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CAIRO - EGYPT

CONTROL SCHEME OF A PERMANENT-MAGNET SYNCHRONOUS MACHINE-DRIVE

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ABSTRACT

Among the different types of variable speed or position drives, the permanent-magnet synchronous motor, fed by a semiconductor inverter is applied increasingly for different applications on aircraft technology, information techniques and industrial automation.

This paper examines the operational characteristics of conventional permanent-magnet synchronous motor supplied via a three-phase transistor inverter. The characteristics of the. machine depends largely on its feeding scheme. These may be current or voltage supply. Here a current source with a linear smoothing inductor or a voltage source with a voltage smoothing circuit are used.

The control strategy of the studied system is based on the control of the machine phase current in order to have the machine phase angle in a permissible limit and to minimize the torque pulsation. The inverter drive signals are synchronized to the rotor position using a simple position detector so that synchronism between feed currents and the rotor flux is ensured for any speed.

The system and its control scheme are simulated in Basic using pc-158 microcomputer of Zenith Data system. The simulation algorithm which is given in the paper is simple and can easy changed for any voltage wave form source or for current source.

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I. INTRODUCTION

As quality and strength are improved permanent magnets are being increasingly used in synchronous motors to provide excitation, eliminating the need for slip rings and a field supply. The motor magnet must, however, be designed to resist the demagnetizing force of the stator currents.

In order to simplify the analysis, the following assumptions are taken into account with respect to the motor and inverter.

i- The magnetic circuit is assumed to be linear and magnetic saturation is negligible.

ii- All parameters of the machine are assumed to be constant and independent of frequency or heat.

iii- The harmonic torques resulting from the supply or due to the switching of the phase currents are very small /5/ and can be neglected.

iv- The inverter is assumed to be ideal with no losses and has instantaneous switching devices.

II. MATHIMATECAL ANALYSIS

1. System Configuration

The schematical diagram of the system studied drive is given in Fig.1. It consists of a permanent magnet synchronous motor (PM.SM.), a transistor inverter coupled with the feeding system, and a position sensor PD mounted on motor shaft. The inverter drive signals are synchronized to the position sensor output signals so that synchronism between feed currents and the rotor flux is ensured for any speed. Also, with position feedback control, no hunting occurs.

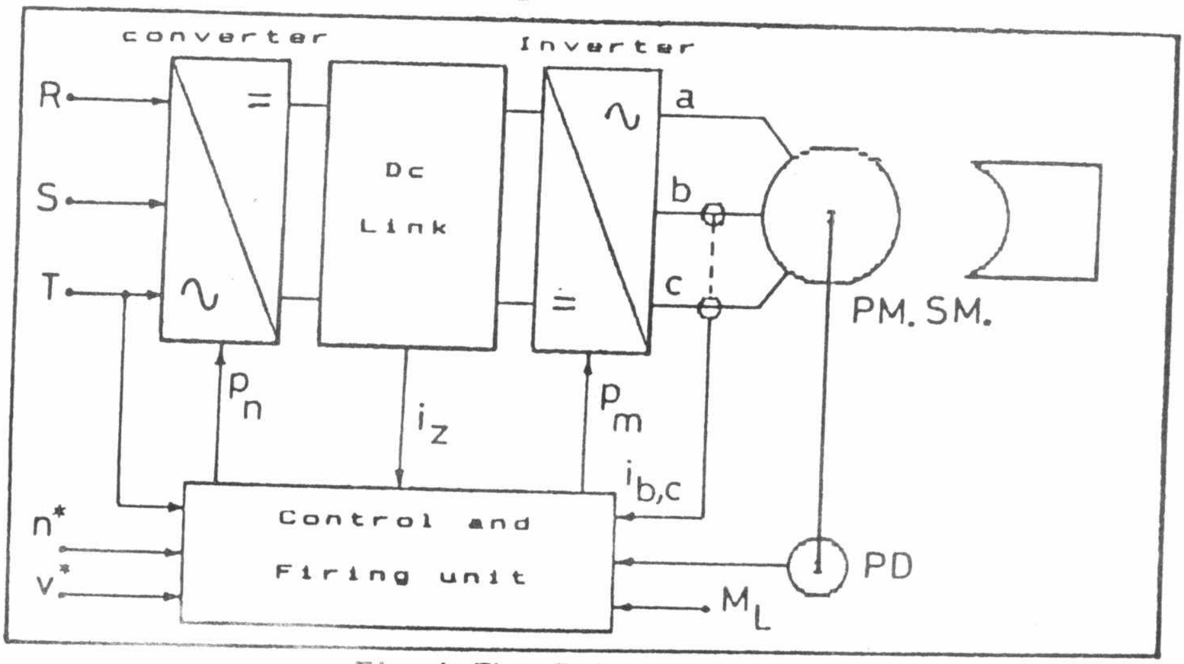

Fig.1 The Drive System

The characteristics of the permanent magnet synchronous machine depends largely on its feeding scheme. It can be driven in a variety of ways. These may be classical sinusoidal voltage and current sources as well as switched nonsinusoidal voltage or current-sources. In this analysis the interaction between such a machine and a nonsinusoidal-voltage-source with a voltage smoothing circuit or a current-source with a linear smoothing inductor are examined.

In the case of rectangular or sinusoidal PWM voltages, the command of transistors is obtained from position and control circuit. In the case of current imposed PWM, the different instantaneous values of phase currents are compared with reference and the transistors are commutated consequently.

The main two parts of the drive system (Synchronous machine and Inverter), depending on the feeding supply, are studied in the following sections.

2. The PM-Synchronous Machine

In fact, we can consider that the permanent magnet synchronous machine is comparable to the constant field-excited synchronous machine. The two machines are identical from the air-gap outwards. Therefore the permanent magnet system can be represented by a constant current field winding I_{fo}, whose ampere turns are proportional to the coercivity of permanent magnet material and the magnet geometries /1/-/3/.

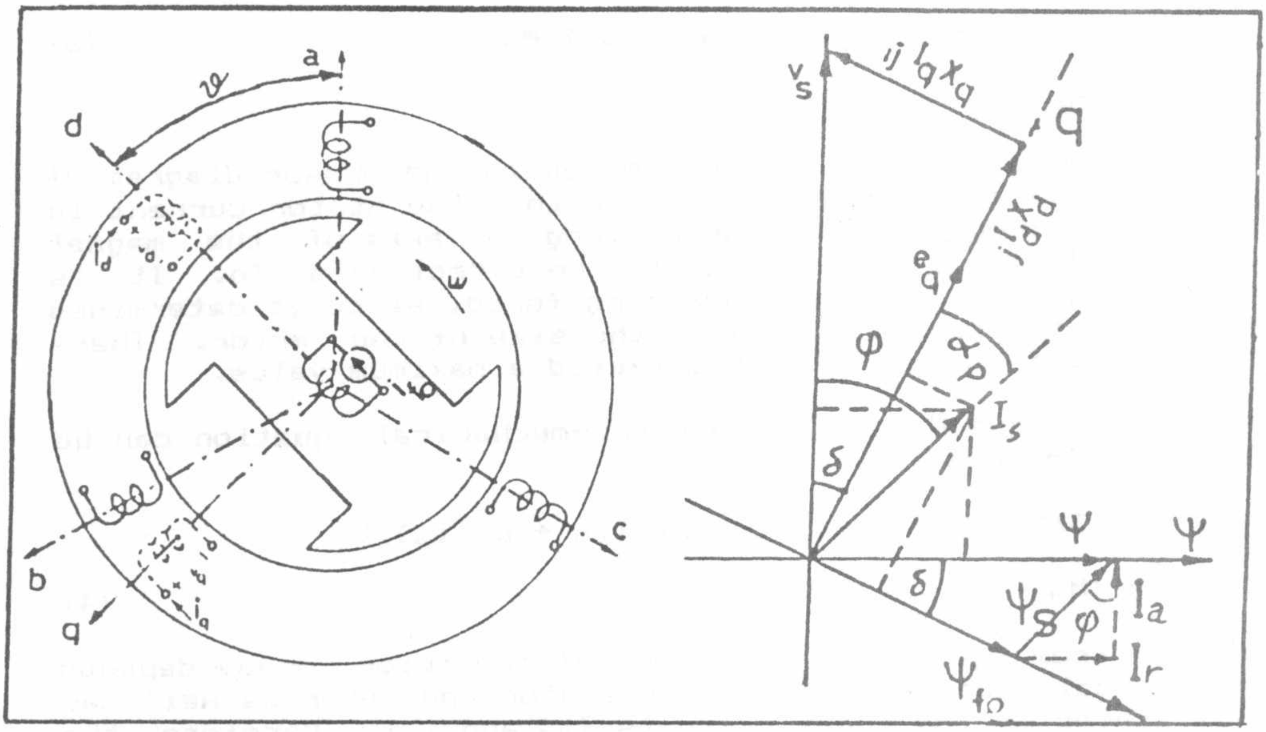

Fig.2 PM-Synchronous Machine

Fig.3 Phasor Diagram

The PM-synchronous motor used has a nonsalient pole structure and no damper windings (Fig.2). Since the magnetic circuit is assumed to be linear, the magnet fields produced by the armature in the direct- and quadrature-axis can be determined separately. The total field in the air-gap can then be obtained by superposition. The dynamic model may be obtained from its analogy to the field-excited synchronous motor.

$$\psi_{fo} = K_f . I_{fo}$$

$$\psi_{ds} = L_d . i_d + l_{sf}(\theta) . I_{fo}$$

$$\psi_{qs} = L_q . i_q$$

$$\psi_s = \psi_{ds} + \psi_{qs}$$

$$\psi = \psi_s + \psi_{fo} \qquad (1)$$

Due the pole structure of the machine, the different inductances are modulated by a frequency proportional to the angle of rotation θ . The change in the direct and quadrature inductances are very small and therefore Ld and Lq are assumed to be constant /6/-/7/. Here the mutual inductance $l_{sf}(\theta)$ is,

$$l_{sf}(\theta) = L_{sf} . \cos(\theta) \qquad (2)$$

The voltage equations are expressed as follows,

$$v_d = r_s . i_d + p i_d - w L_q . i_q$$

$$v_q = r_s . i_q + p i_q + w L_d . i_d + e_q \qquad (3)$$

$$e_q = w L_{sf} . \cos(\theta) . I_{fo}$$

For steady state Eqs.3 are represented in the phasor diagram of Fig.3. It is seen from this figure that the stator current Is produces a demagnetizing force along the axis of the magnet proportional to its component in the direct axes Id. It is important to know this demagnetizing force, since it determines the size of the magnet and hence the size of the motor. There for the direct current must not exceed a maximum value.

The motor torque M_m and the electro-mechanical equation can be written as follows,

$$M_M = (3/2) . (P/2) . [L_{sf} . \cos(\theta) . I_{fo} + L_d . i_d] . i_q$$

$$p w = (M_M - M_L) / T_M \qquad (4)$$

As deduce from Eqs.4, the harmonics of the motor torque depends on the mutual coupling between the stator and rotor as well as the switching of the phase currents (i_d and i_q). Therefore, the inertia of such motor must has a minimum value in order to damp the oscillations.

3. Control and Firing Scheme

For a preset speed, the machine voltage, air-gab-flux and stator current components, are obtained. Then the power angle δ and the firing lag angle α_p are defined. This is the base of the control circuit for each inverter.

Consider the phasor diagram given in Fig.3. The phase current components can be written as follows

$$I_d = I_s.\sin(\alpha_p)$$

$$I_q = I_s.\cos(\alpha_p)$$

$$I_a = I_s.\cos(\varphi)$$

$$I_r = I_s.\sin(\varphi) \qquad (5)$$

where $\varphi = \pi - \varphi_s$

$$\alpha_p = \varphi - \delta = \gamma - \pi/2$$

and $\sin(\delta) = C.[I_d/I_{fo}]$ (6)

The torque may be also written in the form,

$$M_M = G.\psi_{fo}.\psi_s.\sin(\gamma) \qquad (7)$$

At angle $\gamma = \pi/2$, the machine can give the maximum torque and its oscillations are minimum /8/. The unity power factor as seen in Fig.4 corresponds to $\delta + \gamma = \pi/2$.

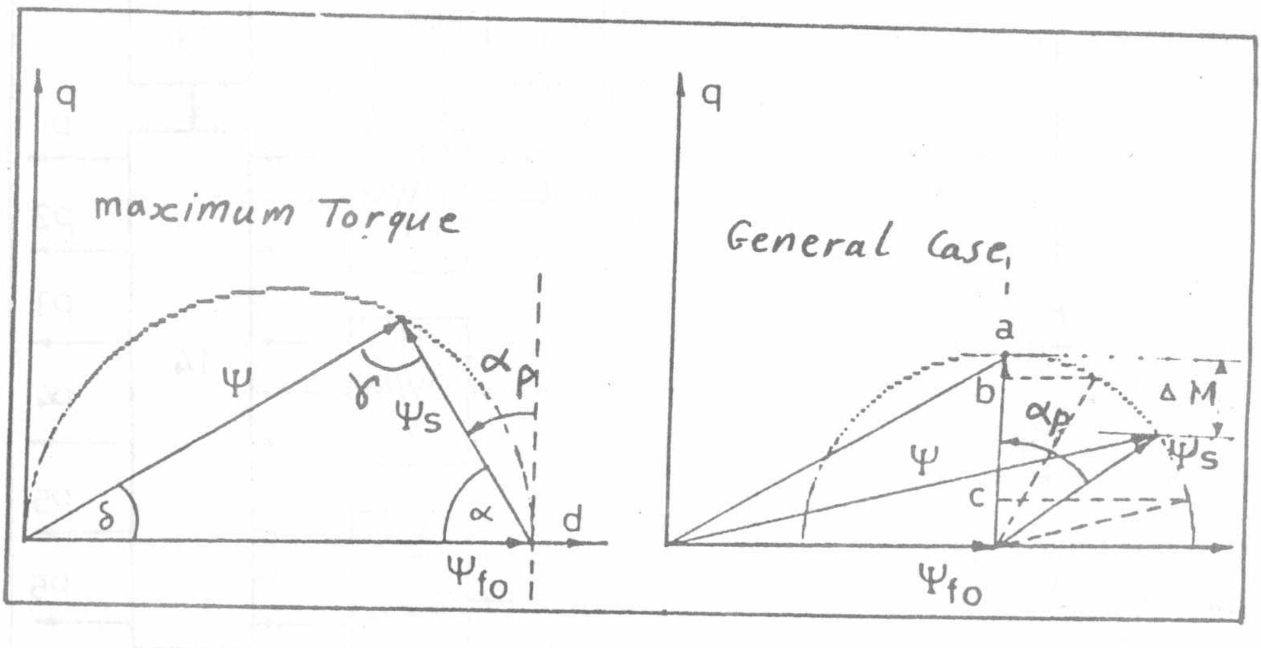

Fig.4 Torque variation

In order to vary the torque two ways can be followed (Fig.3):

i- The flux linkage ψ can be varied but keeping the power angle δ constant at the value required to deliver maximum torque. This follows by changing the reactive component of stator current, and keeping the active component constant.

ii- The flux linkage ψ is keep constant but varying the power angle δ. This follows by changing the active and reactive components of stator current. The way is limited at $\varphi = 0$, thereafter the machine may be overexcited, which is not our case.

The above two cases can be clarified by the equation,

$$\psi = C_2 . I_r + \psi_{fo} . \cos(\delta) \tag{8}$$

As the speed of the drive is increased above the base speed, it is assumed that no further increase in supply voltage E_a is available and that this voltage is held constant at its maximum value. As speed increases, the air-gap flux ψ decreases, while maintaining the power angle (δ) constant. This can only be done as in the first way (i).

The block diagram in Fig.5 declares the control and firing strategy. This scheme is normalized for current PWM(B.10), voltage PWM (B.11), and square wave voltage (B.12).

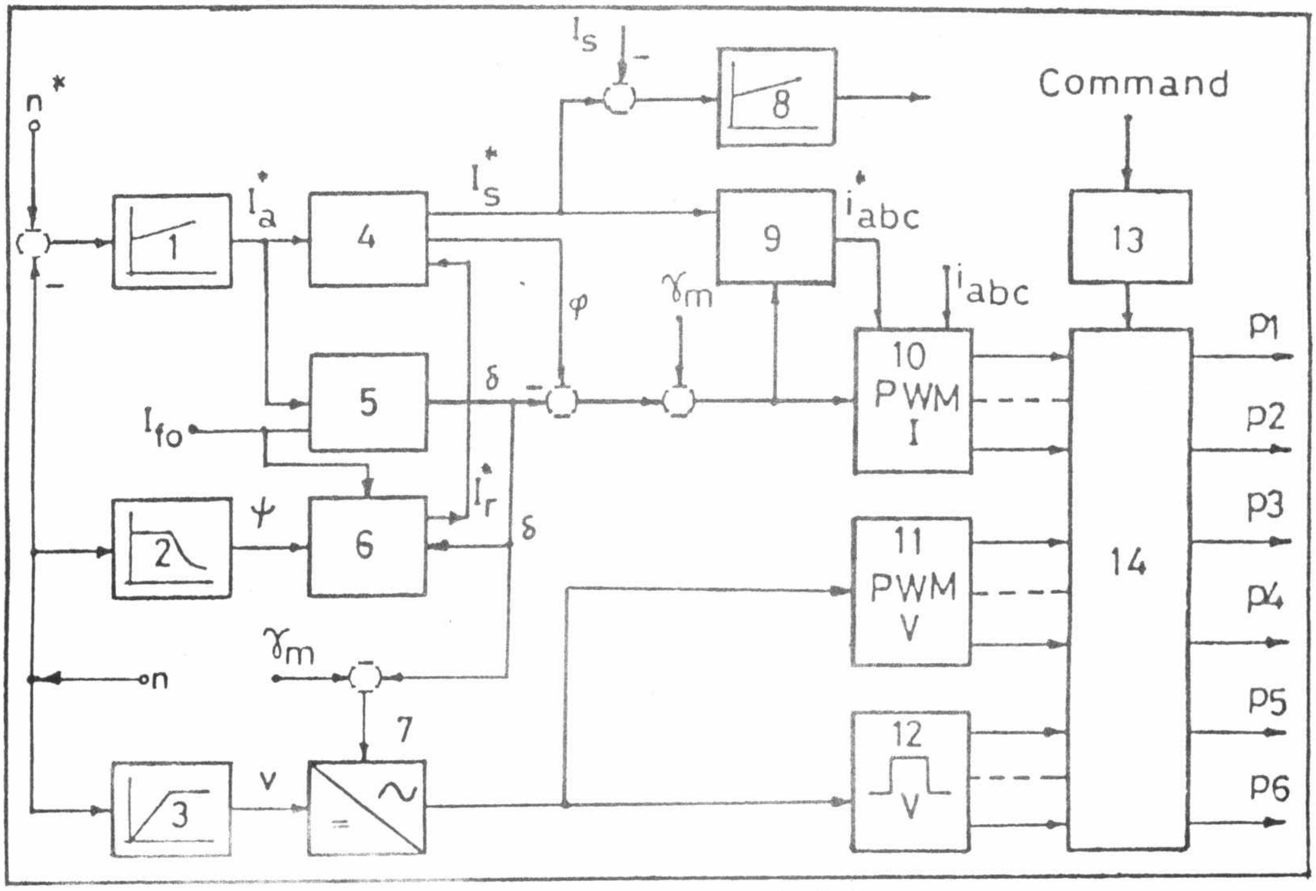

Fig.5 Firing and Control Scheme

The dc link voltage (or current) can be controlled as by normal synchronous machine drive, via an inner current controller (B1) and an outer speed controller (B.8). In this analysis the dc link voltage (or current) is adjusted by means of a frequency dependent characteristic which provides approximately constant magnetic flux linkage in the machine below nominal speed and inversely proportional to the speed above it (B2). The voltage is then supplied to the synchronous motor via any of the mentioned inverters. Thus the equipment supplies a three phase system with adjustable voltage and frequency.. From the actual (or desired) speed the machine voltage and air-gap flux may be obtained with given curves or tables (by digital control) as shown in B.3 and B.2 respectively. The output of the speed controller (B1) is assumed proportional to the active component of stator current (I_a), where the reactive component (I_r) is proportional to the air-gap flux given by Eq.8. According Eq.6, the load angle for the motor is calculated via B.5. The desired machine current and the phase angle φ are defined in B.4 using Eq.5.

This analysis assumes that position feedback is used for the mode of operation of the voltage- or current-source inverter. Using PWM current-source, the lagging firing angle α_p with respect to the back e.m.f. voltage e_q can now be obtained by Eqs.6. Thus the three desired phase currents can be calculated in (B9) and compared with the measured phase currents to deduce the pulses for the inverter in (B10).

In case of voltage-source, two ways can be followed, the PWM voltage-source or square voltage-source. For each, three constant voltages in the direction of the phase voltages can be deduced in (B7) by adding the motor load angle δ to the rotating angle θ. These voltages are manipulated in B.10 obtaining the needed 6-pulses for PWM voltage-source. The same voltages of (B7) can be manipulated in other way to give the 6-pulses for a square voltage-source of width of 180° or 120°.

If there is an controlled rectifier on the mains or a dc supply is used, a chopper can be used in the dc link to control its voltage.

III. SIMULATION AND RESULTS

Figure 6 shows the flow chart describing the procedure used in such simulation. The data of the program are mains voltage (or battery voltage), dc link and motor parameters, the speed of the machine n^{*} and the load current. The speed-voltage and speed flux for the used motor are given with simplified equations. The output of the voltage-source drive are the current and torque wave form and the speed. The output of the current-source drive are the phase voltage, torque and speed.

Figure 7 shows the simmulated phase-current with respect to the e.m.f and torque waveforms at rated speed and rated current for

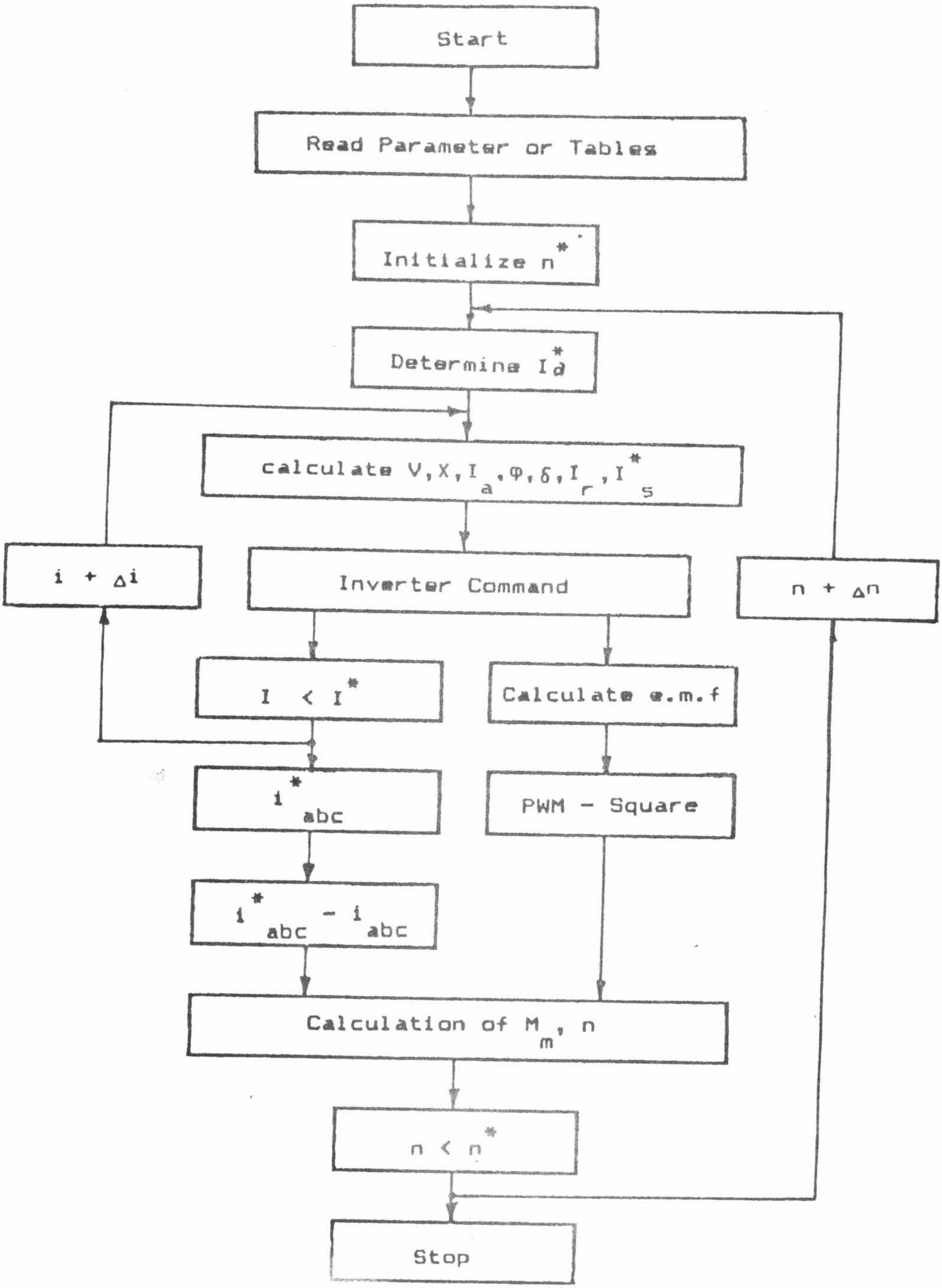
Start
Read Parameter or Tables
Initialize n*
Determine Id*
calculate V, X, Ia, φ, δ, Ir, Is*
i + Δi
Inverter Command
n + Δn
I < I*
Calculate e.m.f
i*abc
PWM - Square
i*abc - iabc
Calculation of M, nm
n < n*
Stop

Fig. 6

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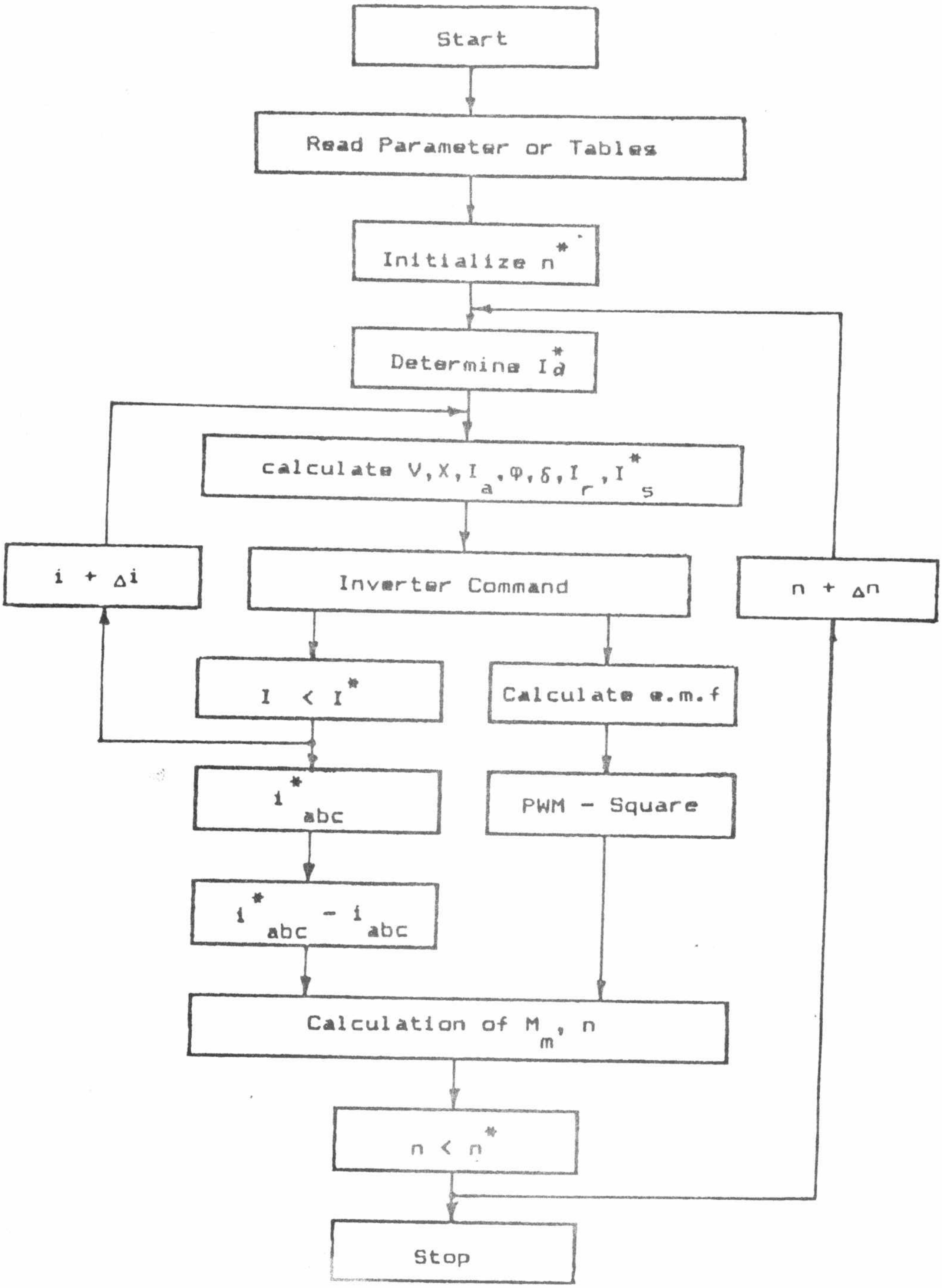
Start
Read Parameter or Tables
Initialize n^*
Determine I_d^*
calculate $V, X, I_a, \varphi, \delta, I_r, I_s^*$
$i + \Delta i$
Inverter Command
$n + \Delta n$
$I < I^*$
Calculate e.m.f
i^*_{abc}
PWM - Square
$i^*_{abc} - i_{abc}$
Calculation of M_m, n
$n < n^*$
Stop

Fig. 6

current-PWM, sinusoidal PWM-voltage, and rectangular fed voltage supply respectivly. Fig.8 shows the starting period to rated speed.

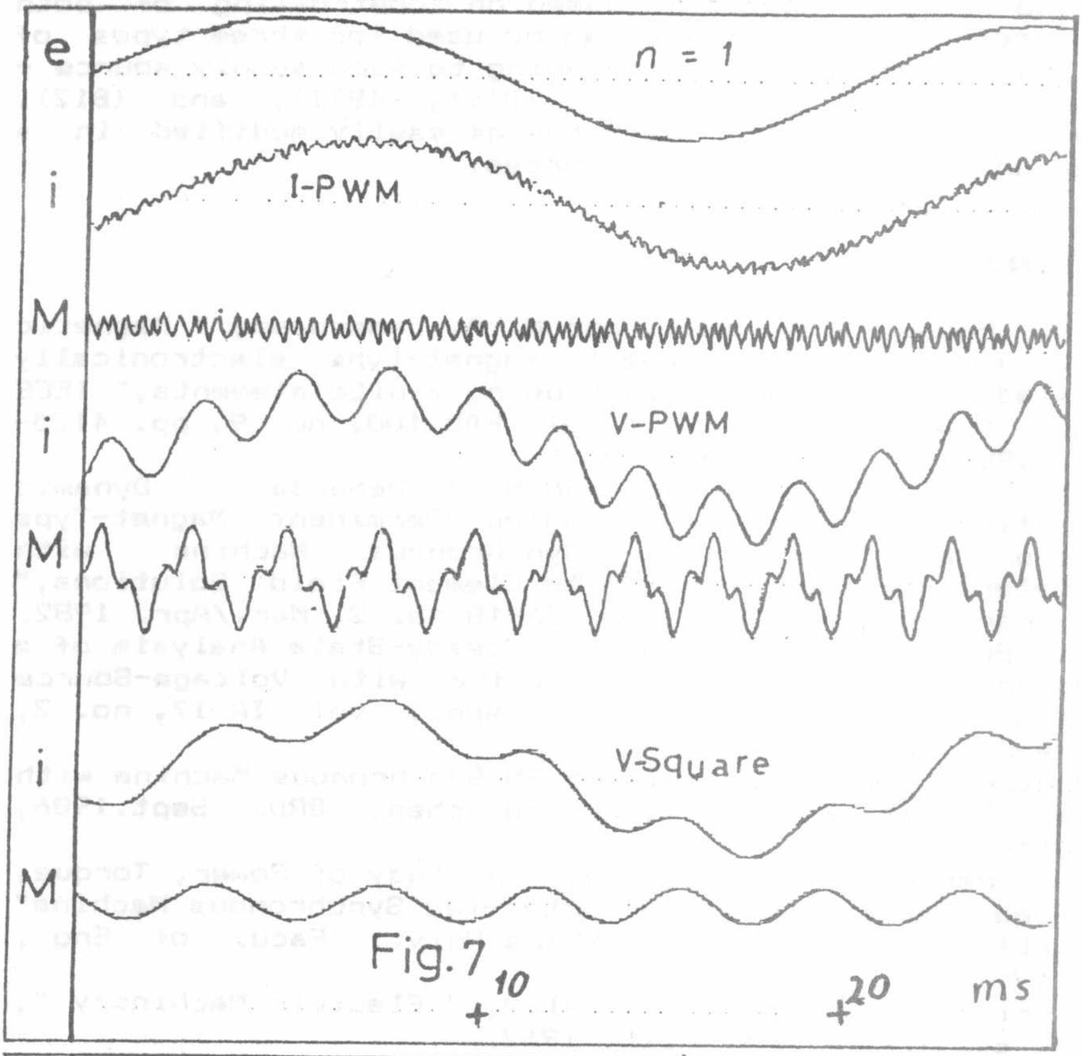

Fig.7

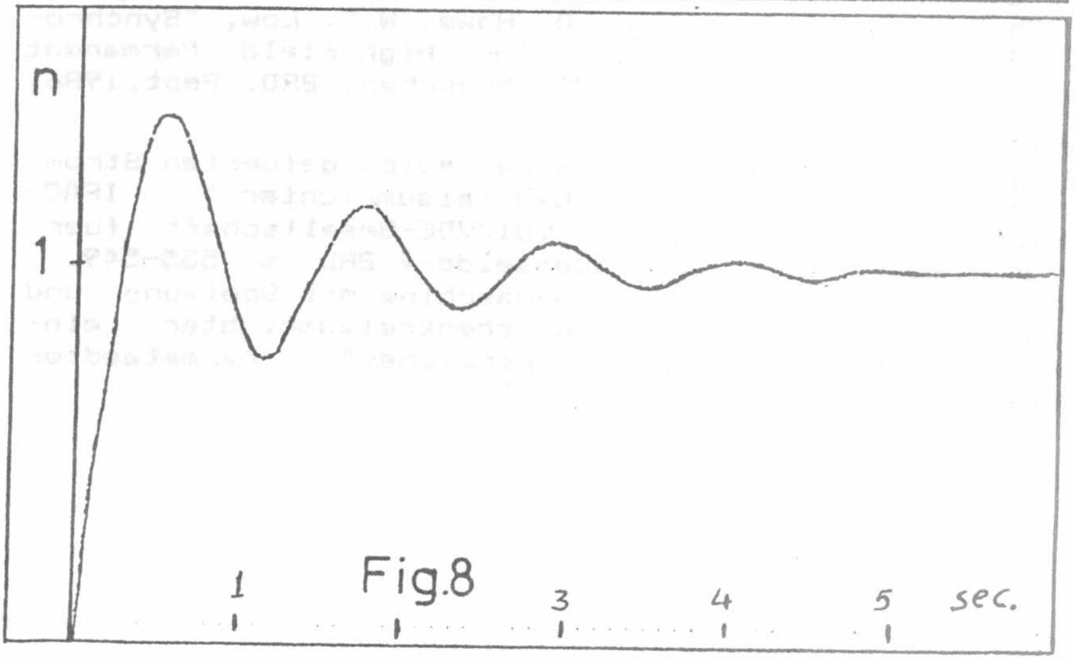

Fig.8

IV. CONCLUSION

A new control concept for feeding the PM-synchonous machine using a rotor position encoder is presented. This simplified control and firing method is based on controlling of both active and reactive current and can be used for three types of sources. The difference - corresponding to each supply source - is in the last part only here (B10), (B11), and (B12). Thereafter, this control scheme can be easily modified in a normalized unit for any type of sources.

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List of symbols

i = instantaneous values of machine phase currents
I = r.m.s value of fundamental component of machine phase current
  = fictious constant field current referred to stator
  = r.m.s. value of magnetising current corresponding to resultant mean airgap m.m.f.
L = stator winding inductance per phase
  = fictious field inductance referred to stator per phase
  = magnetising inductance per phase
  = d.c. link inductor
M = instantaneous airgap torque or average airgap torque
n = speed
p = number of pole pairs
P = instantaneous airgap power or average airgap power
t = time
T = circuit time constant or Transistor
u = overlap angle
v = instantaneous stator phase voltage
V = r.m.s. value of fundamental component of phase voltage
  = average value of dc voltage
α_p = firing angle with respect to emf
δ = machine load angle
φ = machine phase angle
γ = rotating angle
w = angular frequency in stator windings
ψ = flux

Suffixes

a = active component
a,b,c = stator phases
c = constant
f = field component
d,q = rotor fixed orthogonal coordinate system
0 = average or no load value
n = supply side
m = machine side
s = stator component
z = d.c. link