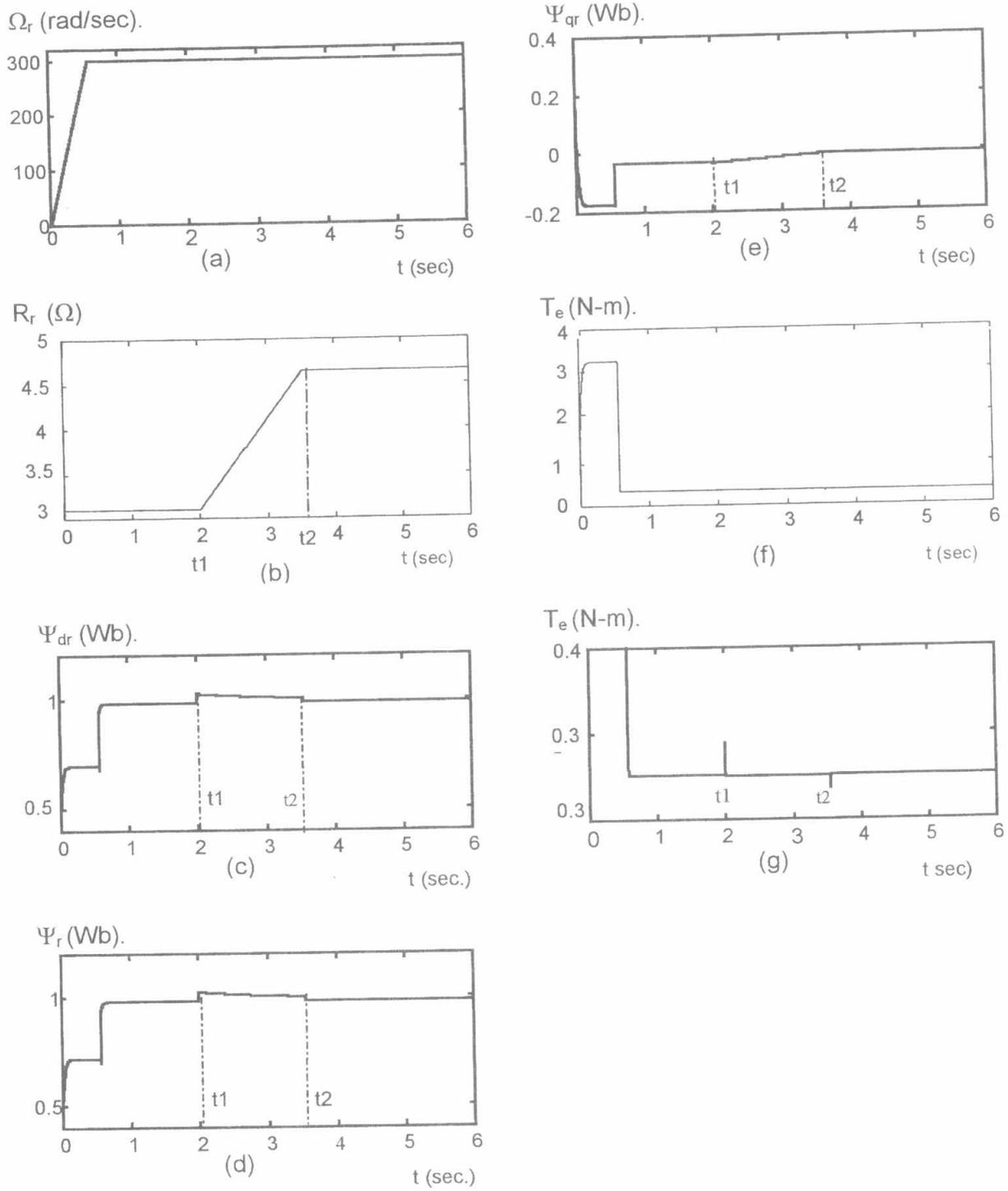


Fig.6. Simulation results of the field oriented control system with rotor resistance adaptation. (a) Speed response Ω_r . (b) Rotor resistance (R_r) variation. (c) Flux component: Ψ_{dr} . (d) Flux response Ψ_r . (e) Flux component Ψ_{qr} . (f) Torque response T_e . (g) Zoom of the torque response T_e .