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A SOFTWARE MODIFICATION PROCEDURE FOR CONVERSION OF A SCALAR CONTROLLER TO A VECTOR TYPE FOR AN INDUCTION MOTOR*

M. EBRAHIMI [1], H. SEIFI [2], A. SHOULAIE [3**] AND H. S. SARRAF [4]

[1]Department of Elec. Engineering, Esfahan University of Technology, Esfahan, I. R. of Iran
[2]Department of Elec. Engineering, Tarbiat Modarres University, Tehran, I. R. of Iran
[3]Department of Elec. Engineering, Iran University of Science and Tech., Tehran, I. R. of Iran
and [4]Department of Elec. Engineering, University of Tennessee, TN, USA

Abstract – This paper establishes a relationship between two techniques for the control of current controlled induction motors, namely scalar control with flux loop and direct vector control. This is accomplished through theoretical comparison of the governing equations that relate the input and the output signals in the respective controllers. In traditional scalar control, the controller outputs are $|I_s^*|$ and ω_e^*, while in vector type they are i_{ds}^{s*} and i_{qs}^{s*}. In each method two signals are produced which define the reference current. It is desirable to improve these two controllers, so that similar information is derived for the reference current. With this achievement, it will be shown how an existing scalar controller may be converted to a vector control type (with improved responses) by software modifications. Computer simulation is demonstrated for a typical 3 HP motor.

Keywords – Induction motors, scalar control, vector control, software modification

1. INTRODUCTION

In the past decade, dc motors have been commonly used for electric traction. As the flux and torque control variables of a dc motor are inherently physically decoupled, a dc motor drive system can have very good dynamic behavior. However, the advantages of dc motors can be offset by their large size, heavy weight, high cost, and complicated maintenance when compared with ac squirrel-cage induction motors.

Several control methods with various level of complexities are developed and divided into two main groups: scalar and vector control methods. The scalar control, associated with the magnitude control of a variable, can in turn be categorized into slip control [1], voltage-frequency control [2], flux control [3] and dependent flux control [4].

In the vector control where both magnitude and phase of a vector variable are controlled, two generic types exist. The direct vector control scheme senses the air-gap flux by use of the Hall effect sensor, search coil, or other measurement techniques [5]. The indirect vector control method regulates the flux indirectly by using the rotor speed and setting the slip frequency as a function of the stator currents [6].

It has been shown in the literature that vector control methods for induction motor drives allow better dynamic performances than scalar ones. However, the production of induction motors with

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**Corresponding author

scalar controllers still continues. Some supporters of the scalar controller argue that these are simpler to implement than vectorial types, and some recent works [7-10] compare the overall performance (such as speed or torque responses) of the scalar and vector controller. In this paper, the structural similarities and differences of a scalar controller with flux loop and a direct vector controller with rotor flux oriented compared. To perform comparative tests, it is shown how both techniques can be implemented with the same hardware blocks. As a result it is also shown how a scalar controller may easily be converted to a vector type.

Sections 2, 3 and 4 describe the dynamic model of an induction motor and present its control via scalar and direct vector control methodologies. The structural comparison between these controllers is presented in section 5. Converting a scalar controller to a vector type is explained in section 6. Simulation results are included in section 7 and, finally, concluding remarks are provided in section 8.

2. DYNAMIC MODEL OF AN INDUCTION MOTOR

Stator and rotor voltages and currents are related by the following equation [11].

$$\begin{bmatrix} V_{abcs} \\ V'_{abcr} \end{bmatrix} = \begin{bmatrix} r_s + \rho L_s & \rho L'_{sr} \\ \rho (L_{sr}')^T & r'_r + \rho L'_r \end{bmatrix} \times \begin{bmatrix} I_{abcs} \\ I'_{abcr} \end{bmatrix} \tag{1}$$

Transferring Eq. (1) to d-q axes, will lead to:

$$\begin{bmatrix} V_{qs} \\ V_{ds} \\ V'_{qr} \\ V'_{dr} \end{bmatrix} = \begin{bmatrix} r_s + \frac{\rho}{\omega_b} X_{ss} & \frac{\omega}{\omega_b} X_{ss} & \frac{\rho}{\omega_b} X_m & \frac{\omega}{\omega_b} X_m \\ -\frac{\omega}{\omega_b} X_{ss} & r_s + \frac{\rho}{\omega_b} X_{ss} & -\frac{\omega}{\omega_b} X_m & \frac{\rho}{\omega_b} X_m \\ \frac{\rho}{\omega_b} X_m & \left(\frac{\omega - \omega_r}{\omega_b}\right) X_m & r'_r + \frac{\rho}{\omega_b} X'_{rr} & \left(\frac{\omega - \omega_r}{\omega_b}\right) X'_{rr} \\ -\left(\frac{\omega - \omega_r}{\omega_b}\right) X_m & \frac{\rho}{\omega_b} X_m & -\left(\frac{\omega - \omega_r}{\omega_b}\right) X'_{rr} & r'_r + \frac{\rho}{\omega_b} X'_{rr} \end{bmatrix} \times \begin{bmatrix} i_{qs} \\ i_{ds} \\ i'_{qr} \\ i'_{dr} \end{bmatrix} \tag{2}$$

This equation can be solved for the currents, and the torque can be calculated by:

$$T_e = (\frac{3}{2})(\frac{P}{2}) L_m (i_{qs} i'_{dr} - i_{ds} i'_{qr}) \tag{3}$$

The relation between mechanical and electrical torque is described by:

$$T_e - T_l = \frac{2}{P} J \frac{d\omega_r}{dt} \tag{4}$$

It is clear that voltage-fed induction machines are described by 5th order differential equations whereas a current fed machine is described by 3rd order differential equations [11] .

3. SCALAR CONTROL OF A CURRENT-CONTROLLED INDUCTION MOTOR

Figure 1 shows the control block diagram of a scalar controller by which flux and torque are controlled independently.

G1, G2 and G3 are assumed to be controllers. The output of flux controller is the amplitude of the current reference $|I_s^*|$ and the output of the torque controller is the "slip reference" ω_{sl}^*, which add to

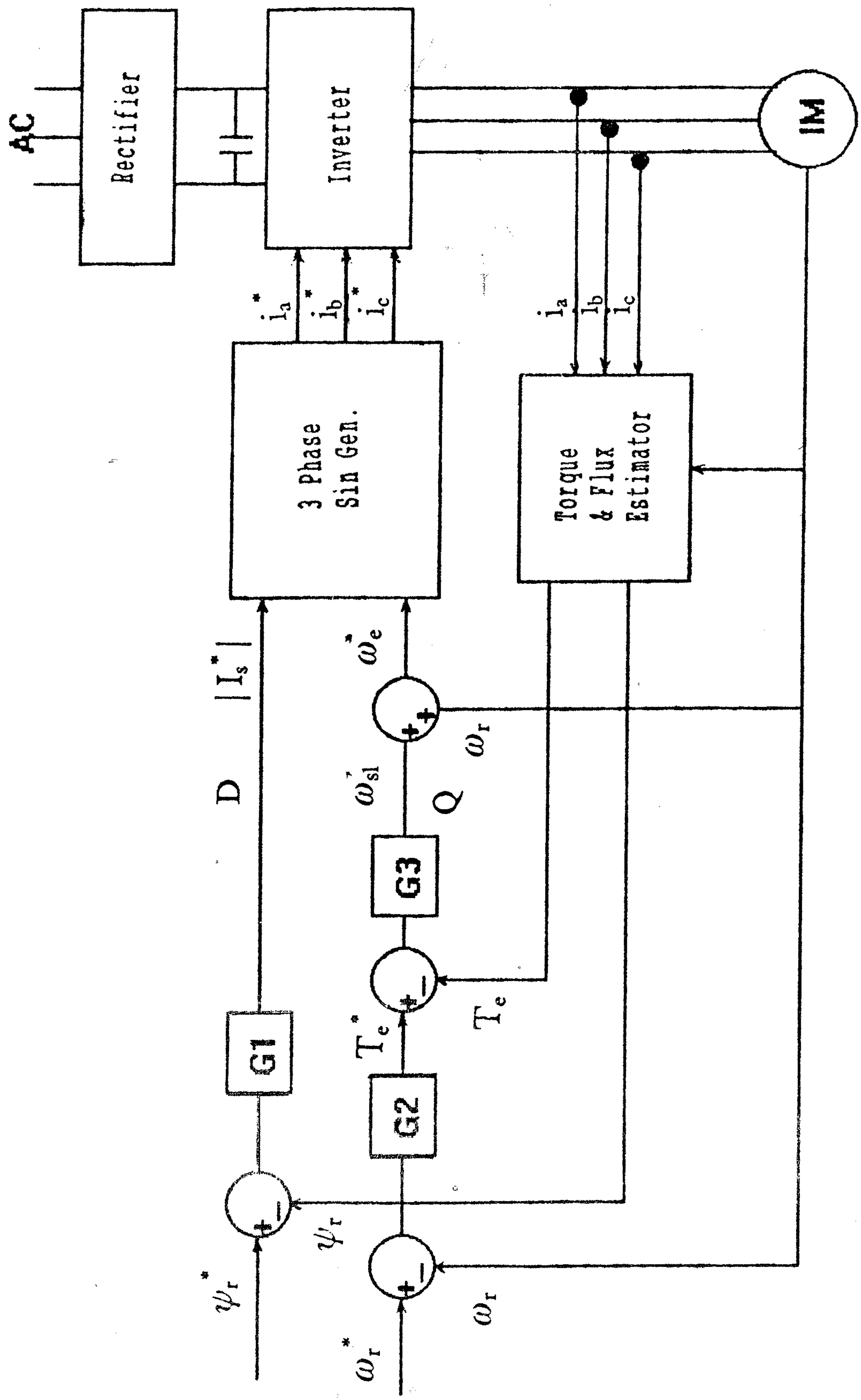

Fig. 1. Scalar control block diagram

the speed ω_r resulting in frequency reference ω_e^* [12]. In the next stage $|I_s^*|$ and ω_e^* are given to a 3-phase sinusoidal wave generator. At this point, the shape of the current reference for each phase will be generated from a look-up table stored in a ROM and a counter [13]. Then the 3-phase current reference will be produced through a PWM method such as a hysteresis band [14] and will be fed to the induction motor.

By sampling the fed current and speed, torque and flux can be estimated and used as feedback. The flux reference (Ψ_r^*) is calculated as:

$$i_m = \frac{V}{X_m} \tag{5}$$

$$\Psi_r^* = \frac{X_m}{\omega_b} i_m \tag{6}$$

4. DIRECT VECTOR CONTROL OF AN INDUCTION MOTOR

Vector control can be direct or indirect. In this paper the direct method with rotor flux field orientation is used. The aim is to decouple the variables in d-q, which results in the relationship between current and flux as shown in Fig. 2.

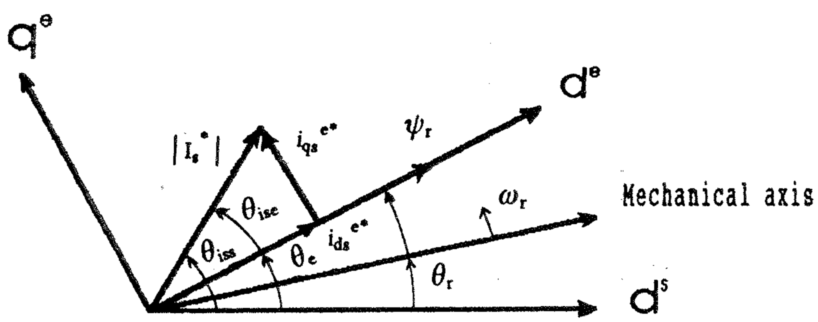

Fig. 2. Phasor diagram for indirect vector control

The control diagram is shown in Fig. 3, in which flux and torque are controlled by feeding back the estimated quantities. The flux and torque controller outputs are i_{ds}^{e*} and i_{qs}^{e*}, respectively. These currents are the elements of the stator current on the axes of the rotating reference frame. In the next stage, the desired quantities are determined through the flux and torque estimator and governed by the following equations. In these equations the rotor variables and parameters are referred to the stator windings.

$$\frac{d\psi_{qr}^s}{dt} = \frac{L_m}{T_r} i_{qs}^s + \omega_r \psi_{dr}^s - \frac{1}{T_r}\psi_{qr}^s \tag{7}$$

$$\frac{d\psi_{dr}^s}{dt} = \frac{L_m}{T_r} i_{ds}^s + \omega_r \psi_{qr}^s - \frac{1}{T_r}\psi_{dr}^s \tag{8}$$

$$|\psi_r| = \sqrt{(\psi_{dr}^s)^2 + (\psi_{qr}^s)^2} \tag{9}$$

$$T_e = \frac{3}{2} \times \frac{p}{2} \times \frac{L_m}{L_r}(i_{qs}^s \psi_{dr}^s - i_{ds}^s \psi_{qr}^s) \tag{10}$$

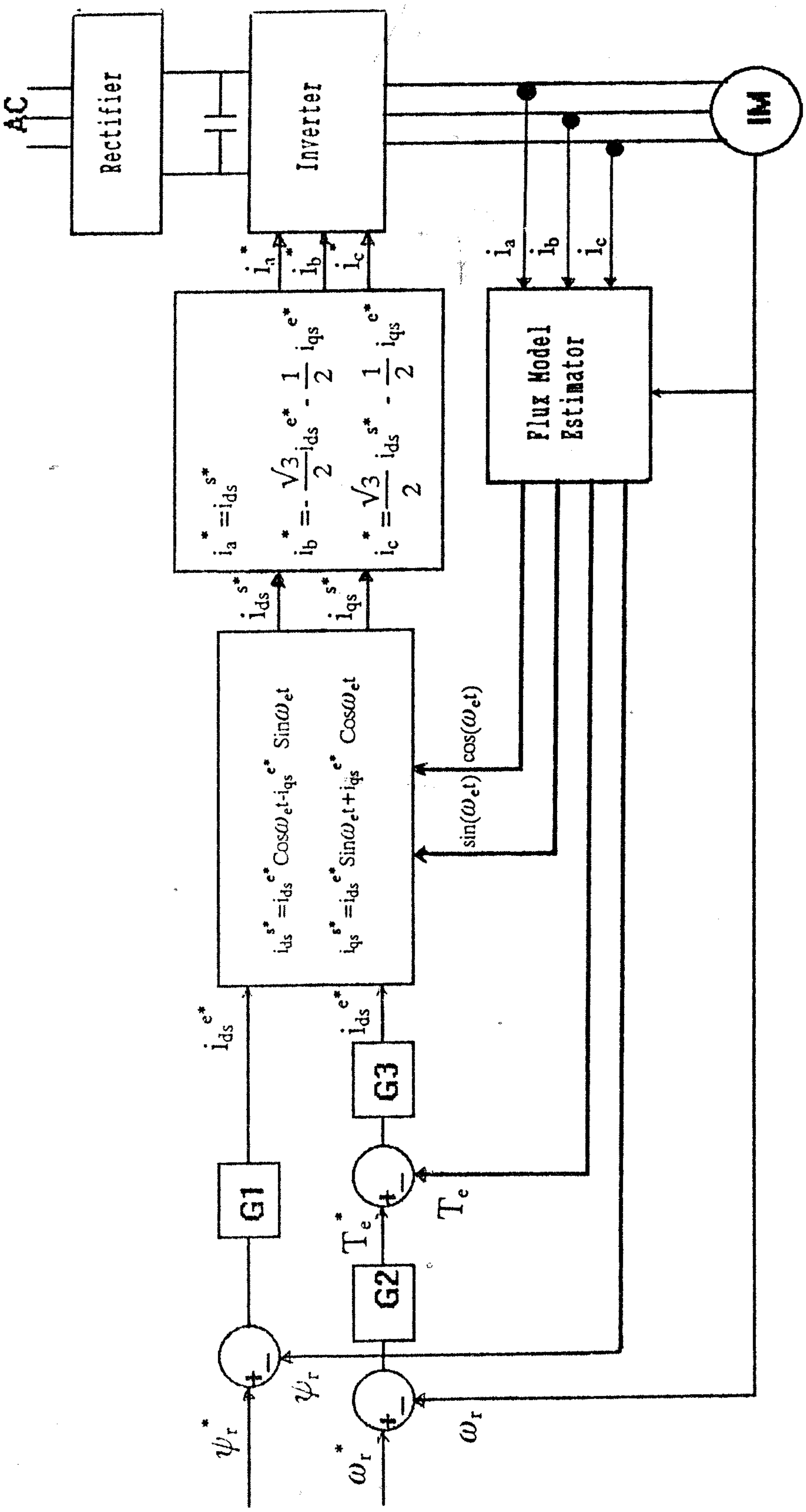

Fig. 3. Vector control block diagram

After calculating ψ^s_{dr}, ψ^s_{qr} and ψ_r, the unit vector that presents the location of vector ψ_r can be determined by:

$$cos(\omega_e t) = \frac{\psi^s_{dr}}{|\psi_r|} \tag{11}$$

$$sin(\omega_e t) = \frac{\psi^s_{qr}}{|\psi_r|} \tag{12}$$

The current is then transformed from rotating reference frame to stationary reference frame by using the unit vectors. Consequently, i^{s*}_{ds} and i^{s*}_{qs} transform from 2 phase to 3 phase. These currents are generated by inverter and fed to the motor [12]. For vector control, the following is desired:

$$\psi_{qr} = \frac{d\psi_{qr}}{dt} = 0 \tag{13}$$

$$\psi_{dr} = \psi_r = cte \Rightarrow \frac{d\psi_{dr}}{dt} = 0 \tag{14}$$

Substituting $\psi_{qr} = 0$ and ψ_{dr} ,$=\psi_r$ in torque, the expression yields:

$$T_e = \frac{3}{2} \times \frac{P}{2} \times \frac{L_m}{L_r} i_{qs} \psi_r \tag{15}$$

5. STRUCTURAL COMPARISON OF SCALAR AND VECTOR CONTROLLERS

Scalar and vector controllers are compared in this section. Following block comparison, it is shown how classical scalar and vector controllers may be modified to generate similar outputs. It is then shown how these two types of controller may be implemented with the same hardware.

a) Block comparison

I. ***Comparison of controller outputs:*** In scalar control, the outputs of controller are $|I^*_s|$ and ω_e^*, while in the vector control they are i^{e*}_{ds} and i^{e*}_{qs}. In each method, two signals are produced that define the reference current. It is desirable to improve these two controllers so that similar information is derived for the reference currents.

II. ***3 - phase reference current generator:*** 3 -phase reference current generator block is required for both methods.

III. ***Torque and flux estimating block:*** This block is also the same for the two methods [13].

b) Modifications of classical scalar and vector controllers to generate similar outputs

The scalar and the vector controllers should be improved so that they produce similar output information. This information will be the magnitude $|I^*_s|$ and the phase θ^*_{iss} of the reference current.

In vector type, these signals are determined by the flux and the torque controller outputs, using the following equations (see Fig. 2):

$$|I^*_s| = \sqrt{(i^{e*}_{qs})^2 + (i^{e*}_{ds})^2} \tag{16}$$

$$\theta^*_{ise} = tan^{-1} \frac{i^{e*}_{ds}}{i^{e*}_{qs}} \tag{17}$$

$$\theta^*_{iss} = \theta_e + \theta^*_{ise} \tag{18}$$

In the scalar method, the magnitude of current is the output of the flux controller, and its phase is derived by adding the slip angle θ_{sl} to the rotor angle θ_r.

$$\left| I^*_s \right| = D \tag{19}$$

$$\theta^*_{sl} = \int \omega_{sl} dt \tag{20}$$

$$\theta_{iss} = \theta^*_{sl} + \theta^*_r \tag{21}$$

In the next step, the 3 phase current is determined by the phase and magnitude of the reference current:

$$i^*_a = \left| i^*_s \right| sin(\theta^*_{iss}) \tag{22}$$

$$i^*_b = \left| i^*_s \right| sin(\theta^*_{iss} + \frac{2\pi}{3}) \tag{23}$$

$$i^*_c = \left| i^*_s \right| sin(\theta^*_{iss} - \frac{2\pi}{3}) \tag{24}$$

The motor feeding currents are generated by an inverter through the reference 3- phase currents. Flux and torque will be estimated using stator currents and speed signals.

c) Implementation of a scalar and vector controller with the same hardware

The control block diagram of both scalar and vector controller is shown in Fig. 4. The flux and torque controller outputs are D and Q, respectively. A pseudo switch has been considered. When the switch is in state " S ", D, Q and θ_r are the input signals and Eqs. (19-21) will hold. As a result, the motor will be controlled through the scalar method, while the switch is in state " V ", D, Q and θ_e (θ_e will be explained in the following section) are the input signals. Equations (16-18) will also hold in this case, thus the controller achieved is based on vector type. The output signals of the controller will be $|I^*_s|$ and $\theta_{iss}{}^*$ in both cases. The block diagram indicates that the hardware structures of scalar and direct vector controllers are the same.

6. CONVERSION OF THE SCALAR CONTROLLER OF AN INDUCTION MOTOR TO DIRECT VECTOR CONTROLLER

To convert an existing scalar controller to a direct vector controller, some modifications in the software must be performed as follows:

a) The rotating reference frame angle θ_e calculated by the following equation,

$$\theta_e = tan^{-1}\left(\frac{\Psi^s_{qr}}{\Psi^s_{dr}} \right) \tag{25}$$

must be added to estimation block.

b) The outputs of a scalar controller are $|I^*_s|$ and $\omega_e{}^*$ should be calculated by the following equations:

$$\left| I^*_s \right| = D \tag{26}$$

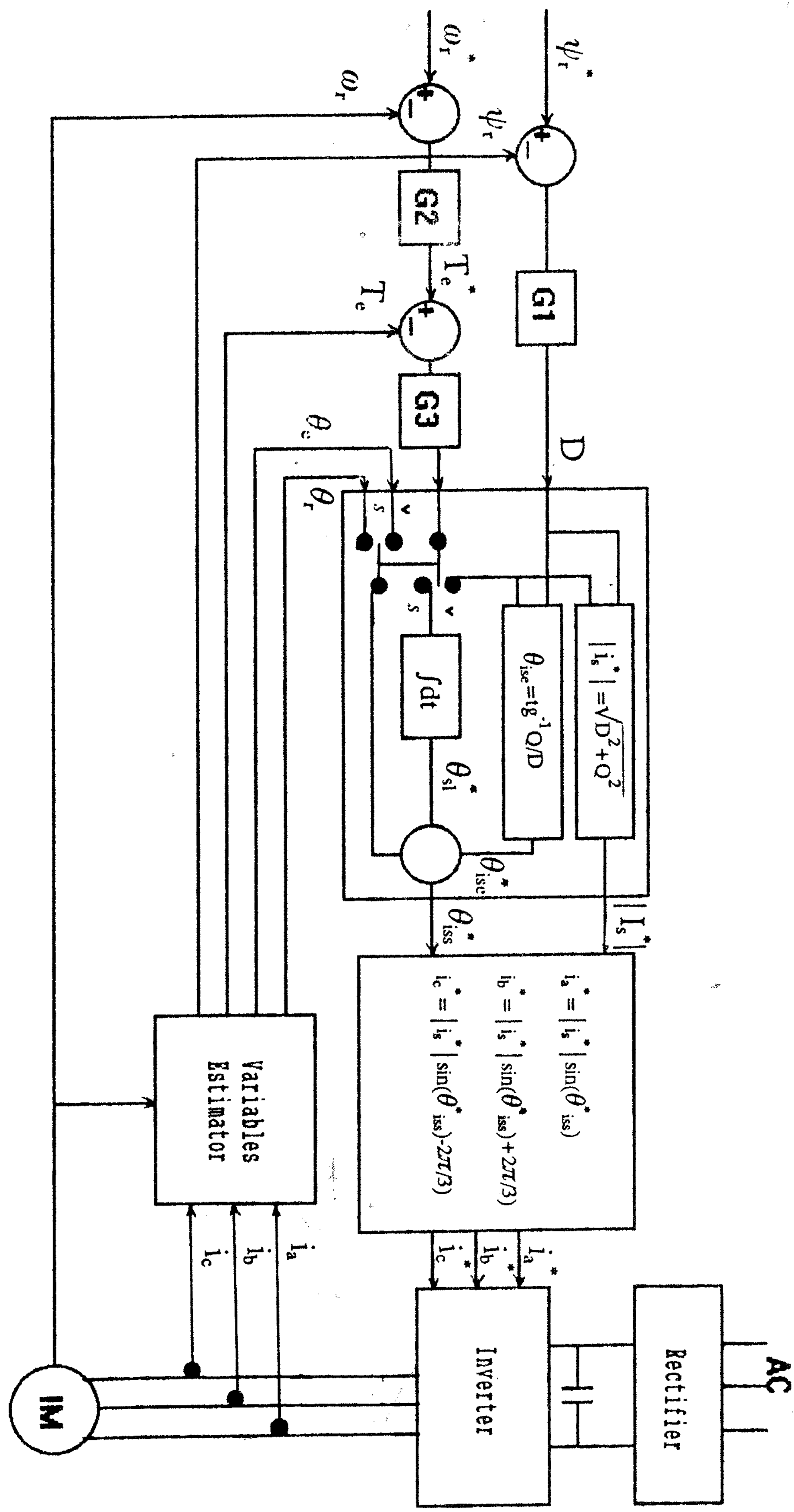

Fig. 4. A generic block diagram for scalar and vector controller

$$\omega_e^* = Q + \omega_r \tag{27}$$

In the modified controller, the outputs will be determined by:

$$|I_s^*| = \sqrt{D^2 + Q^2} \tag{28}$$

$$\theta^*_{iss} = tan^{-1}\left(\frac{Q}{D}\right) + \theta_e \tag{29}$$

c) In the scalar controller, the current references are produced by feeding $|I_s^*|$ and ω_e^* as input signals to a 3-phase sinusoidal wave generator [13]. In the modified controller, $|I_s^*|$ and θ^*_{iss} will be used as input signals and a 3-phase current reference will be produced by using Eqs. (22-24).

When these modifications are performed, the controller will resemble the block diagram of Fig. 4, when the switch is in state " V ". The controller achieved is thus a vector type.

7. COMPUTER SIMULATION RESULTS

The complete system of an induction motor with its controller has been simulated. The machine fifth order differential equation was described in section 2. These nonlinear differential equations are solved by 4th order Runge - Kutta method. The parameters of the motor considered are as follows:

Power = 3 HP, Voltages = 220 volts, Number of poles = 4 poles, Frequency = 60 HZ,
$J = 0.089\, kg.m^2$
$r_s = 0.435\Omega,\quad r_r' = 0.816\Omega,\quad X_{ss} = 26.884\Omega,\quad X'_{rr} = 26.884\Omega,$
$X_m = 26.13\Omega$

Figures 5 and 6 show the dynamic responses of flux and torque in scalar and vector modes. Figures 7 and 8 show the dynamic responses of flux and speed in those two modes. Table 1 compares the results in response to steps in torque reference and speed reference settings. Generally and as expected, a vector controller performs more satisfactorily than a scalar type.

Table 1. Results of response of a generic block diagram for scalar and vector controller

Speed control		Torque control				
Change command from 50 to 100 Rad/Sec	Change command from 0 to 50 Rad/Sec	Change command from 6 to 12 Nm	Change command from 6 to 12 Nm			
0.51	0.47	0.2150	0.2450	Settling time (Sec)	Flux	Scalar control
It has oscillation	It has oscillation	It has oscillation	It has oscillation	Dynamic performance		
-	-	0.05	0.11	Settling time (Sec)	Torque	
-	-	Soft change	Soft change	Dynamic performance		
0.90	0.95	-	-	Settling time (Sec)	Speed	
It has oscillation	It has oscillation	-	-	Dynamic performance		
0	0	0	0	Settling time (Sec)	Flux	Vector control
cte	cte	cte	cte	Dynamic performance		
-	-	0.0001	0.0001	Settling time (Sec)	Torque	
-	-	Immediate change	Immediate change	Dynamic performance		
0.50	0.47	-	-	Settling time (Sec)	Speed	
Soft change	Soft change	-	-	Dynamic performance		

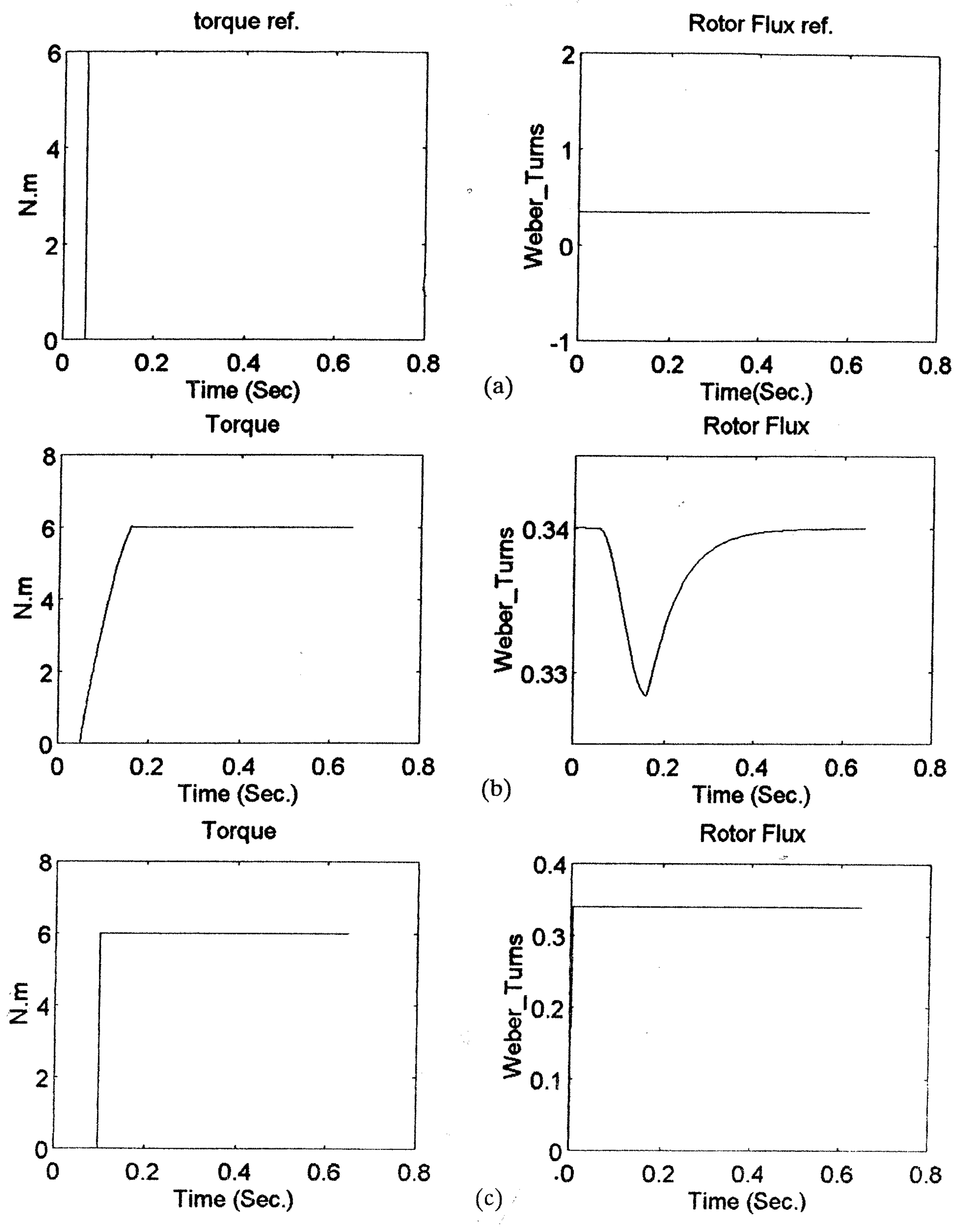

Fig. 5.Dynamic responses of flux and torque after changing the torque command from 0 to 6 Nm (a) flux and torque command (b) scalar mode (c) vector mode

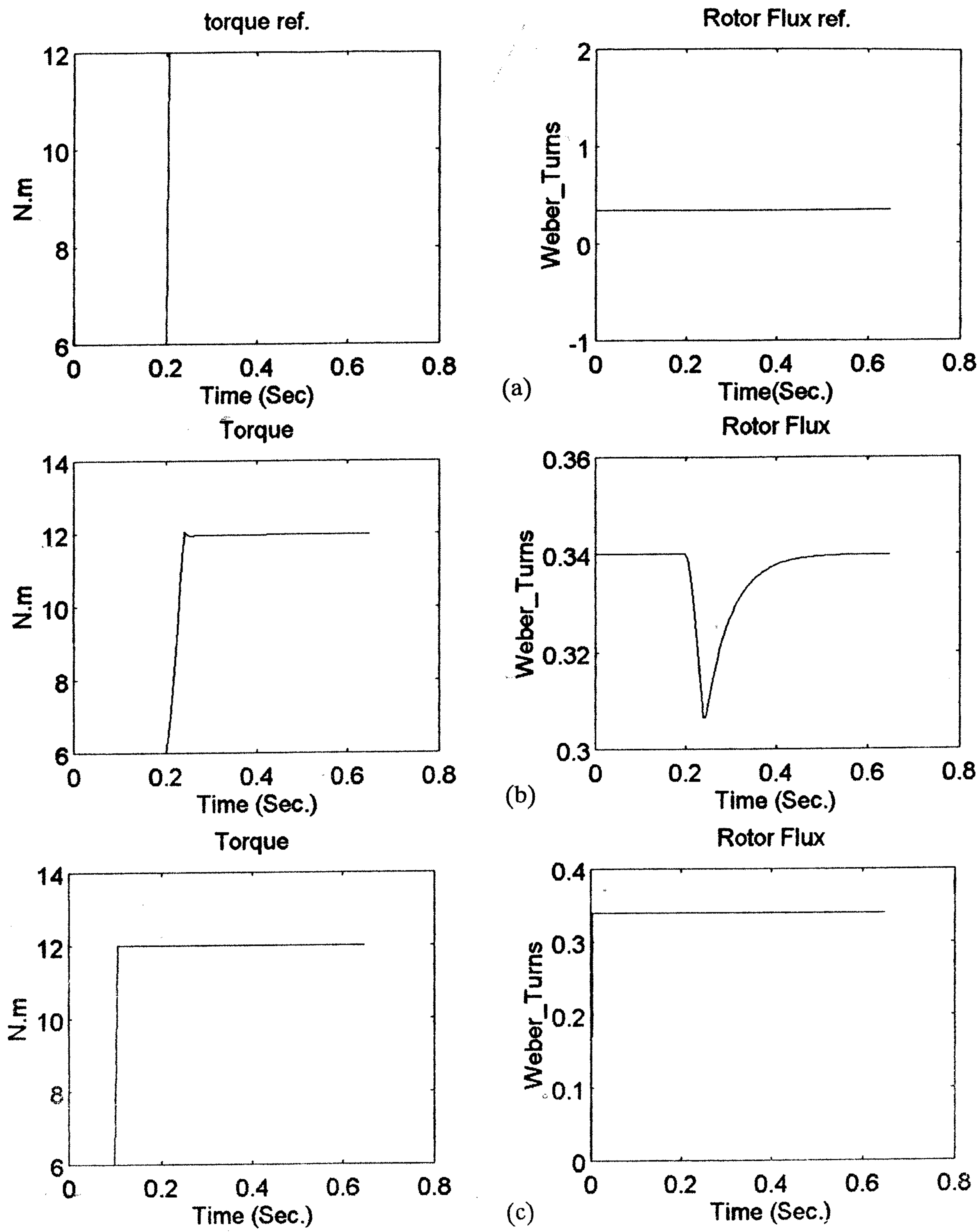

Fig. 6. Dynamic responses of flux and torque after changing the torque command from 6 to 12 Nm (a) flux and torque command (b) scalar mode (c) vector mode

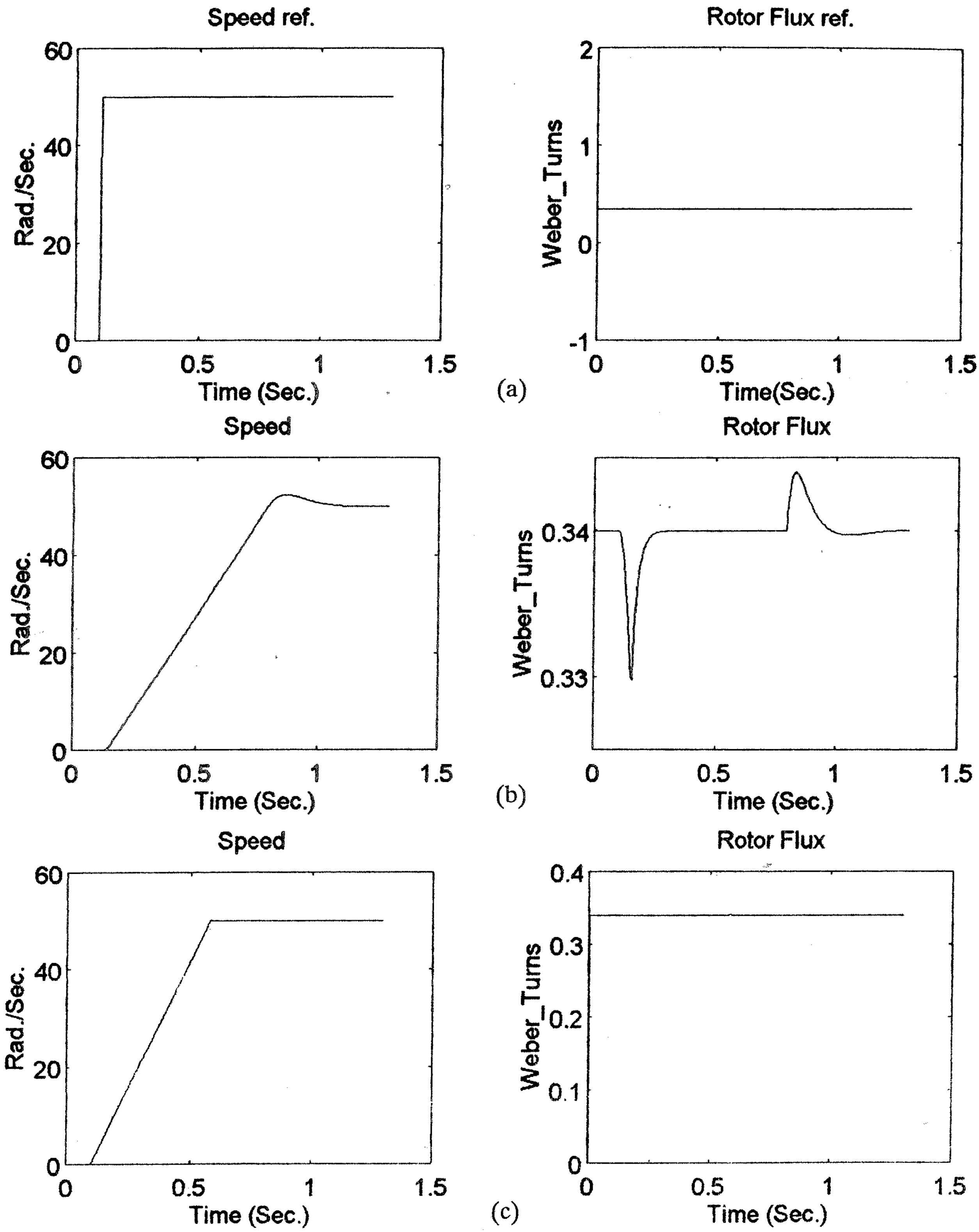

Fig. 7. Dynamic responses of flux and speed after changing the speed from 0 to 50 Rad/Sec
(a) flux and speed command (b) scalar mode (c) vector mode

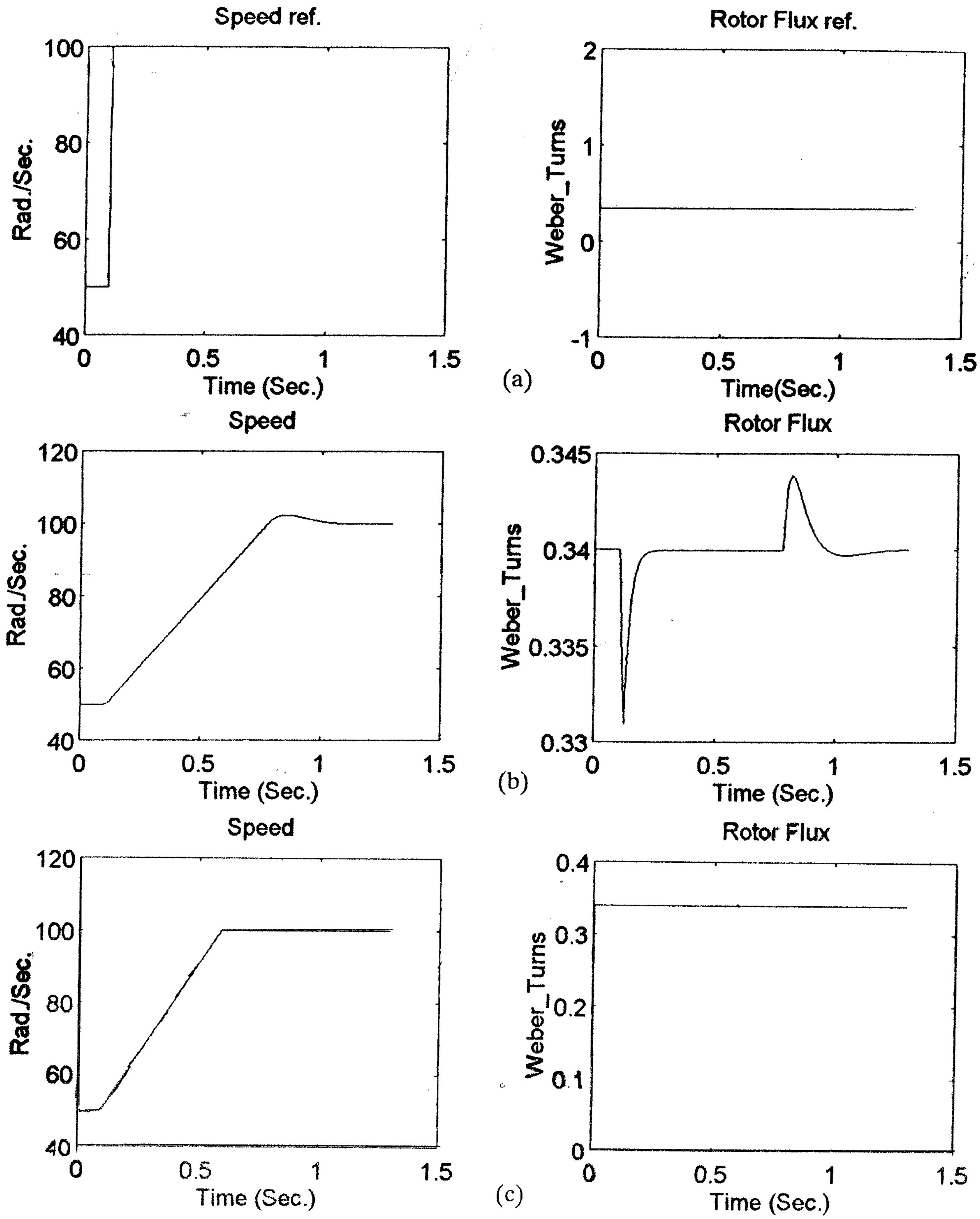

Fig. 8. Dynamic responses of flux and speed after changing the speed command from 50 to 100 Rad/Sec (a) flux and speed command (b) scalar mode (c) vector mode

8. CONCLUSIONS

Comparison was made of the governing equations that relate the input and output signals in scalar control with flux loop and direct vector control with rotor flux oriented by current-controlled induction motors. A relationship between these two controllers was established and it was concluded that it is possible to implement both control techniques using the same hardware. Therefore, the implementation difficulties and costs of both control strategies are indicated. It was shown how a scalar controller may be readily converted to a vector type by software modifications so that the advantages of both types are achieved. Some computer results were demonstrated.

NOMENCLATURE

L_m	Magnetizing inductance
L_r	Rotor inductance
L_s	Stator inductance
r_s	Stator resistance
r_r	Rotor resistance
T_r	Rotor time constant
X_{rr}	Rotor reactance
X_{ss}	Stator reactance
X_m	Magnetizing reactance
P	Number of poles
J	Rotor inertia
D	Flux controller output
Q	Torque controller output
i_{ds}	d-axis stator current
i_{qs}	q-axis stator current
i_{dr}	d-axis rotor current
i_{qr}	q-axis rotor current
i_m	Magnetizing current
$\|I_s\|$	Stator current magnitude
$i_a\ i_b\ i_c$	Three phase stator current
V_{ds}	d-axis stator voltage
V_{qs}	q-axis stator voltage
V_{dr}	d-axis rotor voltage
V_{qr}	q-axis rotor voltage
V	Nominal stator voltage
T_e	Developed torque
T_l	Load torque
ψ_{dr}	d-axis rotor flux linkage
ψ_{qr}	q-axis rotor flux linkage
$\|\psi_r\|$	Rotor flux linkage magnitude
θ_{ise}	Angle between rotor flux and current
θ_e	Rotating reference frame angle
θ_{iss}	Reference current phase
θ_{sl}	Slip angle

θ_r Rotor angle
ω Arbitrary reference frame frequency
ω_b Base frequency
ω_e Stator frequency
ω_r Rotor frequency
ω_{sl} Slip frequency
$(\hat{\ })$ Peak value of a variable
$(')$ Rotor variables or parameters that are referred to the stator windings
$(*)$ Reference variables

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