Speed Control of High Speed Synchronous Reluctance Motor By Vector Control

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ABSTRACT – *In the High-speed range for salient type synchronous reluctance motors, the effect of iron loss can not be negligible. In this paper, the SynRM without cage is analyzed mathematically to model and the speed control system is examined by simulation. In order to control the revolution speed, a closed-loop control with vector control and decoupling control are applied to the high-speed SynRM drives. The speed control system is analyzed to investigate the desired speed characteristics of high speed SynRM by simulation.*

1. Introduction

There are increasing needs in using High-Speed Motors because the equipment with small size, light eight and High-Speed revolution are required in the electrical power industry and/or the aircraft industry. Induction Motors mainly have been used for High-Speed applications. But Induction Motors have the critical weakness that is the separation of rotor windings and the heat loss of the rotor under the High-Speed revolution.

The advantage of Synchronous Reluctance Motors (SynRM) compared with the Induction Motors is the absence of the starting cage in the rotor, which results in strengthening the mechanism, reducing the heat losses and improving reliability. The conventional SynRM have low power factor. But SynRM is suitable essentially for High-Speed revolution. For past few years, a considerable amount of work has been done by a number of investigators to utilize SynRM for High-Speed applications. The combination of the voltage source inverter and Reluctance Motor without cage has been used for High-Speed applications requiring adjustable speed up to 100,000 rpm and higher and less than 10kW[1][2][3].

According to development of motor control lately, it is expected for variable speed drives to apply to High-Speed SynRM. Various vector control methods of ac motor controls with closed-loop have been developed for speed and position. [1][4][5][6][7]

In this paper, the salient-pole type SynRM without cage is analyzed mathematically to model and the speed control system is examined by computer simulation. In order to control the revolution speed, a closed-loop control with vector control and decoupling control are applied to the high speed SynRM drives. The speed control system is used to investigate the speed characteristics of high speed SynRM by simulation. [3] [4] [8]

Fig. 1 shows the structure of cross section of the salient pole type SynRM.

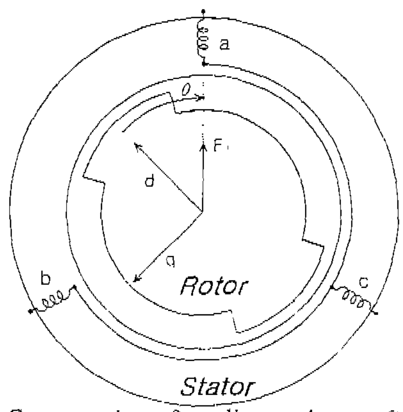


Fig 1. Cross section of a salient pole type SynRM

2. SynRM Modeling including Iron Loss

For the structure of SynRM used to obtain a machine model, the stator is the same type as a 3-phase AC motor, and the rotor is similar to salient pole type in a synchronous motor.

In order to model the machine, it is assumed that the cause of iron loss is in the equivalent eddy current circuits of stator windings. It is considered that the eddy currents of stator are concentric winding circuits, and the equivalent eddy current circuits have the inductance, functions of the same winding resistor and the position angles of rotor on each axes of the 3-phase winding model. In this assumption, we start on the machine modeling.

In the SynRM, because the inductance of stator windings or equivalent eddy current windings are changed by position angle θ, the self inductance and the mutual inductance of stator windings and equivalent eddy current windings can be represented of the function of 2θ. Consequently, the voltage equation of 3-phase winding model is

$$[v_{abc}] = [R][i_{abc}] + p[L_{abc}(\theta)][i_{abc}] \quad (1)$$

Where,

$$[v_{abc}] = [v_{as} \quad v_{bs} \quad v_{cs} \quad 0 \quad 0 \quad 0]^t,$$
$$[i_{abc}] = [i_{as} \quad i_{bs} \quad i_{cs} \quad i_{ae} \quad i_{be} \quad i_{ce}]^t$$
$$[R] = diag[R_s \ R_s \ R_s \ R_e \ R_e \ R_e]$$
$$[L_{abc}(\theta)] = \begin{bmatrix} L_{as} & M_{abs} & M_{acs} & M_{asae} & M_{asbe} & M_{asce} \\ M_{bas} & L_{bs} & M_{bcs} & M_{bsae} & M_{bsbe} & M_{bsce} \\ M_{cas} & M_{cbs} & L_{cs} & M_{csae} & M_{csbe} & M_{csce} \\ M_{aeas} & M_{aebs} & M_{aecs} & L_{ae} & M_{abe} & M_{ace} \\ M_{beas} & M_{bebs} & M_{becs} & M_{bae} & L_{be} & M_{bce} \\ M_{ceas} & M_{cebs} & M_{cecs} & M_{cae} & M_{cbe} & L_{ce} \end{bmatrix}$$

The voltage equation (1) is transformed 3-phase/2-phase by stator angle speed ω_r in the d-q axis rotating frame Fig. 2 shows a d-q winding model. The voltage equations and the flux linkages are

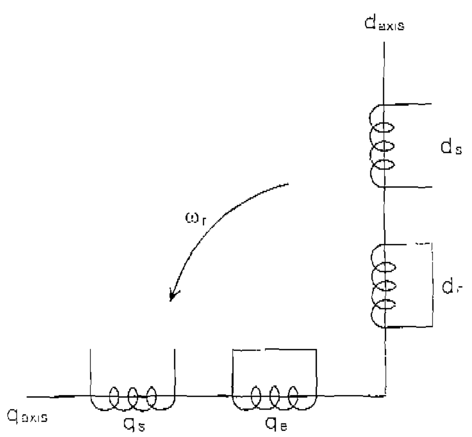


Fig.2 dq winding model of SynRM

$$\begin{aligned} v_{ds} &= R_s i_{ds} + p\lambda_{ds} - \omega_r \lambda_{qs} \\ v_{qs} &= R_s i_{qs} + p\lambda_{qs} + \omega_r \lambda_{ds} \\ 0 &= R_e i_{de} + p\lambda_{de} - \omega_r \lambda_{qe} \\ 0 &= R_e i_{qe} + p\lambda_{qe} + \omega_r \lambda_{de} \end{aligned} \quad (2)$$

$$\begin{aligned} \lambda_{ds} &= L_{ds} i_{ds} + M_d i_{de} \\ \lambda_{qs} &= L_{qs} i_{qs} + M_q i_{qe} \\ \lambda_{de} &= L_{de} i_{de} + M_d i_{ds} \\ \lambda_{qe} &= L_{qe} i_{qe} + M_q i_{qs} \end{aligned} \quad (3)$$

Where,

$$L_{ds} = 3/2(L_{ls} + L_{0s}),\ L_{qs} = 3/2(L_{ls} - L_{0s}),$$
$$L_{de} = 3/2(L_{le} + L_{0e}),\ L_{qe} = 3/2(L_{le} - L_{0e}),$$
$$M_d = 3/2(L_{se} + L_{0se}),\ M_q = 3/2(L_{se} - L_{0se})$$

From the voltage equation (2) and the flux linkage (3), the voltage equations including equivalent eddy current are derived as follows

$$\begin{aligned} v_{ds} &= (R_s + pL_{ds})i_{ds} - \omega_r L_{qs} i_{qs} + pM_d i_{de} - \omega_r M_q i_{qe} \\ v_{qs} &= \omega_r L_{ds} i_{ds} + (R_s + pL_{qs}) i_{qs} + \omega_r M_d i_{de} + pM_q i_{qe} \\ 0 &= pM_d i_{ds} - \omega_r M_q i_{qs} + (R_e + pL_{de}) i_{de} - \omega_r L_{qe} i_{qe} \\ 0 &= \omega_r M_d i_{ds} + pM_q i_{qs} + \omega_r L_{de} i_{de} + (R_e + pL_{qe}) i_{qe} \end{aligned} \quad (4)$$

Because the detection of equivalent eddy current is very difficult, the measurement of equivalent eddy current is embarrassed. The eddy currents can be eliminated by some manipulations of the voltage equation represented by the variables of stator. But, if the equivalent eddy currents, i_{de} and i_{qe}, are eliminated, the equation is very complex. By using the approximate equation of equivalent circuit constants, the voltage equation of transient state is derived.

For the definition of circuit constants, it is considered in the steady state. So, each currents, i_{de} and i_{qe}, are the components of DC and p, differential operator, is zero. Accordingly, i_{de} and i_{qe} are

$$\begin{aligned} i_{de} &= -\frac{\omega_r^2 L_{qe} M_d i_{ds} - \omega_r R_e M_q i_{qs}}{R_e^2 + \omega_r^2 L_{de} L_{qe}} \\ i_{qe} &= -\frac{\omega_r^2 L_{de} M_q i_{qs} + \omega_r R_e M_d i_{ds}}{R_e^2 + \omega_r^2 L_{de} L_{qe}} \end{aligned} \quad (5)$$

And, because the equation (4) is the voltage equation with the rotor angle speed ω_r in rotational coordinate frame, the equation (4) is changed as follows

$$
\begin{aligned}
v_{ds} &= R_s i_{ds} - \omega_r L_{qs} i_{qs} - \omega_r M_q i_{qi} \\
v_{qs} &= \omega_r L_{ds} i_{ds} + R_s i_{qs} + \omega_r M_d i_{di}
\end{aligned} \tag{6}
$$

From the equation (5) and (6), a new voltage equation (7) is derived as follows

$$
\begin{bmatrix} v_{ds} \\ v_{qs} \end{bmatrix} = \begin{bmatrix} R_s + R_m & -\omega_r L_q \\ \omega_r L_d & R_s + R_m \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} \tag{7}
$$

Where, circuit parameters are defined as follows

$$
\begin{aligned}
&D = 1/(R_i^2 + \omega_r^2 L_{di} L_{qi}),\ R_m = \omega_r^2 D R_i M_d M_q \\
&L_{sd} = L_{ds} - \omega_r^2 D L_{qi} M_d^2,\ L_{sq} = L_{qs} - \omega_r^2 D L_{di} M_q^2
\end{aligned} \tag{8}
$$

We can understand that the equivalent iron loss resister Rm is inserted to the excitation inductance in series from the equation (7).

The d-axis and the q-axis approximate equations are obtained through the circuit parameters, Lsd, Lsq and Rm. And, the d-axis and the q-axis eddy currents are defined as follows

$$
\begin{aligned}
i_{di} &= -D\{(\omega_r^2 L_{qi} + pR_i) M_d i_{ds} - \omega_r R_i M_q i_{qs}\} \\
i_{qi} &= -D\{(\omega_r^2 L_{di} + pR_i) M_q i_{qs} - \omega_r R_i M_d i_{ds}\}
\end{aligned} \tag{9}
$$

From the equation (4) and (9). the voltage equations in the transient state are obtained as follows

$$
\begin{bmatrix} v_{ds} \\ v_{qs} \end{bmatrix} = \begin{bmatrix} R_s + R_m + pL_d & -\omega_r L_q - pR_m/\omega_r \\ \omega_r L_d - pR_m/\omega_r & R_s + R_m + pL_q \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} \tag{10}
$$

From the equation (3) and (9), the flux linkages are obtained as follows

$$
\begin{aligned}
\lambda_{ds} &= L_d i_{ds} + \frac{R_m}{\omega_r} i_{qs} \\
\lambda_{qs} &= L_q i_{qs} - \frac{R_m}{\omega_r} i_{ds}
\end{aligned} \tag{11}
$$

And, the torque equation is obtained as follows

$$
\begin{aligned}
\tau_{em} &= \frac{3}{2}\frac{p}{2}(\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}) \\
&= \frac{3}{2}\frac{p}{2}\left\{(L_d - L_q) i_{ds} i_{qs} + \frac{R_m}{\omega_r}(i_{ds}^2 + i_{qs}^2)\right\}
\end{aligned} \tag{12}
$$

Where, p is the pole numbers of rotor.

3. Decoupling control

When vector control is applied to the SynRM drive, the voltage equation (10) including the iron loss is converted to the equation (13).

$$
\begin{aligned}
p\begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} = &-\frac{1}{L_{ds} L_{qs} + \left(\dfrac{R_m}{\omega_r}\right)^2} \begin{bmatrix} (R_s + R_m) L_{qs} - L_{ds} R_m & -\omega_r L_{qs}^2 - \dfrac{(R_s + R_m) R_m}{\omega_r} \\ \omega_r L_{ds}^2 + \dfrac{(R_s + R_m) R_m}{\omega_r} & (R_s + R_m) L_{ds} + L_{qs} R_m \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} \\
&+ \frac{1}{L_{ds} L_{qs} + \left(\dfrac{R_m}{\omega_r}\right)^2} \begin{bmatrix} L_{qs} & -\dfrac{R_m}{\omega_r} \\ \dfrac{R_m}{\omega_r} & L_{ds} \end{bmatrix} \begin{bmatrix} v_{ds} \\ v_{qs} \end{bmatrix}
\end{aligned} \tag{13}
$$

The stator currents, ids and iqs, are obtained from the equation (13) by the Laplace transforms. The resultant equations are as follows

$$
i_{ds} = \frac{\dfrac{1}{L_{ds}}}{s + \dfrac{R_s + R_m}{L_{ds}}} v_{ds} + \frac{\dfrac{L_{qs}}{L_{ds}} - s\dfrac{R_s}{\omega_r^2 L_{ds}}}{s + \dfrac{R_s + R_m}{L_{ds}}} \omega_r i_{qs} \tag{14}
$$

$$
i_{qs} = \frac{\dfrac{1}{L_{qs}}}{s + \dfrac{R_s + R_m}{L_{qs}}} v_{qs} - \frac{\dfrac{L_{ds}}{L_{qs}} - s\dfrac{R_s}{\omega_r^2 L_{qs}}}{s + \dfrac{R_s + R_m}{L_{qs}}} \omega_r i_{ds} \tag{15}
$$

The equation (14) and (15) are simplified by considering the steady state. If the motor parameters are known, the estimation and the compensation for the interference terms are possible by current sensing.

The compensation voltage equations are as follows

$$v_{ds} = v_{ds} - \omega_r L_{qs} i_{qs}$$
$$v_{qs} = v_{qs} - \omega_r L_{ds} i_{ds} \qquad (16)$$

Then the equation (13) is changed to the equation (17).

$$p\begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} = \begin{bmatrix} -\frac{R_s+R_m}{L_{ds}} & 0 \\ 0 & -\frac{R_s+R_m}{L_{qs}} \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \end{bmatrix} + \begin{bmatrix} \frac{1}{L_{ds}} & 0 \\ 0 & \frac{1}{L_{qs}} \end{bmatrix} \begin{bmatrix} v_{ds} \\ v_{qs} \end{bmatrix} \qquad (17)$$

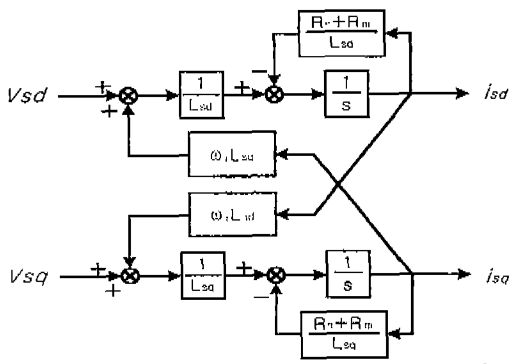


Fig. 3. The block diagram of SynRM with the decoupling compensation.

The decoupling control is accomplished by choosing voltage commands such as the equation (18).

$$V_{ds}^* = \left(K_p + \frac{K_i}{s}\right)\left(i_{ds}^* - i_{ds}\right) - \omega_r \overline{L_{qs}} i_{qs}$$
$$V_{qs}^* = \left(K_p + \frac{K_i}{s}\right)\left(i_{qs}^* - i_{qs}\right) - \omega_r \overline{L_{ds}} i_{ds} \qquad (18)$$

Where, Kp, Ki > 0 denote the proportional and integral gains.

4. Simulation Results

All the speed control simulations are accomplished using Matlab/Simulink. Fig. 4 shows the block diagram of the speed control system with decoupling compensation.

Table 1 shows the parameters of SynRM.

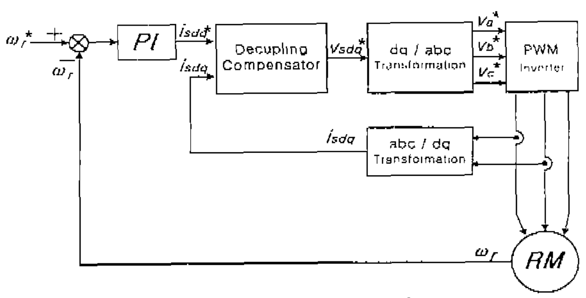


Fig. 4. The speed control system configuration

Table 1. The parameters of SynRM

V	220 [V]	P	3.5 [Kw]
I	16 [A]	F	400 [Hz]
Rs	1.8 [Ohm]	Kp	2.284
Rm	488 [Ohm]	Ki	5.070
Lds	0.328 [H]	Jm	0.00206[Kgm^2]
Lqs	0.204 [H]	Pole	2

When a sine wave voltage with 60[Hz] frequency is supplied for the input of the SynRM, the Fig. 5 shows the simulation results for a speed waveform, a d-axis and q-axis current waveform and a 3-phase current waveform.

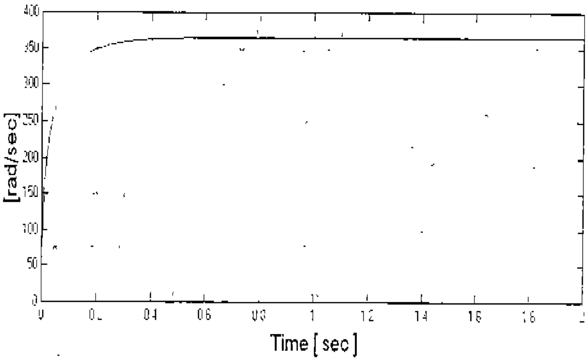
When a speed command is input, Fig. 6 shows a speed response without decoupling compensation. In the Fig. (a), (b), the differences between a solid line and a dotted line show the errors compared with the speed command.

Fig. 7 shows a speed response with decoupling compensation. The speed command is the same value as Fig. 6. The current responses of d-axis and q-axis coincide with the speed command.

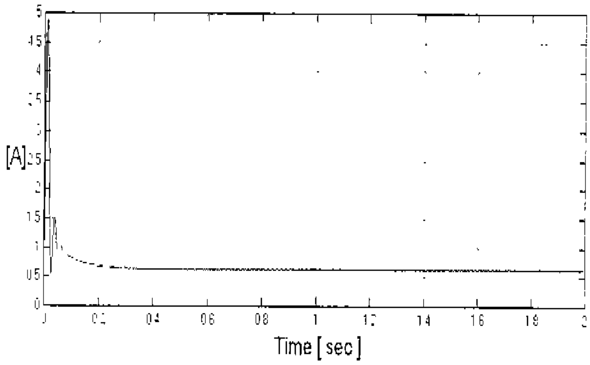
5. Conclusion

This paper shows new voltage equations of SynRM including iron loss. And decoupling compensation control is applied to the new voltage equation. The speed control system is used to investigate the desired speed characteristics of the high speed SynRM by simulation.

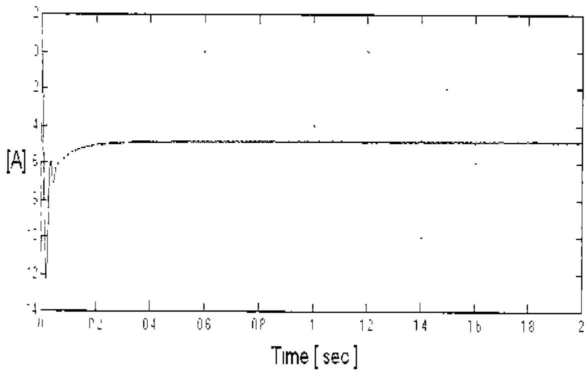
The simulation results show that response characteristics, speed, dq axis current, and torque, are well coincided with theoretical values compared with the speed command.



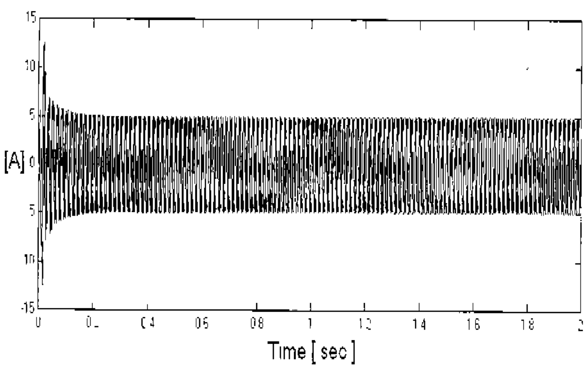
(a) Speed



(b) ids



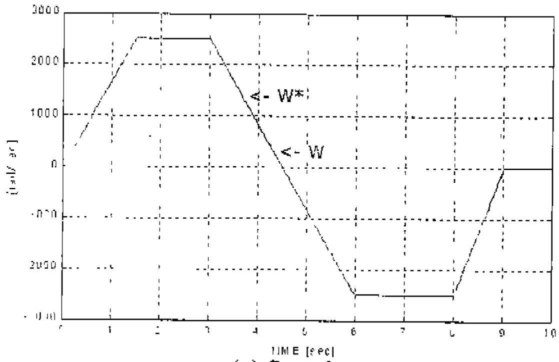
(c) iqs



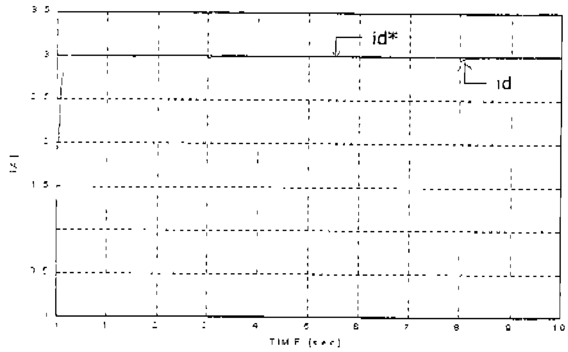
(d) 3-phase current

Fig 5. Response characteristics for sine wave input.

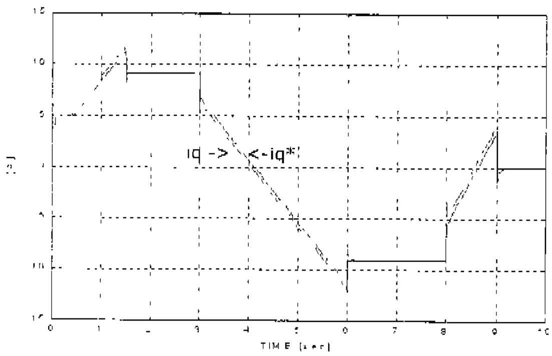
(a)



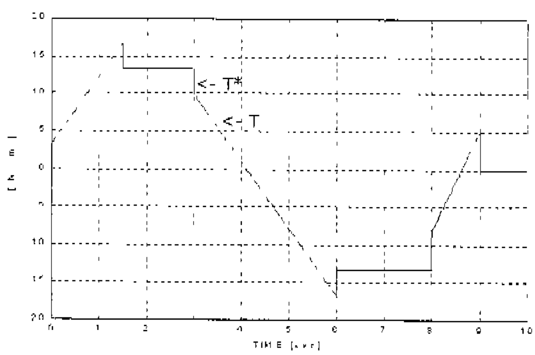
(a) Speed



(b) ids

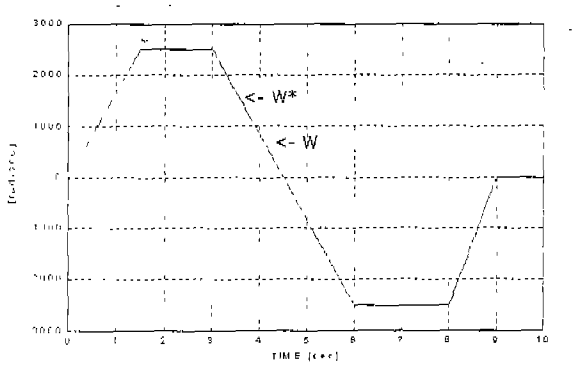


c) iqs

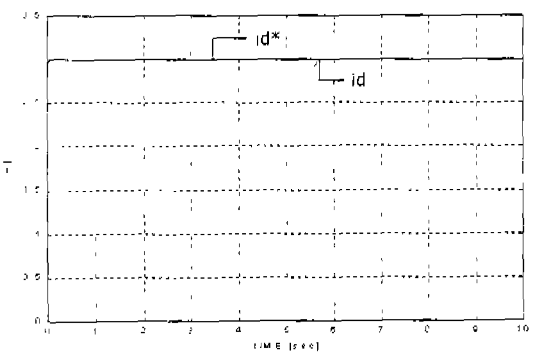


(d) Torque

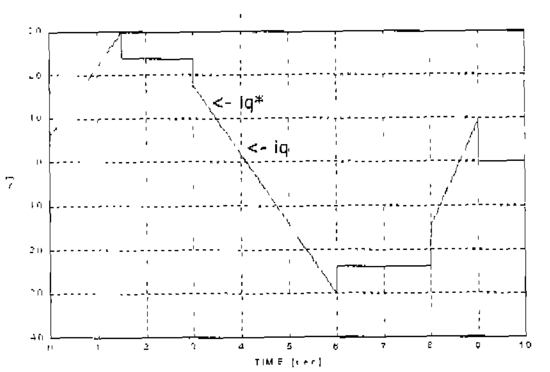
Fig 6. Response characteristics without decoupling compensation.



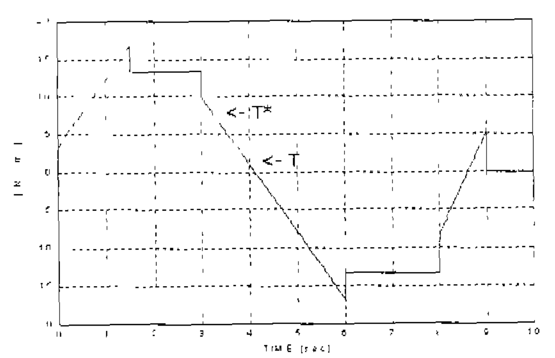
(a) Speed



(b) ids



(c) iqs



(d) Torque

Fig 7. Response characteristics with decoupling compensation.

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