Pakistan Journal of Information and Technology 1(2): 106-117, 2002

Dynamic Performances of Adjustable Speed AC Drives Part 2: Control and Simulation of AC Machines

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Abstract: In this part, an alternating current machines drives and control methods were implemented. Fortran Language program were used for digital simulation. A six-step inverter and sinusoidal pulse-width modulation inverter are used for the induction machine. With indirect vector control method introducing into the current-controlled dead-beat inverter drive system, the induction motor can be operated in all four quadrants and speed can be controlled from zero to full value where a smooth and fast torque response is obtained throughout the range of the operation. Different types of simulation examples are examined for AC machines and results are discussed.

Key Words: Dynamic Performance, Simulation, AC Drives

Introduction

Recent years have seen the evolution of a new control strategy for AC motors, called "vector control", which has made a fundamental change in this picture of AC motor drives in regard to dynamic performance. Vector control makes it possible to control an AC motor in a manner similar to the control of a separately excited DC motor, and achieve the same quality of dynamic performance. Vector control recognizes the fact that the inferior, dynamic performance of AC motor drives is not because of a basic limitation of the AC motor itself, but because of the manner in which power is fed to the motor and the way this is controlled. For this reason, vector control is the most significant development in the area of adjustable speed electric motor drives in recent years.

In references (Barton, 1978 and Plunkett, 1979) direct method of vector control the unit vectors are obtained from rotor flux which can either be based on the measurement or computation . In reference (Andrieux and Lajoie, 1985) indirect method of vector control, the unit vectors are synthesized by addition of the rotor mechanical position vector and the commanded slip angle vector derived from the torque component of current. Both vector control methods require complex coordinate transformation , phase conversion , and intricate vector signal sensing and processing. Control of AC drives can be basically divided into two groups: Open loop, constant V/Hz control, used in general purpose induction motor packaged drives and multimotor drives. Closed loop, field oriented control with regulated current, used in torque controlled and high performance drives (both with induction and synchronous motors). Control functions for each of these two groups is now presented.

In many applications, the drive system is required to have fast transient response and the capability to operate at zero speed with full torque . Traditionally , for such applications , dc machine has been used . The dc machines are characterized by inherent decoupling between the armature or torque component of current and field flux and therefore give fast response characteristics of torque. The ac machines are attractive in these applications because of the absence of commutators and brushes. The ac machine is a complex multivariable nonlinear coupled system where each of the outputs is a function of the input variables. Because of this coupling nature, the conventional scalar or dc signal control with feedback loops around torque and flux fails to give adequate transient response of torque. If , for example, a step torque demand is established by incrementing the slip signal with the desired rated flux, the flux will diminish temporarily until compensated by the feedback loop in a sluggish manner (Heinemann, 1989). In this part of the paper, the classical and state variable control principles are reviewed and the various scalar control methods by voltage-fed inverter are described.

Control Methods of AC Machines

Implementation of PI Controller: The control loops may contain PID , PI , or PD which are usually given in the form of Laplace transfer function. For microcomputer implementation , it is necessary to convert them into the time domain in the form of difference equations .

Proportional Control: A implementation of proportional control is identical to

$$U(t) = K_p\, e(t) \qquad D(s) = K_p \qquad (1)$$

where e (t) is error signal .

Derivative Control: For the continuous systems , derivative or rate control has the form

$$U(t) = K_p\, T_d\, pe(t) \qquad D(s) = K_p\, T_d\, s \qquad (2)$$

where T_d is called the derivative time .

Integral Control: For continuous systems The error can be integrated to arrive at the Control

$$U(t) = \frac{K_p}{T_i}\int_{t_0}^{t} e(t)dt \Rightarrow D(s) = \frac{K_p}{T_i s} \qquad (3)$$

where T_i is called the integral , or rest time .
When the transient response of a feedback control system is consider satisfactory but the steady-state error is too large , it is possible to eliminate the error by increasing the system type . This must be accomplished without appreciably changing the dominant roots of the characteristic equation . The system type can be increased by operating on the actuating signal x to produce one that is proportional to both the magnitude and the integral of this signal . This proportional plus integral (PI) controller can be expressed

$$\frac{Y(S)}{X(S)} = K_p + \frac{K_i}{s} \tag{4}$$

or

$$SY(S) = K_I X(S) + K_P SX(S) \tag{5}$$

If the sampling time T_s is small , a derivative can be represented in finite difference form , and therefore Equation (4) can be written as

$$\frac{Y(N+1)-Y(N)}{T_s} = K_p X(N) + K_i \left[\frac{X(N+1)-X(N)}{T_s}\right] \tag{6}$$

where N and N+1 are the consecutive sampling instants . Equation (5) can be written

$$Y(N+1) - Y(N) = K_i T_s X(N) + K_p X(N+1) - K_i X(N) \tag{7}$$

or

$$Y(N+1) = Y(N) + K_p X(N+1) + (K_i T_s - K_p) X(N)$$

Scalar Control Methods: In this section, the selected scalar control techniques of ac machines using voltage-fed inverters are described , Scalar control relates to the control of the magnitude of a variable only , and the command and feedback signals are dc quantities which are proportional to the respective variables. This is in contrast to vector control where both magnitude and phase of a vector variable are controlled , and this method is described in the next section .

Volts / Hertz Control: The application of a constant volts/hertz supply at the motor terminals gives constant air gap flux if the stator voltage drop is negligible . This condition is reasonably well satisfied near rated motor frequency , but the stator voltage drop that is developed by the rated motor current remain constant as the frequency is reduced , so that at low frequencies , this IR drop is a large proportion of the terminal voltage . Thus , if the stator IR drop at rated frequency and full load is 4 percent of the phase voltage , the effect on air gap flux is relatively insignificant . However , at one-tenth of rated frequency, with a constant volts/hertz supply , the IR drop at rated current is 40 percent of the applied voltage , causing a significant reduction in air gap emf and flux (Krause and Thomas, 1985 and Finch and Atkinson, 1989).

Open-loop Speed Control: A static frequency converter can independently control motor voltage V_s, and frequency , ω_e , but a programmed voltage/frequency characteristic reduces the number of command variable to one , allowing simple volts/hertz control .

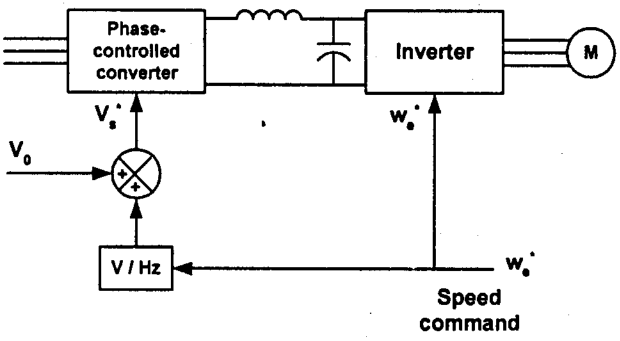

Fig. 1: Open-loop Volts/Hertz Control

Fig .1 shows a block diagram of an open-loop adjustable-speed drive with terminal volts/hertz control . The offset linear voltage/frequency characteristic is implemented . The set point or reference signal is the speed command , n^* , which generates the inverter frequency command , ω_e^*, via a Voltage-Controlled Oscillator (VOC) . The voltage command , V_s^* is also determined directly form the set speed signal .
The static frequency converter in Fig. 1 is a dc link converter employing a six-step or PWM voltage-fed inverter . In the six-step inverter , direct control of the dc link voltage , with inverter frequency tracking voltage , is shown in Fig . 2 . These control techniques are perfectly satisfactory for single or multiple ac machine drives where high dynamic performance is not required

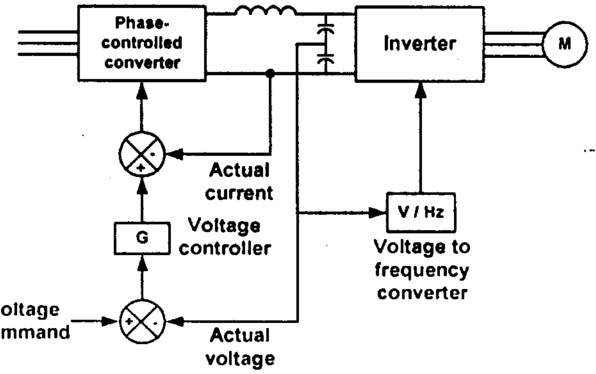

Fig. 2 : Operation of a Six-Step Inverter with Control of DC Voltage

Closed-loop Speed Control: Open-loop speed control has the disadvantage that the rotor slip increases and the ac machine slows down slightly when load torque is applied. Improved speed regulation can be achieved when the motor's natural droop in speed with load is compensated by means of a slip compensation technique in which the inverter frequency is boosted by a signal proportional to motor current . However , open-loop speed control has a poor dynamic performance , and a closed-loop system with tachometer feedback is preferred . Motor speed is then adjusted to the commanded value , giving improved speed regulation and reduced speed sensitivity to shaft load fluctuations. Speed feedback also ensures uniform drive performance over the entire frequency range, there by eliminating the decrease in stability that has traditionally been a problem with open-loop adjustable-frequency drive systems at lower supply frequencies. A drive with terminal volts / hertz control and a speed feedback loop is shown in Fig.3 the set speed, n , is compared with the actual speed, n, to determine the speed error which is then passed through the speed controller and defines the inverter frequency and voltages. As usual, proper controller design is essential if the benefits of closed-loop speed control are to be fully realized.

The control also features a current-limit signal that only comes into effect when motor current rises to a present maximum lever, this signal then controls the rate at which the inverter frequency and voltages are ramped. Thus, if the speed command is suddenly increased, the motor current quickly rises to the present limit; the demanded output frequency and voltages are then gradually increased so that motor speed tracks the inverter frequency and rotor breakdown frequency is not exceeded. This machine accelerates at constant torque under the influence of the current-limit control untilt the set speed is reached. The current then fall below the limit, and steady-state operation is achieve. Above base speed, the power converter can not deliver an increasing voltage, but operation at constant voltage and increasing frequency causes the motor to operate in the field-weakening region.

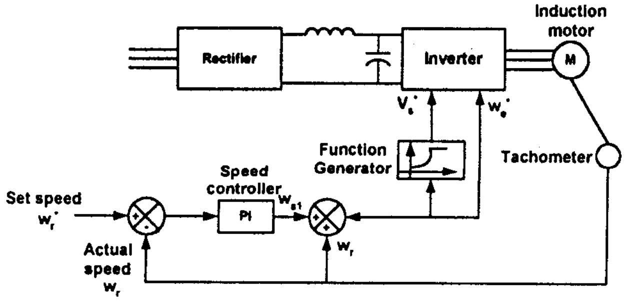

Fig. 3: Closed-Loop volt/hertz Speed Control

Current-Controlled Dead-Beat Inverter: When the PWM inverter is operated as a controlled-current source, using conventional current regulation loops, the stator phase currents track the sine wave reference values. The current controller can be based on a simple hysteresis comparator for each phase. The current error signal , with some hysteresis, controls the switching of an inverter leg. Alternatively, a PWM controller can be employed in which the current error for each phase is compared with a high-frequency triangular wave; the resulting PWM signal controls the inverter switching as before. As long as the maximum or ceiling voltage of the inverter is adequate, the stator phases are effectively fed by sinusoidal current sources, thereby eliminating the influence of the stator resistance and leakage inductance, and simplifying AC machine control. Accurate current tracking is achieved by adopting a high switching frequency, which has the additional advantage of giving a wide bandwidth for control. At low speeds, the sinusoidal phase currents ensure smooth rotation. Beyond base speed, the output current is unable to track the reference current because of insufficient DC link voltage. As a result, the PWM inverter operation will transition to the six-step voltage-source mode and current control by PWM is lost (Andresen and Bieniek, 1984).

Vector Control Methods: In the scalar control methods of voltage-fed drives presented so far, the voltage or current and frequency are the basic control variables of the AC motor. In a voltage-fed drive, both the torque and air-gap flux are functions of voltage and frequency. This coupling effect is responsible for the sluggish response of the AC motor. If, for example, the torque is increased by incrementing the frequency, the flux tends to decrease. However, it is compensated by the sluggish flux control loop feeding in additional voltage. This transient dipping of flux reduces the torque sensitivity with slip and therefore lengthens the response time (Peter, 1990).

Direct Vector Control: Fig. 4 shows a simplified block diagram of a vector control scheme using a current-controlled dead-beat inverter. The two-axis reference currents, i_{qs}^* and i_{ds}^* are the demanded torque and flux components of stator current, respectively, and are generated by the outer control loop. As shown in Fig. 4 i_{qs}^* and i_{ds}^* undergo a coordinate transformation to two-phase to three-phase transformation which generates the stator reference current i_{as}^* , i_{bs}^* and i_{cs}^*. These reference currents are reproduced in the stator phases by the current-controlled dead-beat inverter. The internal action of the motor is to transform the impressed three-phase stator currents to equivalent two-axis current, i_{qs} and i_{ds} . Thus, the external reference current, i_{qs}^* and i_{ds}^* , are reproduced within the ac motor, and control is executed in term of these direct and quadrature axis current components to give decoupled control of flux and torque, as in a dc machine (Peter, 1990) .

control methods. Difference between direct and indirect vector control is generated, because of using coswt and sinwt unit vectors during d-axis q-axis transformations. In indirect vector control method, motor speed is main control parameter separated- excited dc motor torque is,

Indirect Vector Control: There are two different vector control method which are direct and indirect vector

$$\mathrm{Ta} = \mathrm{K}.\psi.\mathrm{Ia} \tag{8}$$

where Ia is armature current, ψ is field flux. Induction motor torque is,

$$\mathrm{Ta} = \frac{3}{2}\left[\frac{\mathrm{P}}{2}\right]\frac{\mathrm{M}}{\mathrm{Lr}}\left(\mathrm{I}_{\mathrm{D}}.\psi_{\mathrm{Q}} - \mathrm{I}_{\mathrm{Q}}.\psi_{\mathrm{D}}\right) \tag{9}$$

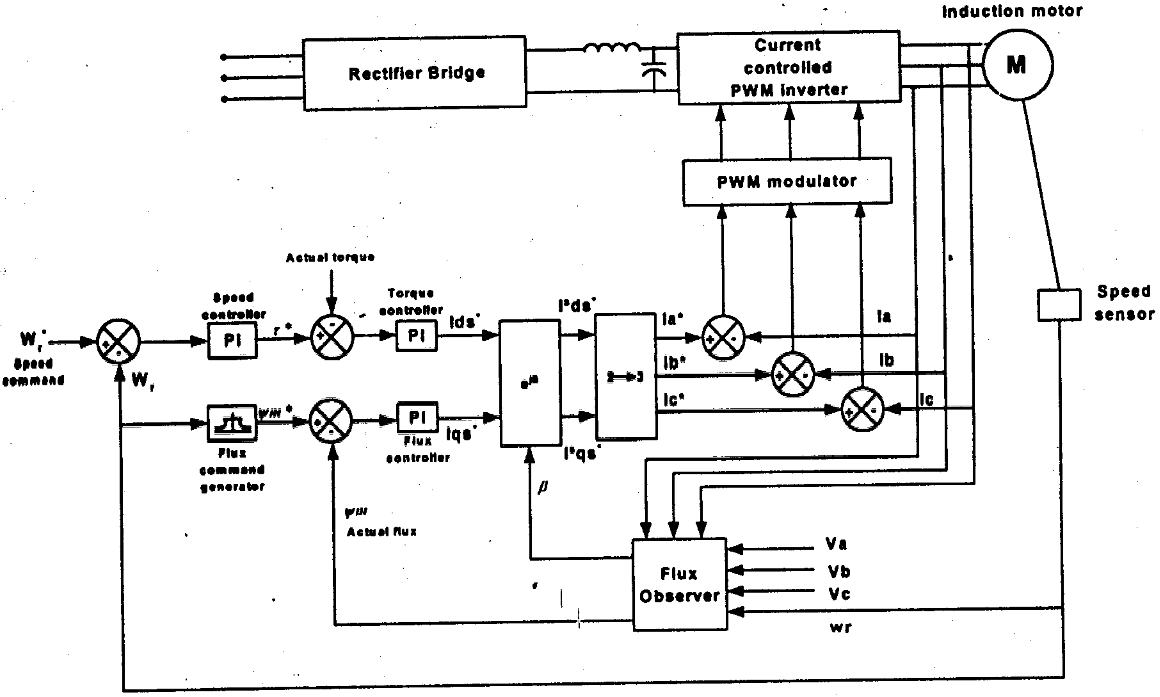

Fig. 4: AC Motor Speed Control System with Direct Vector Control

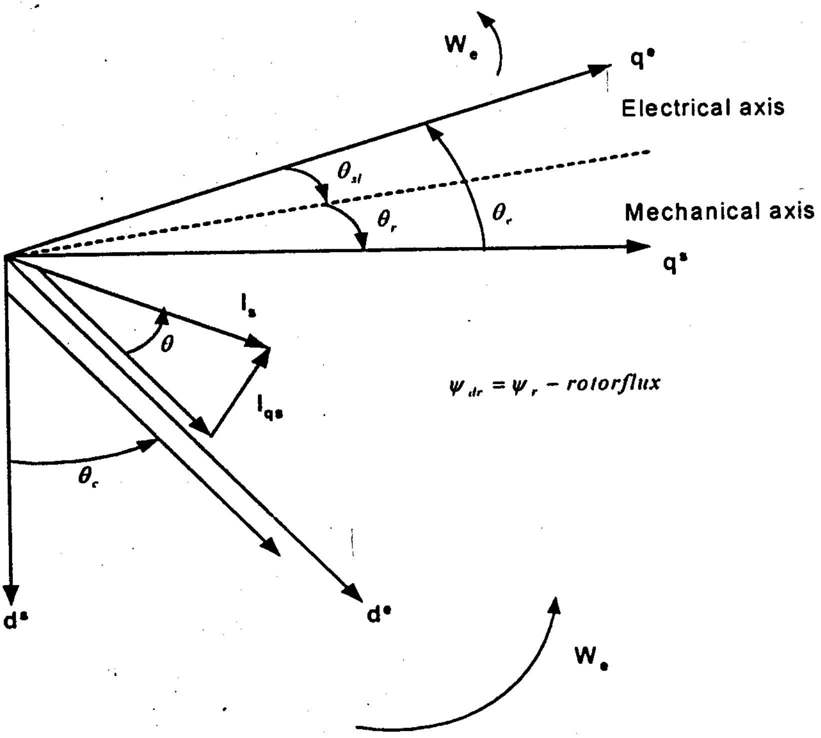

Fig. 5 : Phasor Diagram for Indirect Vector Control

I_{ds}: Current flux component
I_{qs}: Current torque component
θ_{sl}: Slip angular position
θ_r : Rotor angular position
W_e: Angular velocity
θ_r : Angular position (electrical axes)

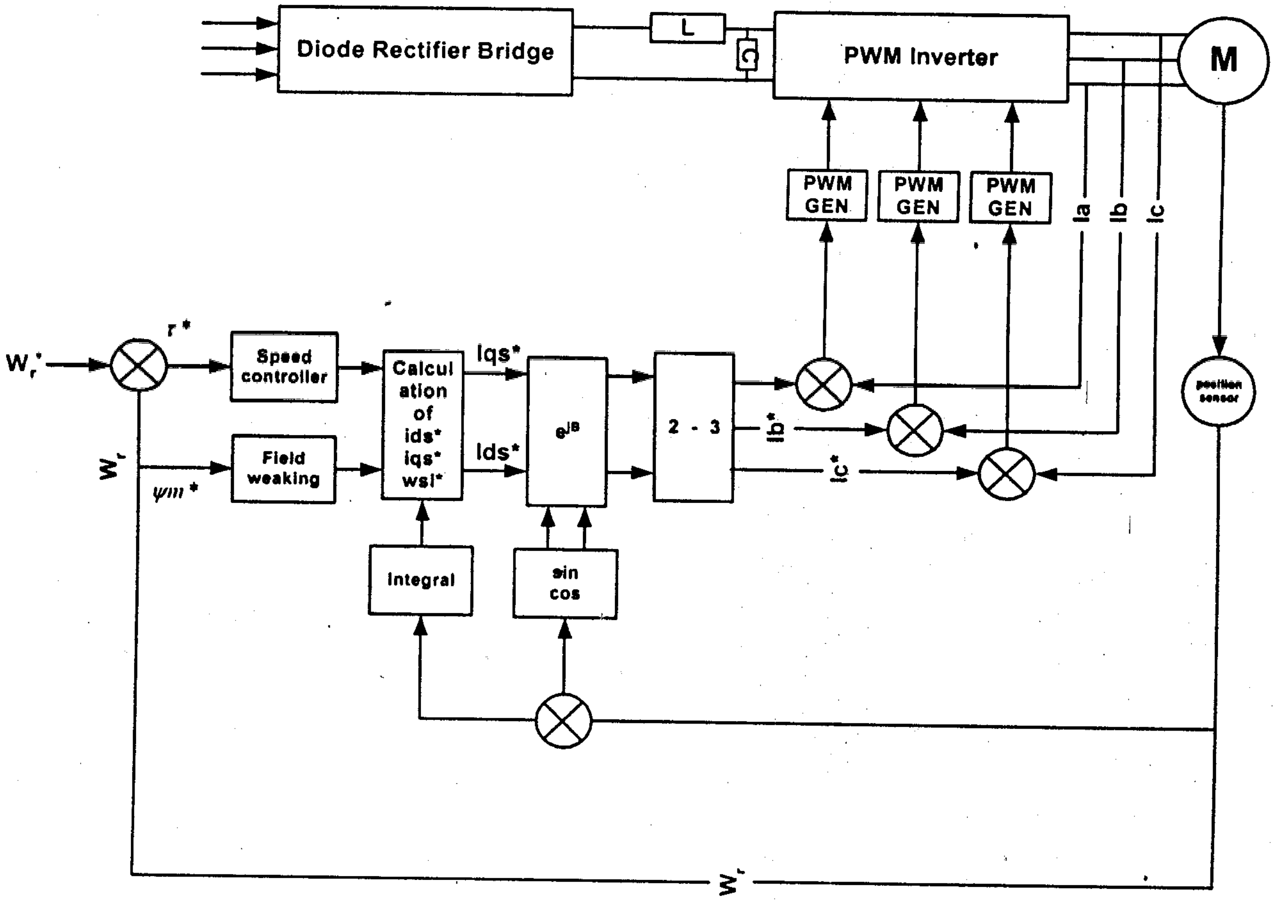

Fig. 6: AC Motor Speed Control System with Indirect Vector Control Method

Table 1: AC machine parameters Used in the Simulation

Induction Motor:			
$R_s = 0.01$	$R_r = 0.1$	$X_m = 3.0$	$H = 1.0$
$X_s = 0.1$	$X_r = 0.015$	$F = 50$	
Synchronous Motor:			
$R_s = 0.01$	$R_{kq} = 0.05$	$X_{md} = 1.0$	$R_{fd} = 0.04$
$X_s = 0.09$	$R_{kd} = 0.04$	$X_{kd} = 0.1$	$X_{fd} = 0.4$
$X_{mq} = 0.9$	$X_{kq} = 0.14$	$H = 1.0$	$F = 50$
Reluctance Motor:			
$R_s = 0.06$	$R_{kq} = 0.03$	$F = 50$	$X_{md} = 2.0$
$X_s = 0.09$	$R_{kd} = 0.03$	$H = 0.5$	$X_{kd} = 0.1$
$X_{mq} = 0.5$	$X_{kq} = 0.1$		

As show in Fig. 5, with rotor flux is oriented to q-axis we can obtain new torque formula is

$$Ta = \frac{3}{2}\left[\frac{P}{2}\right]\frac{M}{Lr} I_D.\psi_r{}' = K.\psi_r.I_D{}' \qquad (10)$$

This equation is similar to dc machine torque equation. Also with rotor flux orientation, obtain equation 11 (Aksoy, 1999).

$$-\frac{M}{L_r}.I_D + W_{sl}\psi_r = 0 \Rightarrow W_{sl} = \frac{L_m R_r}{W_{sl}\psi_r}.I_D \qquad (11)$$

$$\frac{d\psi_r}{dt} + \frac{R_r}{L_r}\psi_r = \frac{MR_r}{L} I_Q = 0 \qquad (12)$$

At this situation, we can obtain Fig. 5 using indirect vector control.

As show in Fig. 5, with rotor flux is oriented to q-axis we can obtain new torque formula is Electromagnetic torque and rotor flux are independently controlled by appropriately regulating

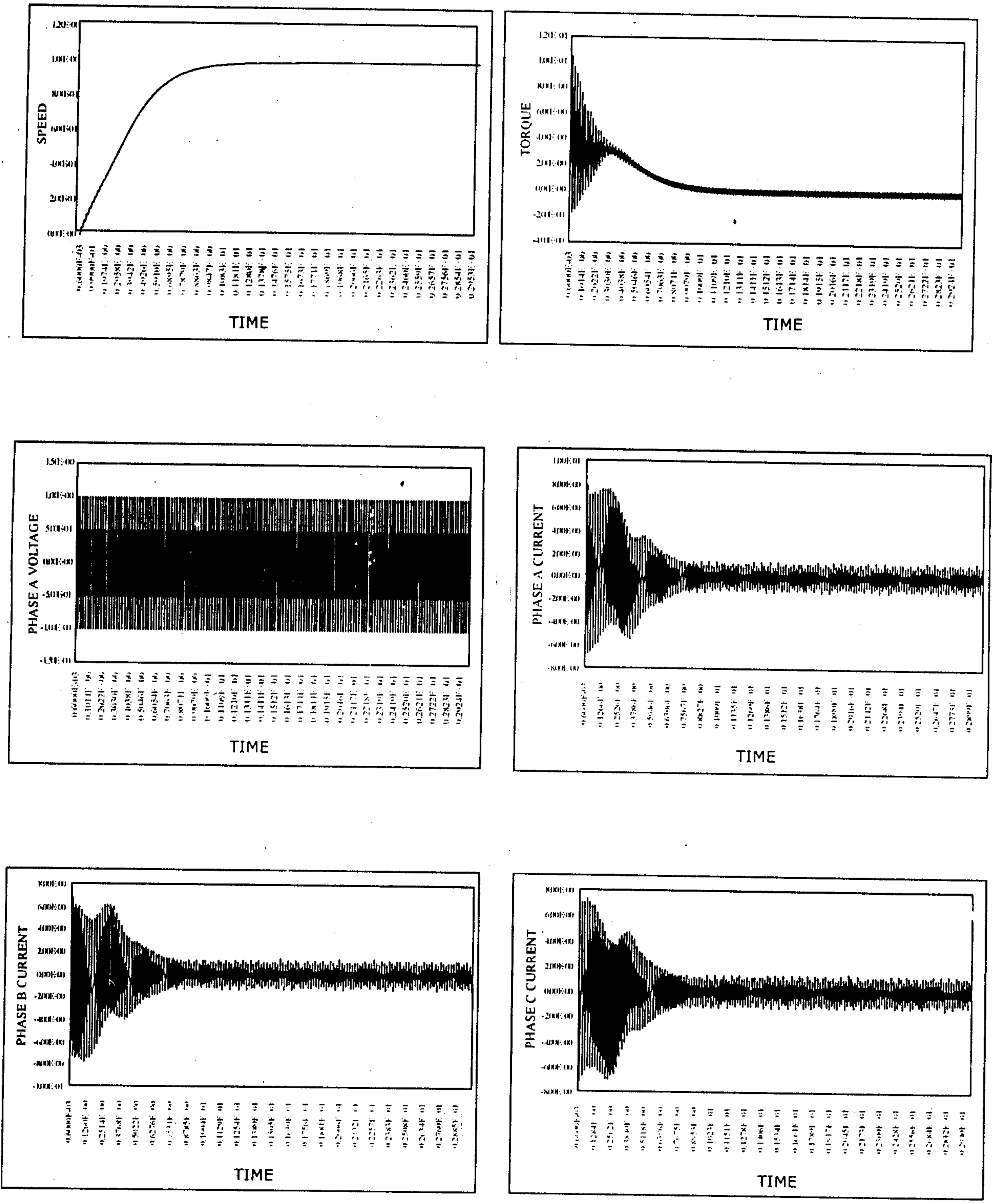

Figure 7: Dynamic performances of six-step PWM inverter-induction motor drive with no load and no fault.

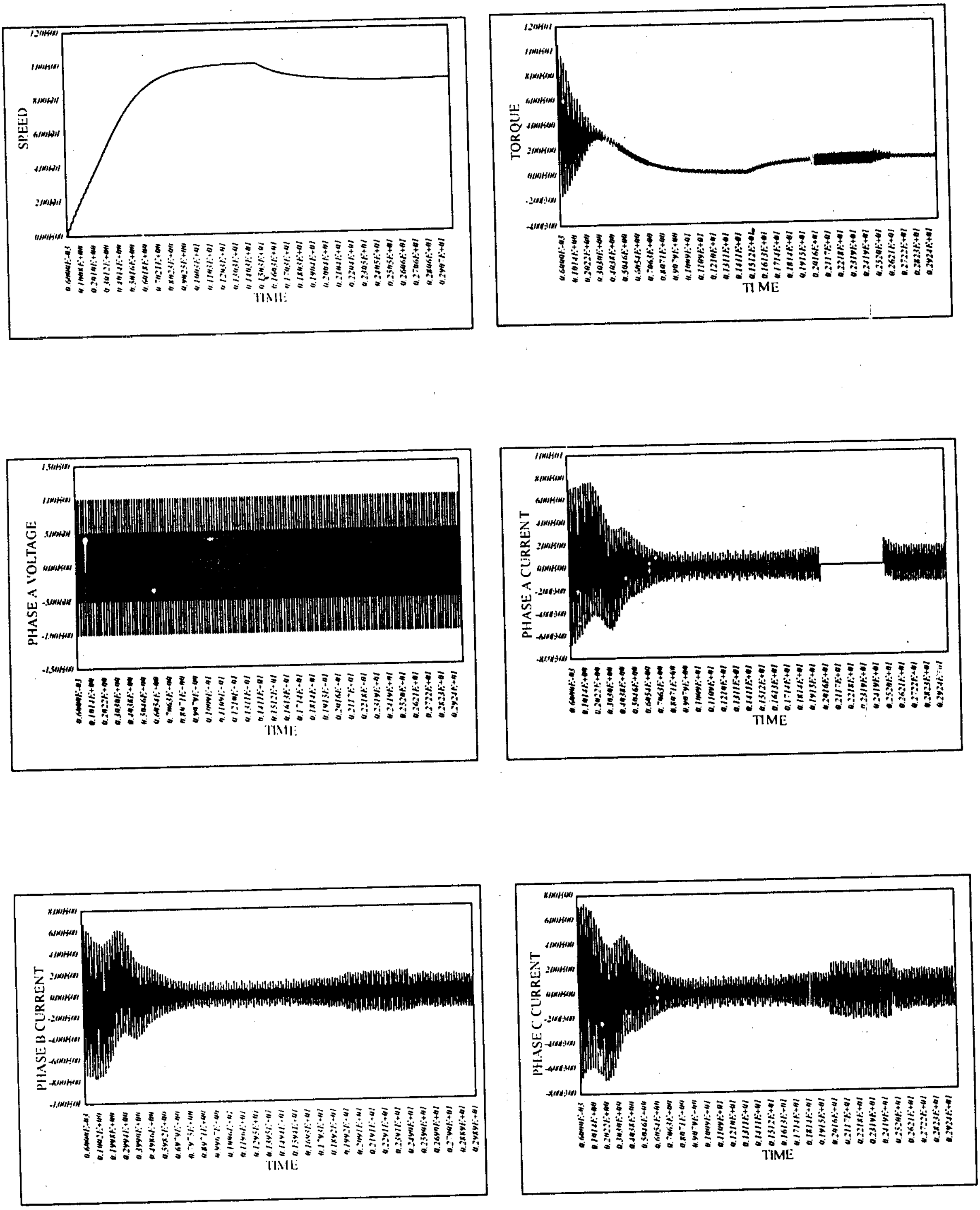

Figure 8 Dynamic performances of six-step inverter-induction motor drive with 1.0 pu step load and 0.5 sec. phase A open circuit fault.

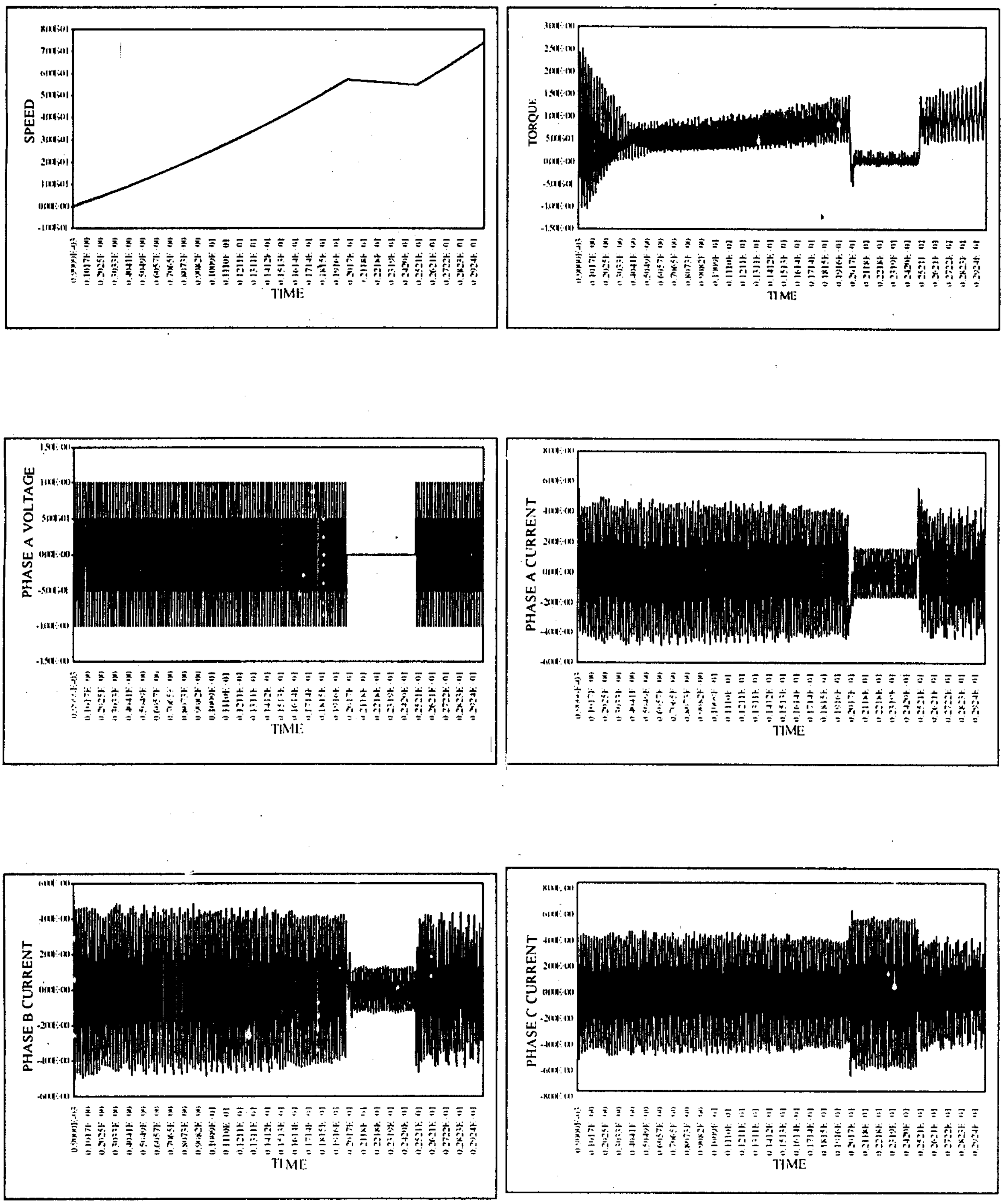

Figure 9: Dynamic performances of six-step PWM inverter-reluctance motor drive with pump load and phase A, B short circuit to earth fault.

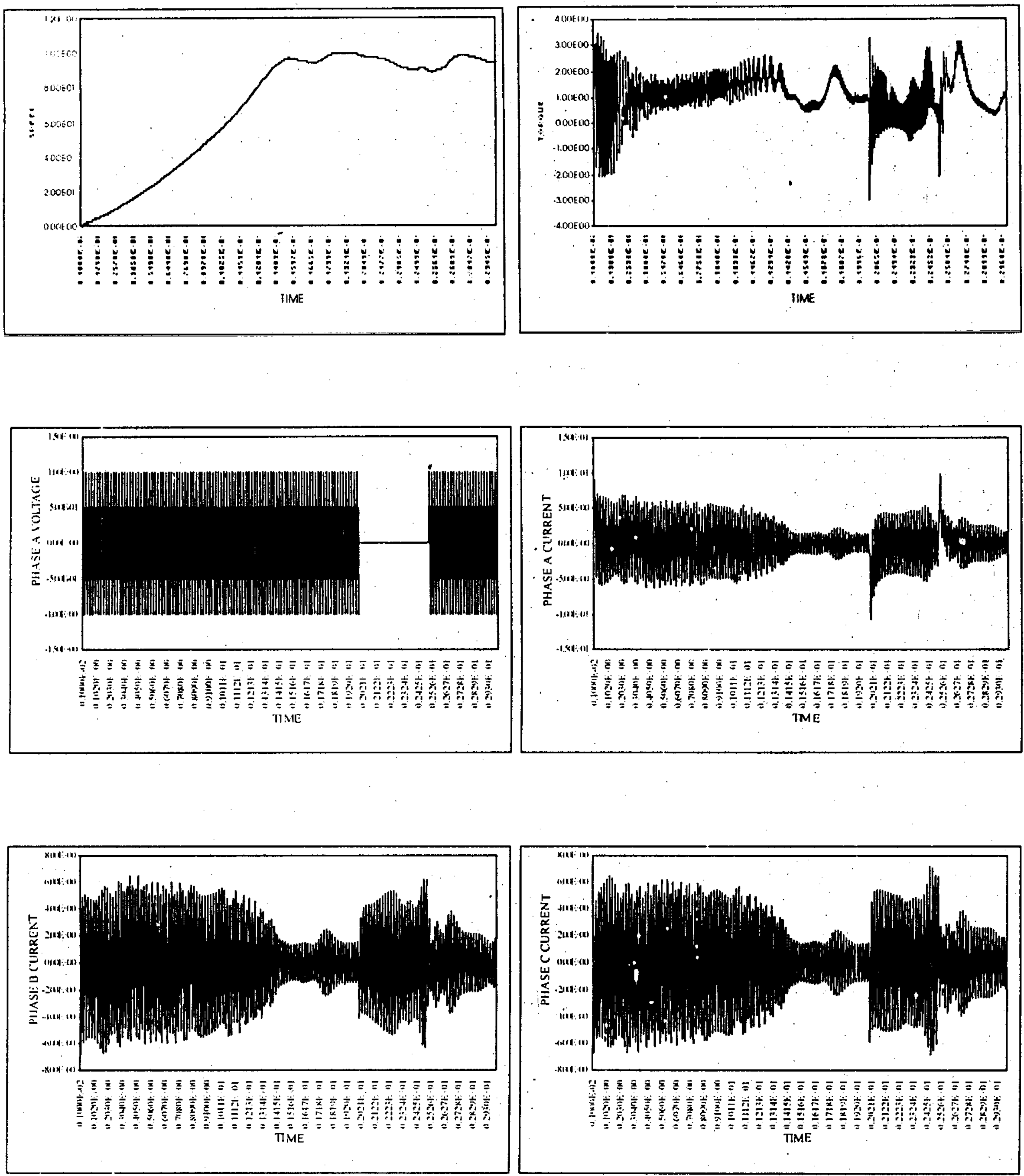

Figure 10 Dynamic performances of six-step PWM inverter-synchronous motor drive with 1.0 pu step load and phase A short circuit to earth fault.

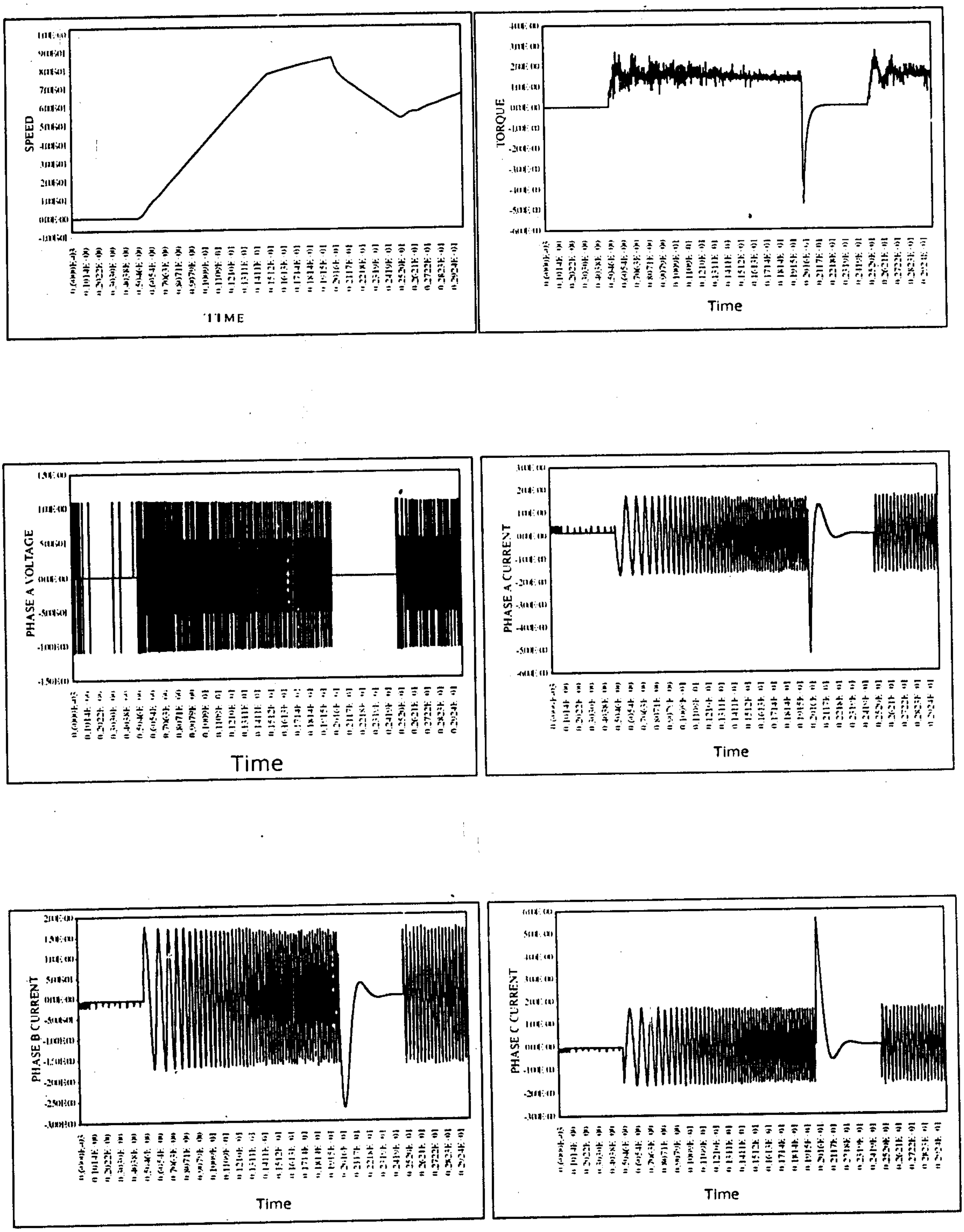

Figure 11: Dynamic performances of current-controlled dead-beat inverter- induction motor drive for 0.5 pre-magnetizing time with 1.0 pu step load and phase A short circuit to B phase fault.

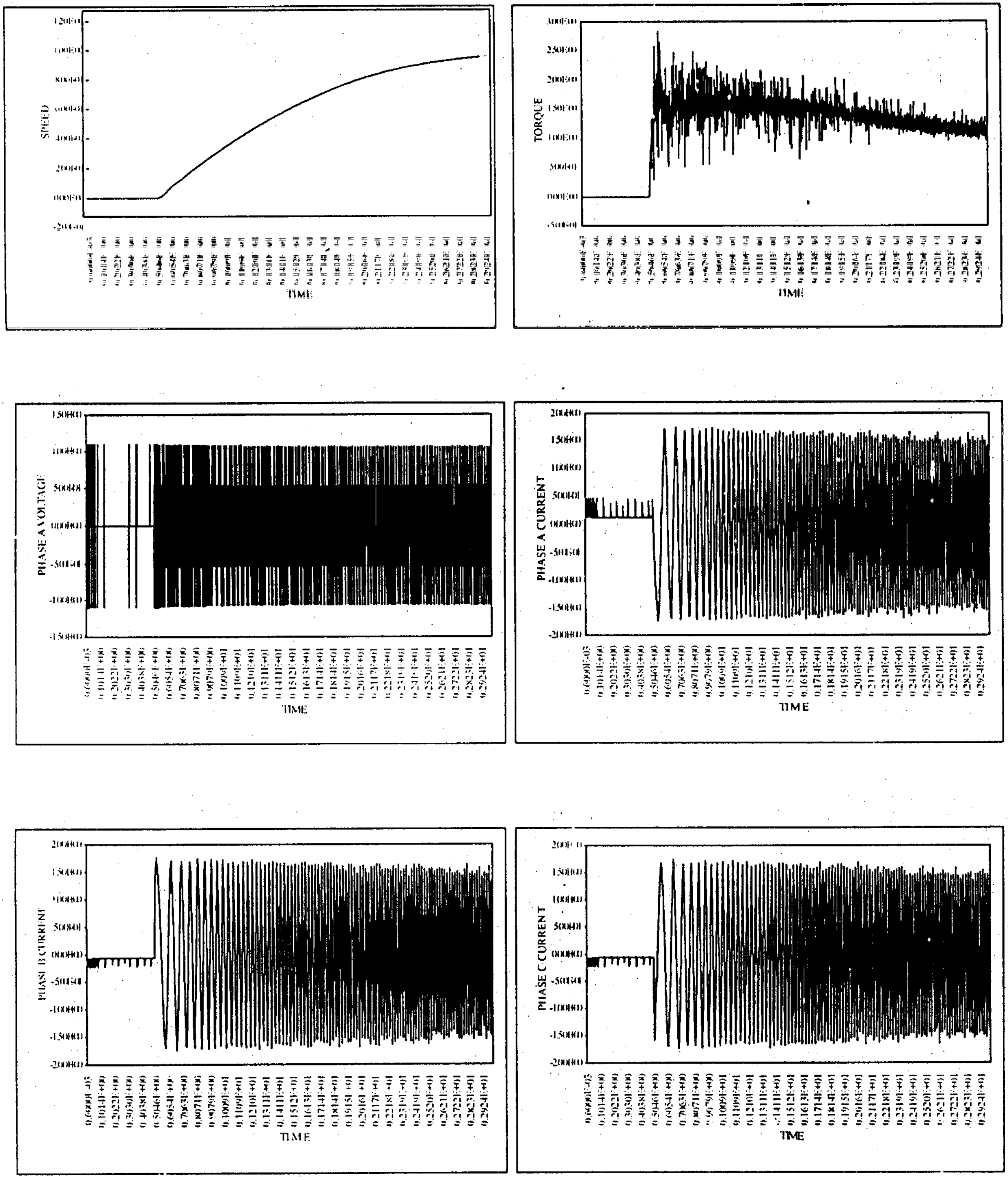

Figure 12: Dynamic performances of current-controlled dead-beat inverter-induction motor drive for 0.5 pre-magnetizing time with pump load and no fault.

, I_{qs} and W_r^*, for demanded value of torque, T^*, and otor flux, W_{mr}^*. Thus,

$$L_m I_{ds}^* = W_{mr}^* + \tau_r \frac{dI_{mr}^*}{dt} \qquad (13)$$

$$I_{qs}^* = \frac{T^*}{kI_{mr}^*} \qquad (14)$$

$$W_r^* = \frac{I_{qs}^*}{\tau_r I_{mr}^*} \qquad (15)$$

These calculations are performed in real time by a microprocessor and the basic implementation of a speed control system for a current-current controlled dead-beat inverter drive is shown in Fig. 6 (Peter, 1990).

Practical Application: In this section, computer simulation results of the AC machines in the different fault conditions are examined. Computer simulation results are used to illustrate performance for the dynamic behavior of the adjustable-speed AC drives with six-step, sinusoidal PWM and current-controlled dead-beat types of inverters. It is instructive to observe the dynamic performance of the AC motors subjected to various fault conditions, although the direct on-line starting performance of the AC motors were simulated on a computer and studies were performed. The sampled data chosen to demonstrate the operation of programs relate to AC motors for which data is given as (Aksoy, 1999).

All units are given in per-unit value in the simulation. Since friction and windage losses are not presented, the motor is accelerated to synchronous speed.

The electromagnetic torque, speed and three phase stator currents for the induction motor during free acceleration shown in Fig. 7, dynamic simulation is applied 3 second with six-step inverter in no load and no fault. The machine is operated at synchronous speed. Fig. 8 shows mechanical torque, speed and three-phase stator currents for the six-step inverter induction motor drive with 1.0 pu step load and single phase fault. Similarly, the dynamic performances of sinusoidal PWM synchronous and reluctance motor drive system are shown in Fig. 9 and 10. Different types of inverters and their application to the AC machines are shown in Fig. 11 and 12.

Conclusion

In this part, the simple practical application of AC machines have been examined and their analysis of dynamic performance has been investigated. The works presented on the adjustable-speed drives in this paper describe and employ simulation techniques of six-step sinusoidal PWM and current controlled dead-beat types of inverters. The three-phase models offers advantages in easy simulation of the adjustable-speed AC drives with generating system in the practically industrial application where the harmonic components in adjustable-speed AC drive may cause significant disturbance to the system. The computer program written can be able to simulate different types of drives, AC machines and disturbance.

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