MILITARY TECHNICAL COLLEGE

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SPEED CONTROL OF THREE-PHASE INDUCTION MOTOR DRIVE

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ABSTRACT

One of the widely used drives in the industry is current source inverter-fed three-phase induction motor drive system. In this paper a complete design of such system, included a 0.5 HP three phase induction motor, is given. It was strongly required, that the design and implementation of the control and logic circuits must be cheap and simple as possible without loosing the stability of the system. A suitable dynamics was also recognized.

The experimental results are given in support of the design procedure used to built the experimental model.

I. INTRODUCTION

As a general-purpose approximately constant-speed motor for general industrial drives, the cage-rotor type has a remarkably simple, cheap, highly reliable and robust construction enabling it to operate in the most adverse circumstances and giving excellent service with little demands on maintenance. Many motor applications, however, require several speeds, or even a continuously adjustable range of speeds. From the earliest days of a.c. power systems, engineers have been interested in the development of adjustable-speed a.c. motor. The relation between the synchronous speed (N_s), the rotor speed (N_r), the number of pole pairs (p), and the slip of the induction motor (s) is given by:

$$N_s = \frac{60f}{p} = \frac{N_r}{1 - s} \qquad (1)$$

So the synchronous speed of an induction motor and thereafter the rotor speed can be changed by: Changing the number of poles (p); Varying the line frequency (f); and Controlling the slip.

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In the performed system, a simple and cheap control and firing circuit is implemented for changing the speed of the induction machine by varying the stator frequency but the slip remains constant. The major problem is to determine the most effective and economical source of adjustable frequency and to improve machine operation. In order to maintain approximately constant flux density, the line voltage should also be varied directly, with the frequency. The maximum torque then remains very nearly constant. An induction motor used in this way has characteristics similar to those of a separately exited d.c. motor with constant flux and variable armature voltage. A solid-state rectifier-inverter set is implemented to satisfy these requirements.

II. CONSTRUCTION OF THE IMPLEMENTED DRIVE SYSTEM

As shown in Fig.1, the implemented drive system consists generally from three-phase fractional hp induction motor (IM) in addition to the following parts;

1. Controlled Current Source
2. Three-Phase transistorized Inverter
3. Measuring Circuits

4. Control circuit:
   The actual motor speed W_{ar} is summed with an external reference signal representing the motor desired speed W_{2r} to give the corresponding speed error e_{wn}. A ramp circuit is used to prevent the sudden change in the reference signal W_{2r}. The speed error e_{wn} is elivered to the speed controller (PI type) which gives a signal proportional to the desired stator current I_s.

   This signal is compared with the measured stator current and their difference (error e_{wi}) is supplied to an other PI controller in order to control the current. The output signal V_c defines the firing angle of the main converter in order to give an output voltage corresponding to the power consumed by the machine.

5. Converter Firing Circuit:
   This circuit is used to generate the six triggering pulses required to turn-on the thyristors. This circuit is as in dc drive systems.

6. Inverter Driving Circuit:
   This circuit is used to supply the three-phase transistorized inverter with the required switching pattern at a frequency proportional to the synchronous speed W_1. This synchronous speed W_1 is obtained by using the reference speed signal W_{2r} after amplifying it by 5% (slip = 5%). In such a system, each transistor conducts only for 120^o of the power cycle, to satisfy condition of current source.

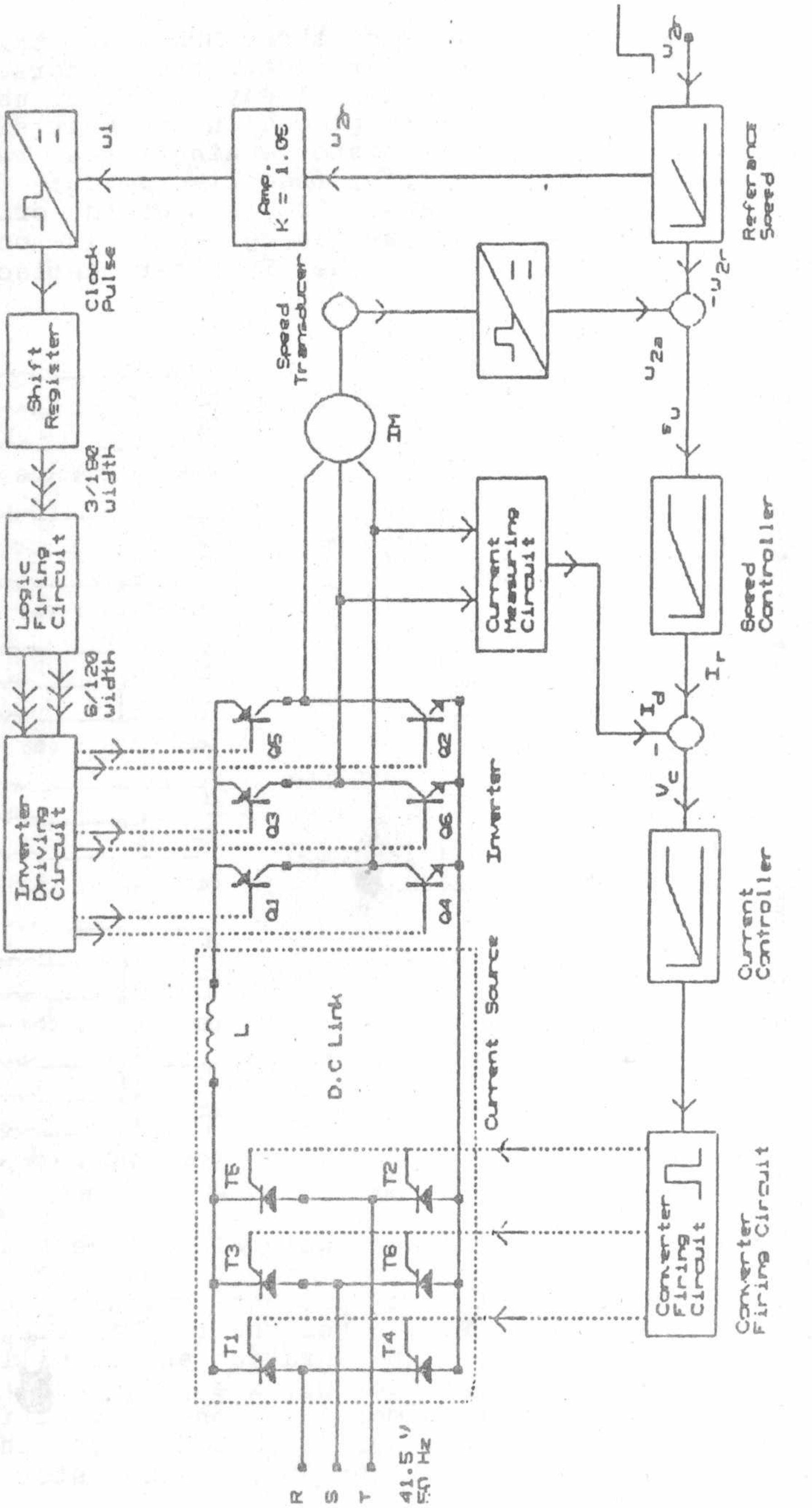


Fig. 1   Block Diagram of the Drive System

III. DESIGN OF THE POWER INVERTER CIRCUIT

The implemented inverter consists of three NPN power Darlington transistors and three PNP power Darlington transistors. These two types are connected in economical way in which each one transistor and its complement are placed on one heat sink. The parallel diode protect the transistor against the reversing voltage and enables the current, by inductive loads, to flow through it if the power transistor is turned off. The transistor must be used in its switching mode in order to avoid excessive losses, hence the inverter replaces an inverter using thyristors.

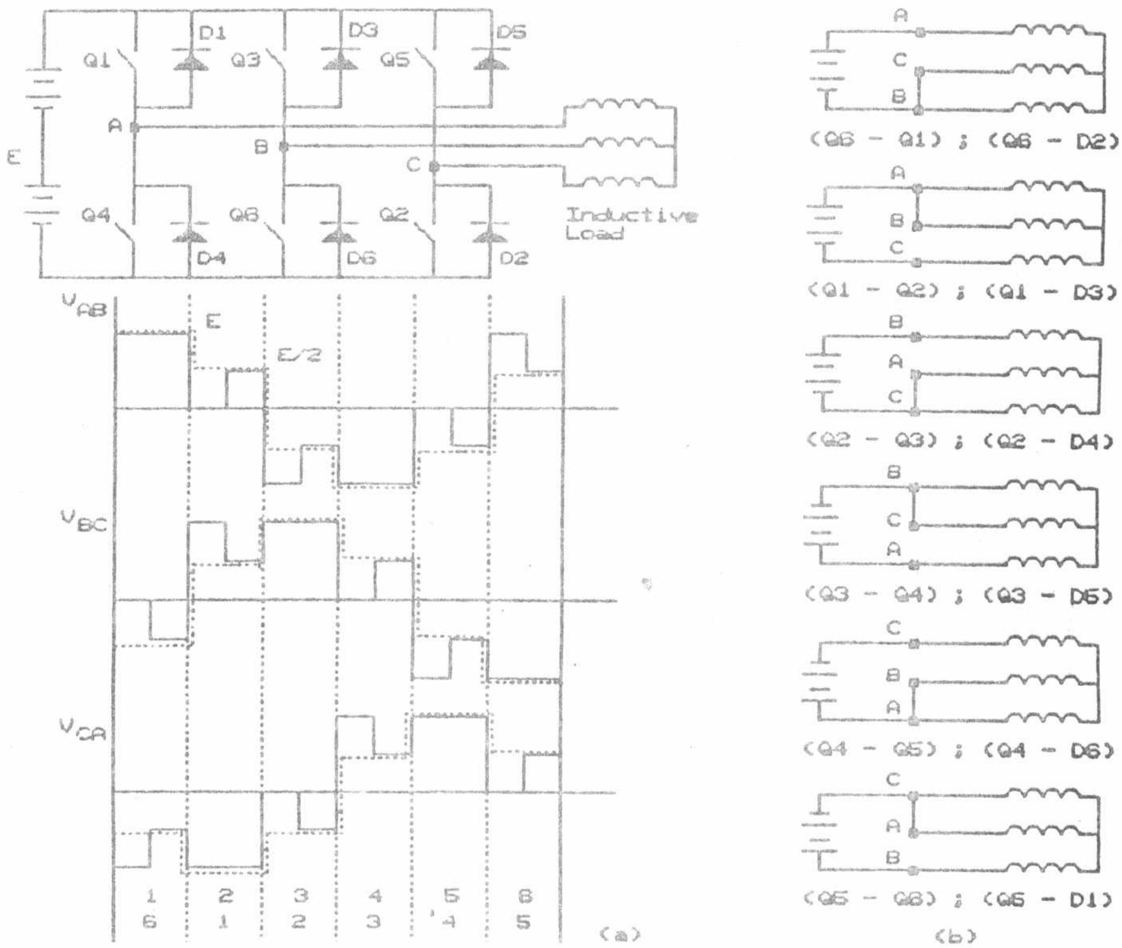


Fig.2 Waveform of load voltages using Inductive Load

The switching operation of the present circuit can be described with the help of Fig.2. For the first stage, the transistor Q_1 will turn on for 120^{o} duration and it will share by 60^{o} conduction with transistor Q_6, i.e., Q_1 and Q_6 are turned on to run the induction motor in one direction. In this case the voltage across lines AB is equal to the d.c. voltage as shown in Fig.2.a. After 60^{o}, transistor Q_6 is turned off, but the motor current continues to flow through freewheeling diode D_3 by means of the stored energy in the motor. In the same instant Q_2 also conducts. During the conducting period of Q_1 and D_3 a short circuit between the lines AB occurred as shown in Fig.2.b. Due to this short circuit the line voltage V_{AB} reaches zero in a certain time depending on the motor time constant but the current continuous to flow until the stored energy in the motor is released and then diode D_3 is turned off. After that, the transistors Q_1 and Q_2 are alone conducting and the voltage across lines AB reaches again half of the d.c. voltage.

In the second 120^o, Q_1 turns off and Q_3 turns on and at the same time D_4 conducts with Q_2 and this causes a dc voltage to be applied between the lines AB until the stored energy is released. This process is repeated until the modified line voltages shown in Fig.2 are produced.

IV. DESIGN AND ANALYSIS OF THE CONTROL SYSTEM

a. POWER INVERTER CONTROL CIRCUITS

The implemented control circuit of the three phase transistorized inverter is depicted in Fig.3 and consists of:

1. **Voltage controlled oscillator** (VCO); A TTL chip SN74LS624 is used as a voltage to frequency converter to generate a pulse train. The output frequency for VCO is established by a single external capacitor in combination with voltage-sensitive inputs used for frequency control connected to pin 2.

2. **Three-Phase Pulse Generator**; A CMOS 4-bit shift register (CD4035A chip) and two CMOS inverter (4009 chip) in special connection are used to generate the three triggering pulses Q_1, Q_3, and Q_5. The circuit is driven by the square-wave pulse train obtained from the VCO. Each of the three pulses is 180^o width and are 120^o shifted from each other. They are inverted to obtain the other three pulses Q_4, Q_6, and Q_2.

3. **Logic Circuit**; The purpose of this logic circuit is to obtain another six pulses of 120^o shifted from each other but of 120^o width. These pulses are used to drive the optocouplers.

   The six pulses Q_1 to Q_6 are passing through a buffer chip (TTL 7404) to obtain the sufficient current required to drive the next six AND gates (TTL 7402 chip). These AND logic circuits are used to combine the pulses to get the needed firing pulses. After that, these signals are amplified by using six transistors (BC 237 type) to drive the optocouplers. This logic circuit is tested using Logic Analyzer Software and the timing diagram shown in Fig.4 is obtained.

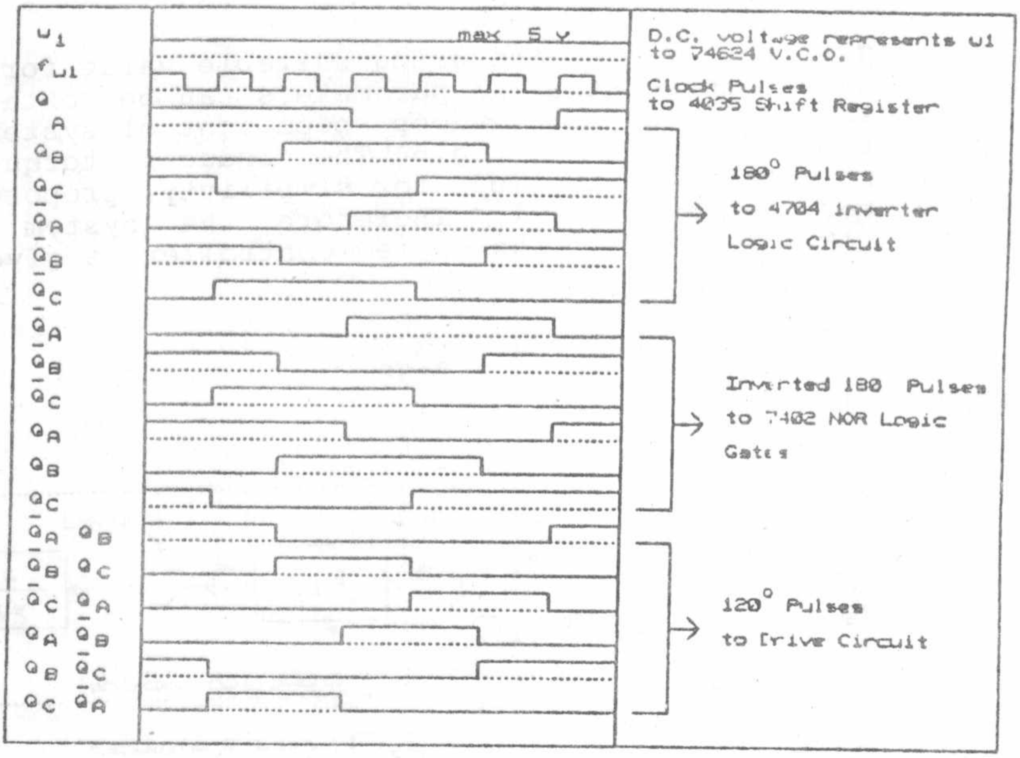


Fig.4 Timing diagram of Inverter Pulses

b. CLOSED-LOOP CONTROL CIRCUIT

As in d.c. drive systems, a current and a speed controllers are used. It is easy to prove that the current controller is PI type. The practical current closed-loop transfer function is given in the form;

$$F_{wi} = \frac{I_a}{I_r} = \frac{(1/T_oT_f)(1 + sT_f)}{s^2 + s(1/T_f) + (1/T_oT_f)} \tag{2}$$

This gives a characteristic equation of second order and it can be rewritten in the general form of:

$$F_{wi} = \frac{I_a}{I_r} = \frac{(1/T_oT_f)(1 + sT_f)}{s^2 + s(2\delta w_n) + w_n} \tag{3}$$

By comparison one obtains, the attenuation $2\sigma = 2\delta w_n = 1/T_f$ and the undamped natural frequency $(w_n)^2 = 1/T_oT_f$

The dynamic behaviour of second order systems can then be described in terms of two parameters δ and w_n. By using a small value of damping ratio $\delta = 1/\sqrt{2}$ which satisfies the condition for under damped system, the forward T.F. time constant T_o and the time constant T_f of the current measuring element are related by:

$$T_o = 2T_f \tag{4}$$

According to this result and using suitable value for the time constant T_f, the controller parameters can be obtained. The block diagram of the closed loop speed control system can be represented as shown in Fig.5. The induced torque of the induction machine is assumed, for simpilicty, proportional to the stator current (K_{IT}). Therefore the system transfer function (F_s) seen from the speed controller is given by:

$$F_s = \frac{1}{sT_s} \cdot \frac{1}{1 + sT_i} \cdot \frac{1}{1 + sT_{gn}} \qquad (5)$$

where $T_s = J/K_{IT}$

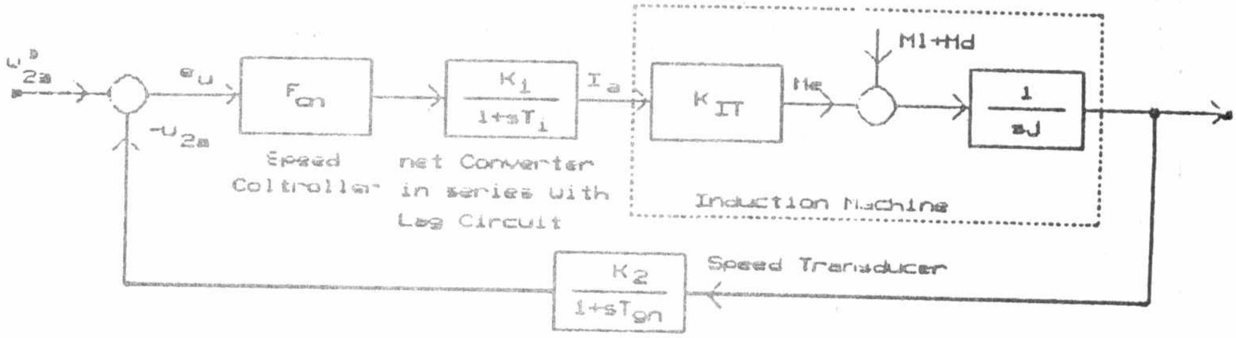


Fig.5 Block diagram of the speed loop

To compensate the machine losses and load torque (T_L, T_{Loss}), PI-controller must be used in speed loop, then the overall open loop transfer function F_o is given by:

$$F_o = F_c . F_s = \frac{1 + sT_n}{sT_1} . F_s \qquad (6)$$

Since T_i and T_{gn} are normally small compared to mechanical time constant T_s, hence $T_\sigma = T_i + T_{gn}$ and neglecting $T_i . T_{gn}$ one obtains;

$$F_o = \frac{1}{s^2 T_1 T_s . (1 + sT_\sigma)} \qquad (7)$$

This principle of symmetrical optimization is used when the open loop of a regulating circuit having two time constants of integral nature are present [ ]. Assuming that $T_1 T_s = T_c T_n$, then the closed loop T.F. (F_w) and its amplitude in frequency domain are given by:

$$F_w(s) = \frac{1 + sT_n}{1 + sT_n + s^2 T_c T_n + s^3 T_n T_c T_\sigma} \qquad (8)$$

$$|F_w^2 (jw)| = \left| \frac{(1 + w^2 T_n^2)}{1 - w^2 (T_n^2 - 2T_n T_c) + w^4 (T_n^2 T_c^2 - 2T_n^2 T_c T_\sigma) + w^6 T_n^2 T_c^2 T_\sigma^2} \right| \qquad (9)$$

For amplitude optimization, coefficient of w^2 and w^4 must be zero, i.e.,

$$T_n^2 - 2T_nT_c = 0 \qquad (10)$$

$$T_n^2T_c^2 - 2T_nT_c^2T_\sigma = 0 \qquad (11)$$

From which one obtains; $T_c = 2T_\sigma$; $T_n = 2T_c = 4T_\sigma$ (12)

This gives the necessary conditions for symmetrical amplitude optimization. Substituting from Eq.12 in Eq.8 then,

$$F_w(s) = \frac{1 + s.4T_\sigma}{1 + s.4T_\sigma + s.8T_\sigma^2 + sT_\sigma^3} \qquad (13)$$

Equation (13) again shows that the closed loop gain is a function of "T_σ" or sum of small time constants T_i+T_{gn} only. The unit-step solution of this equation leads to the actual speed W_a in the form;

$$W_a(t) = 1 + e^{-t/2T\sigma} - 2.e^{-t/4T\sigma}.\cos[\sqrt{3}/4T_\sigma]t \qquad (14)$$

The zero-term $(1+4sT_\sigma)$ in Eq.13 can be compensated using a pole with the same time constant. The dynamic of the system will not be affected through the change of the desired value of the speed. Therefore the slope of the ramp circuit, which protects the inverter from sudden changes in the d.c link voltage, is defined according to the time constant $4T_\sigma$. The graphic solution of Eq.13 with and without the zero-term is shown in Fig.6.

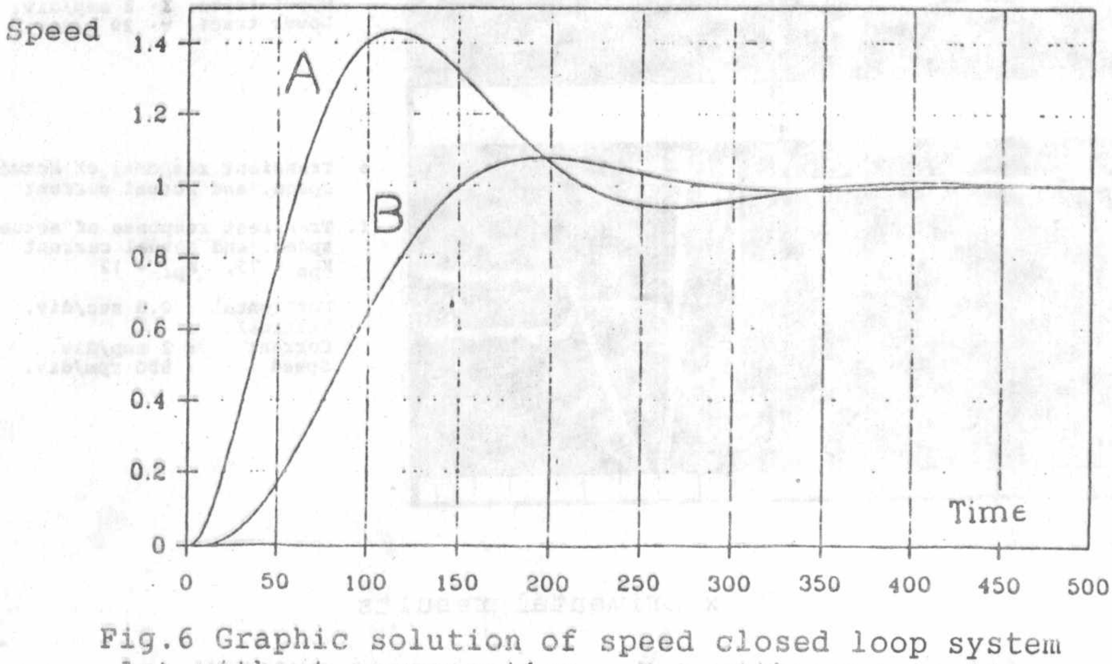
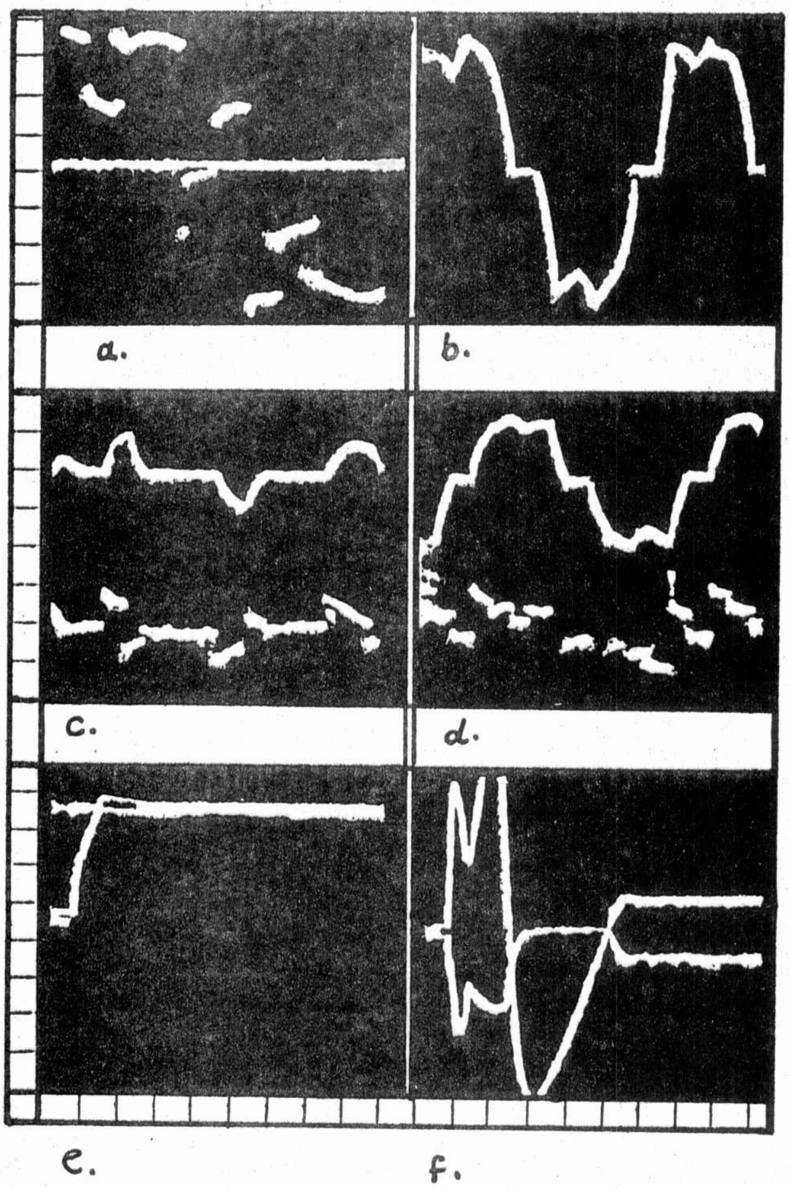


Fig.6 Graphic solution of speed closed loop system
A=> without compensation B=> with compensation

V. EXPERIMENTAL RESULTS

To show the reality and stability of the implemented drive system, some steady state and transient measurements in Fig.7 are depicted. The stepped waveforms of the output line voltage and phase currents are shown. The waveforms are distorted due to the short circuit which occurs by means of the free-wheeling diodes at the commutation instants. The actual motor speed and current are also displayed. The transient and steady state responses are acceptable. The speed is stable and smooth. All of these waveforms are similar and identical with the theoretical results described. A distortion can also occur in these waveforms due to the back e.m.f. of the motor.



a. Waveform of line voltage at heavy load
Horizontal : 2 msec/div.
Vertical : 1 amp./div.

b. Waveform of phase current at heavy load (S.c. current)
Horizontal : 2 msec/div.
Vertical : 10 v/div.

c. Waveforms of phase current and voltage at no-load.

d. Waveforms of phase current and voltage at load.

Horizontal : 2 msec/div.
Vertical :
Upper trace: I- 2 amp/div.
Lower trace: v- 20 v/div.

e. Transient response of actual speed. and actual current

f. Transient response of actual speed. and actual current
K_{pn} = 75, K_{pi} = 12

Horizontal : 0.5 sec/div.
Vertical :
Current : 2 amp/div.
Speed : 800 rpm/div.

Fig.7 Experimental results

CONCLUSION

This paper investigates the speed of a three phase induction motor drive by using a simplified and complete design of current source inverter system. It was found that, it is necessary to use a ramp circuit to protect the system against the high current due to the sudden change in the speed. This addition (ramp circuit) has no effect on the dynamics of the system as remarked in the analysis and given result. A good agreement between the theoretical and experimental results for load voltage, current, and dynamics was achieved.

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