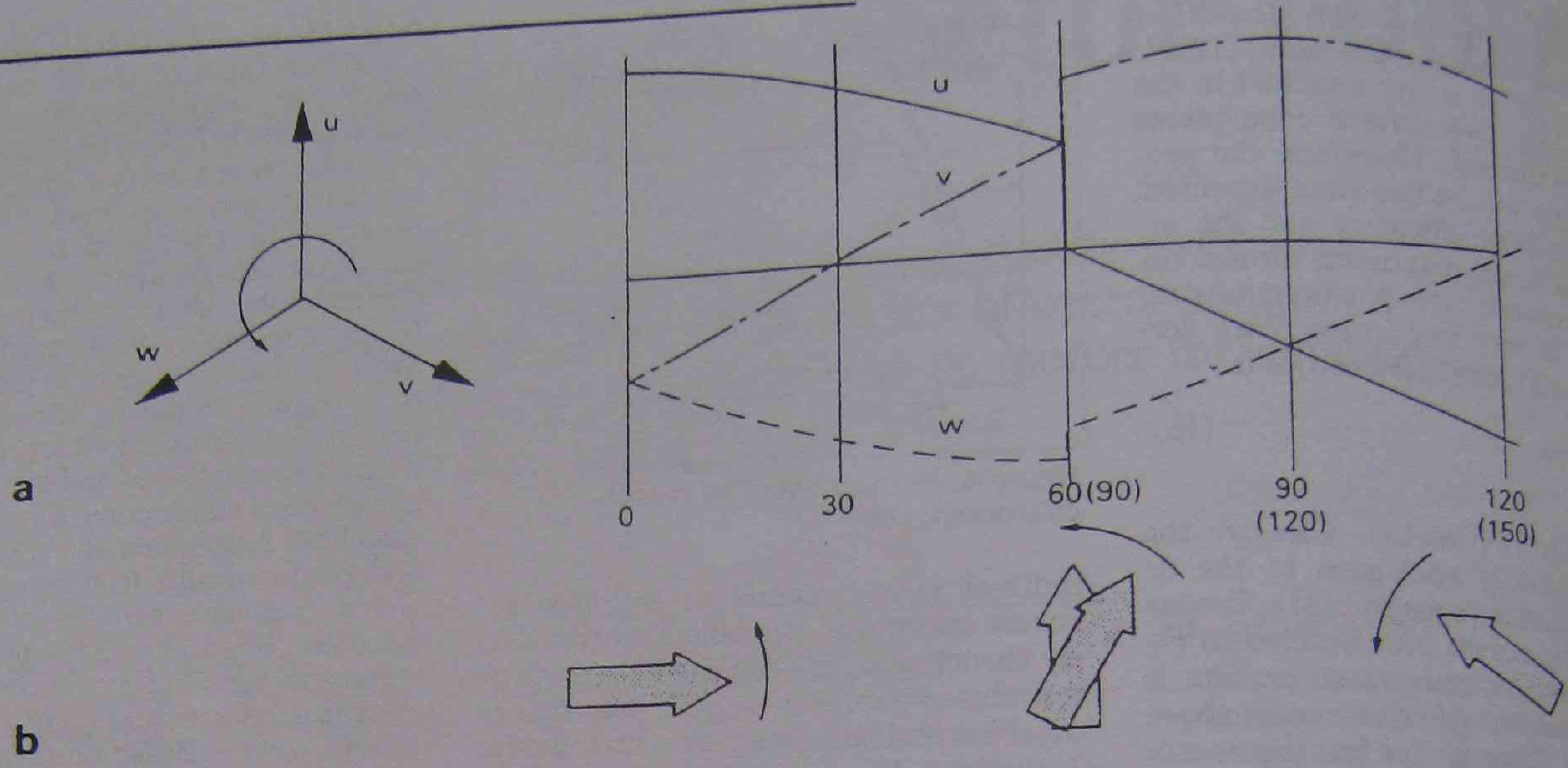
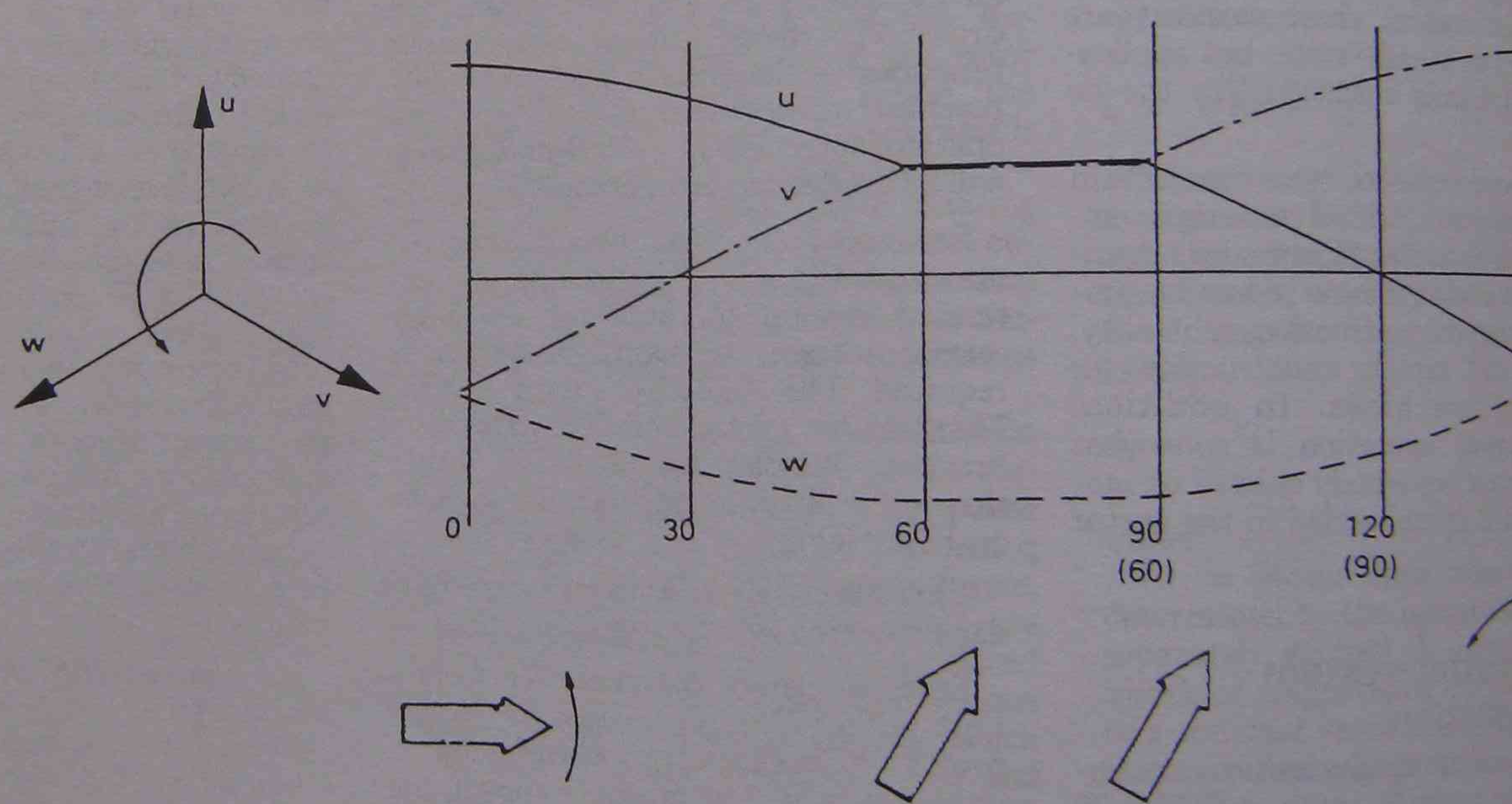


2 *Step-change of field rotation:* **a** *Phase waveform;* **b** *Reorientation of flux vectors.*



3 *Stationary field flux vector.*

TABLE 1
3-Phase Rotating Field — Principal Variations

3-phase Current Vectors	Stator Flux Vector
Normal Mains Supply	
Balanced, sinusoidal, constant frequency and amplitude	Constant magnitude, rotating at constant angular velocity
PWM Supply Changes	
Character of Change:	**Effect:**
Amplitude	Magnitude of current vectors
Phase sequence	Directio[illegible]

Sydney Institute of Technology

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Learners Theory Work Book

Module NE76

A.C. Motor Control

Area ....

Topic ....

Session No. 6·3

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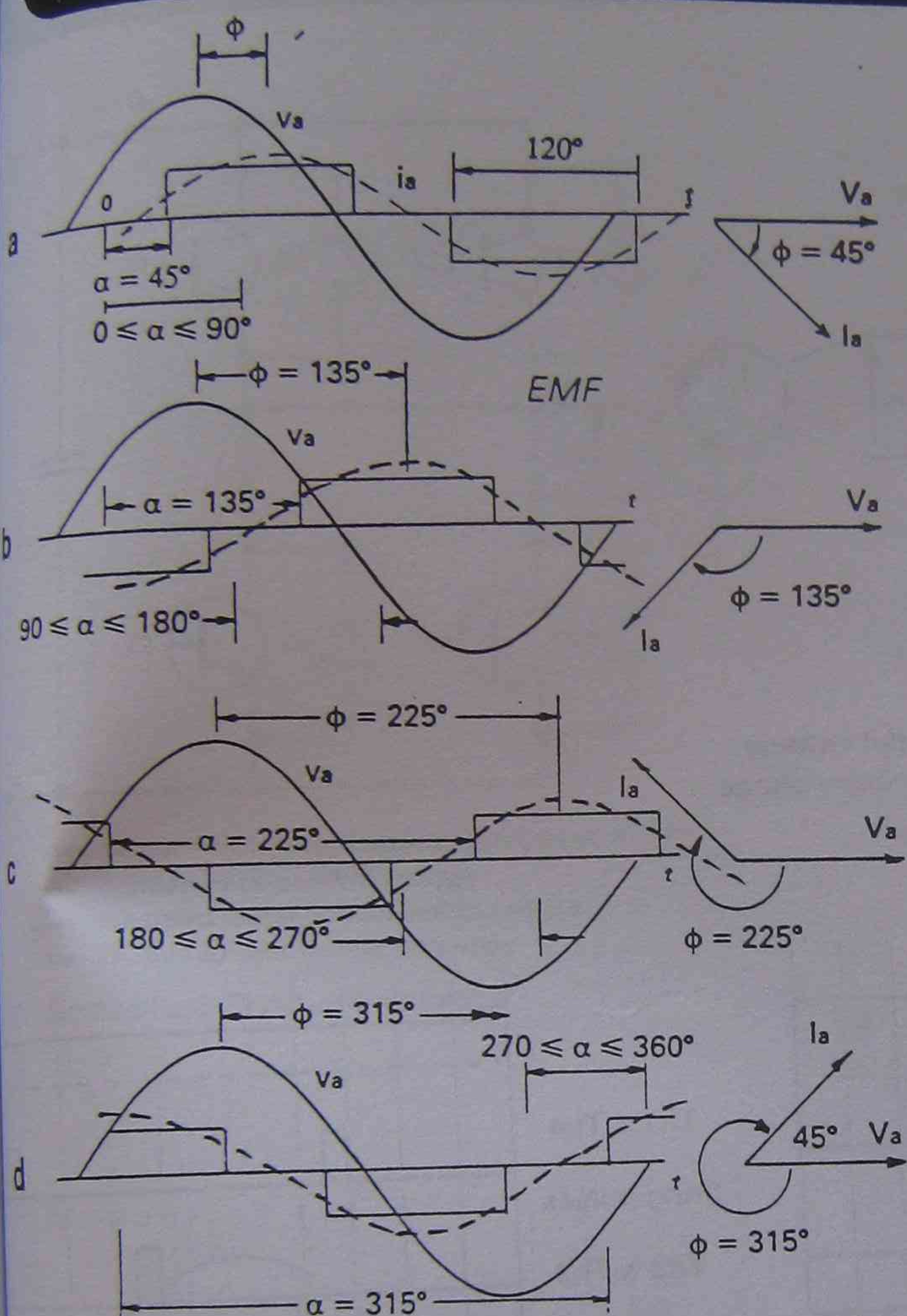
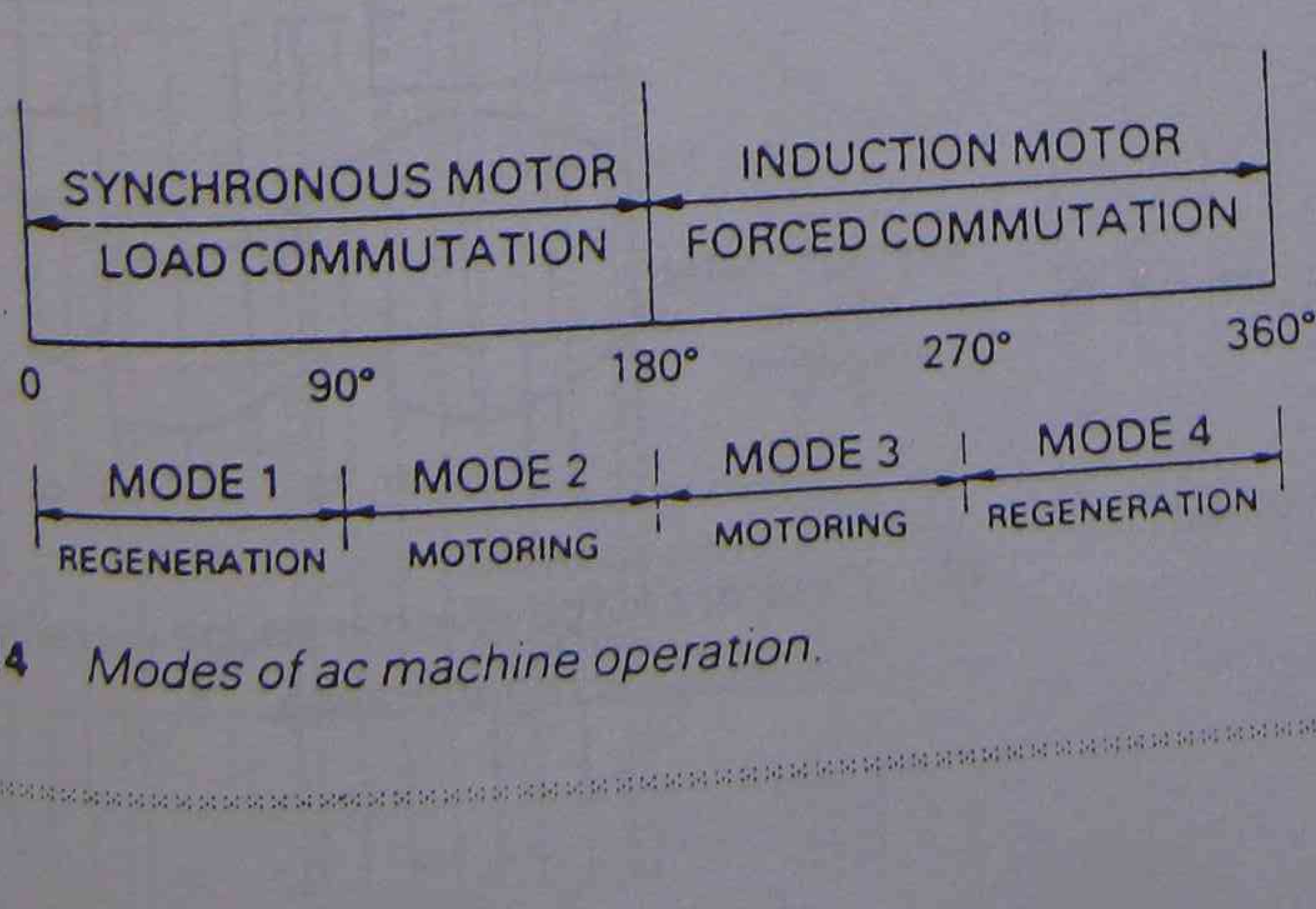
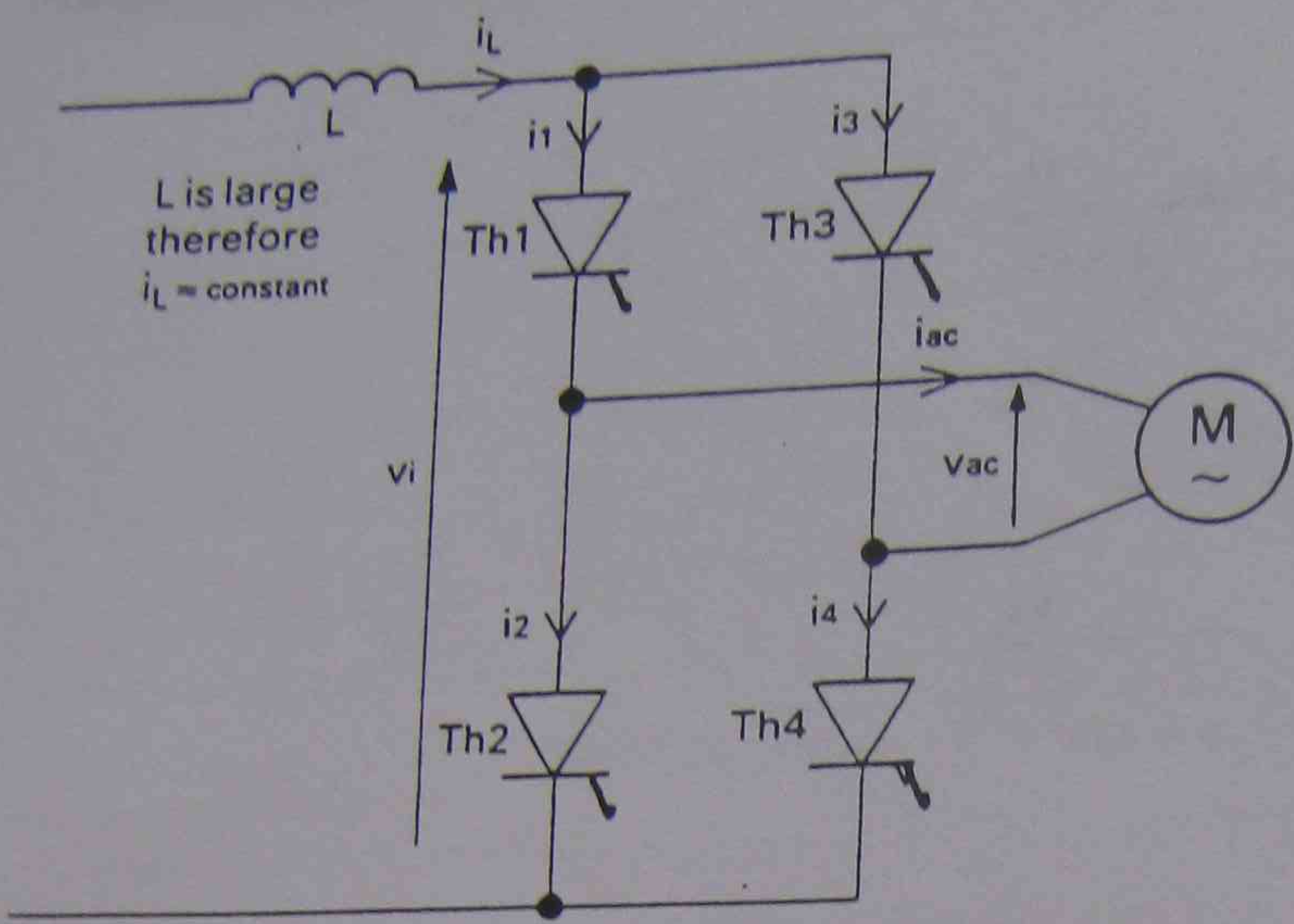


13 Modes of operation with counter-EMF load:

- a $0° \leq \alpha \leq 90°$ = *load-commutated rectifier;*
- b $90° \leq \alpha \leq 180°$ = *load-commutated inverter;*
- c $180° \leq \alpha \leq 270°$ = *force-commutated inverter;*
- d $270° \leq \alpha \leq 360°$ = *force-commutated rectifier.*

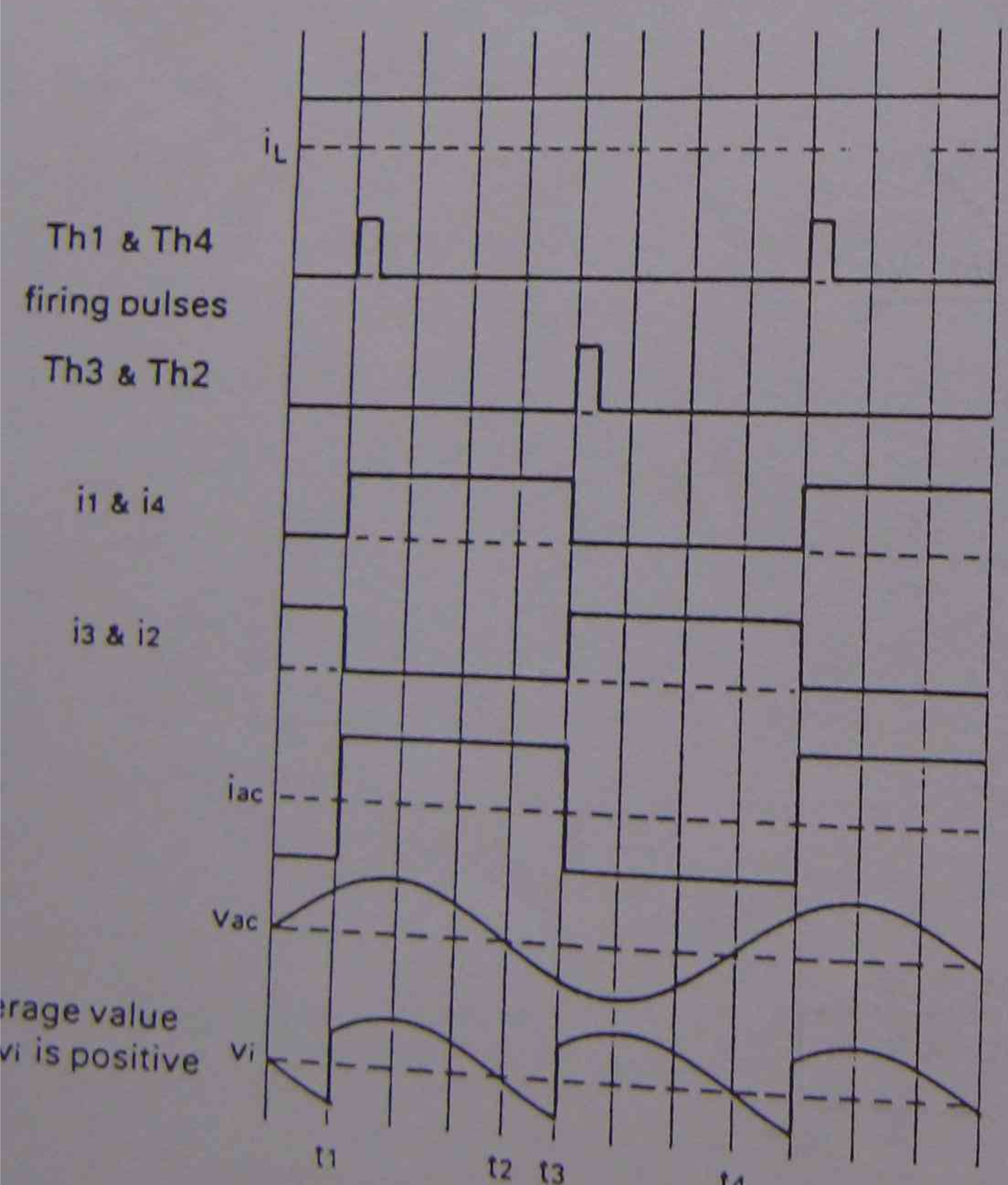


14 *Modes of ac machine operation.*

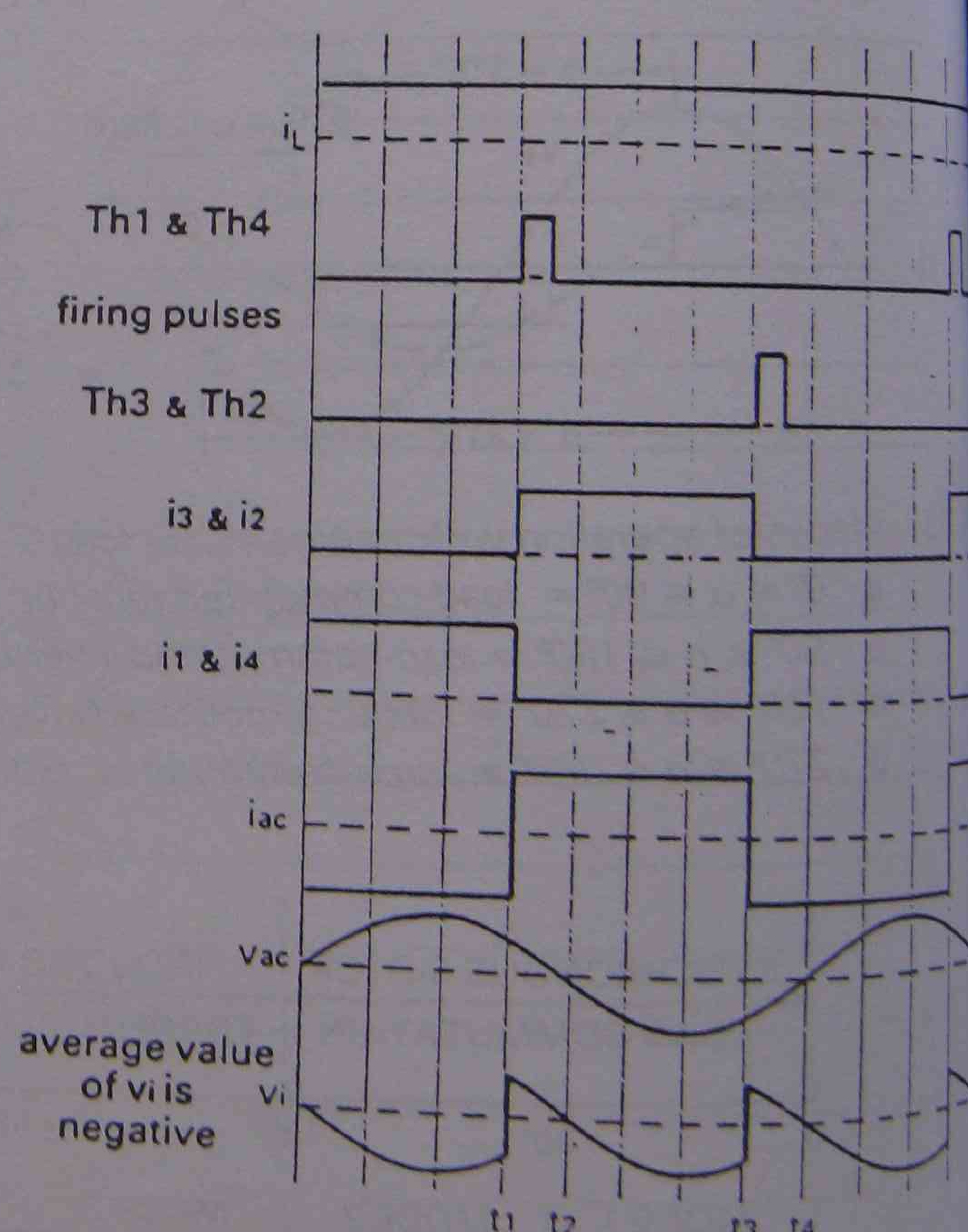


i_L DC link inductor current v_i Inverter bridge input voltage
i_{ac} Motor current v_{ac} Fundamental of motor voltage

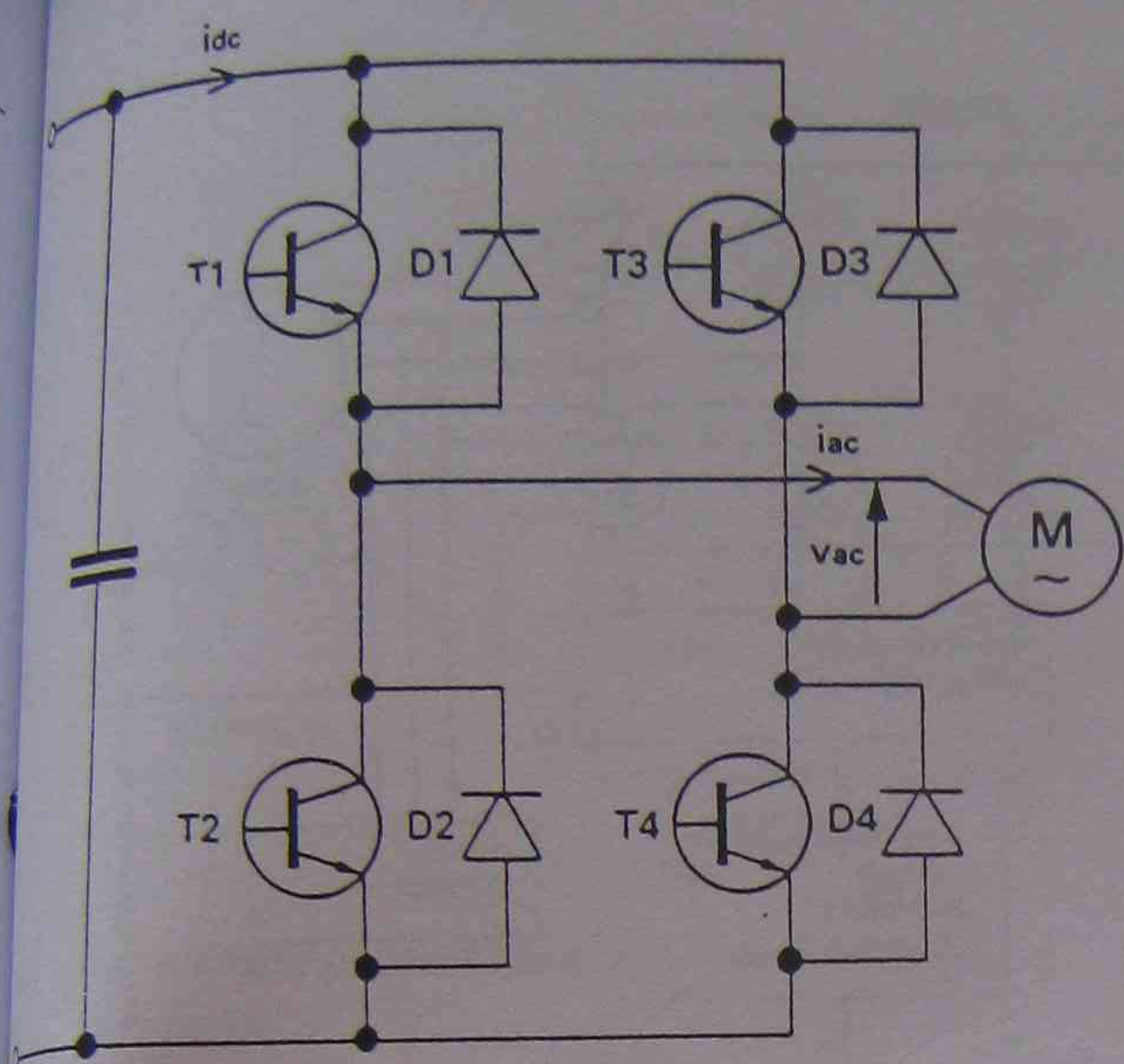
16 *Single-phase current source inverter bridge.*



Current source inverter bridge waveforms when motoring at full load.

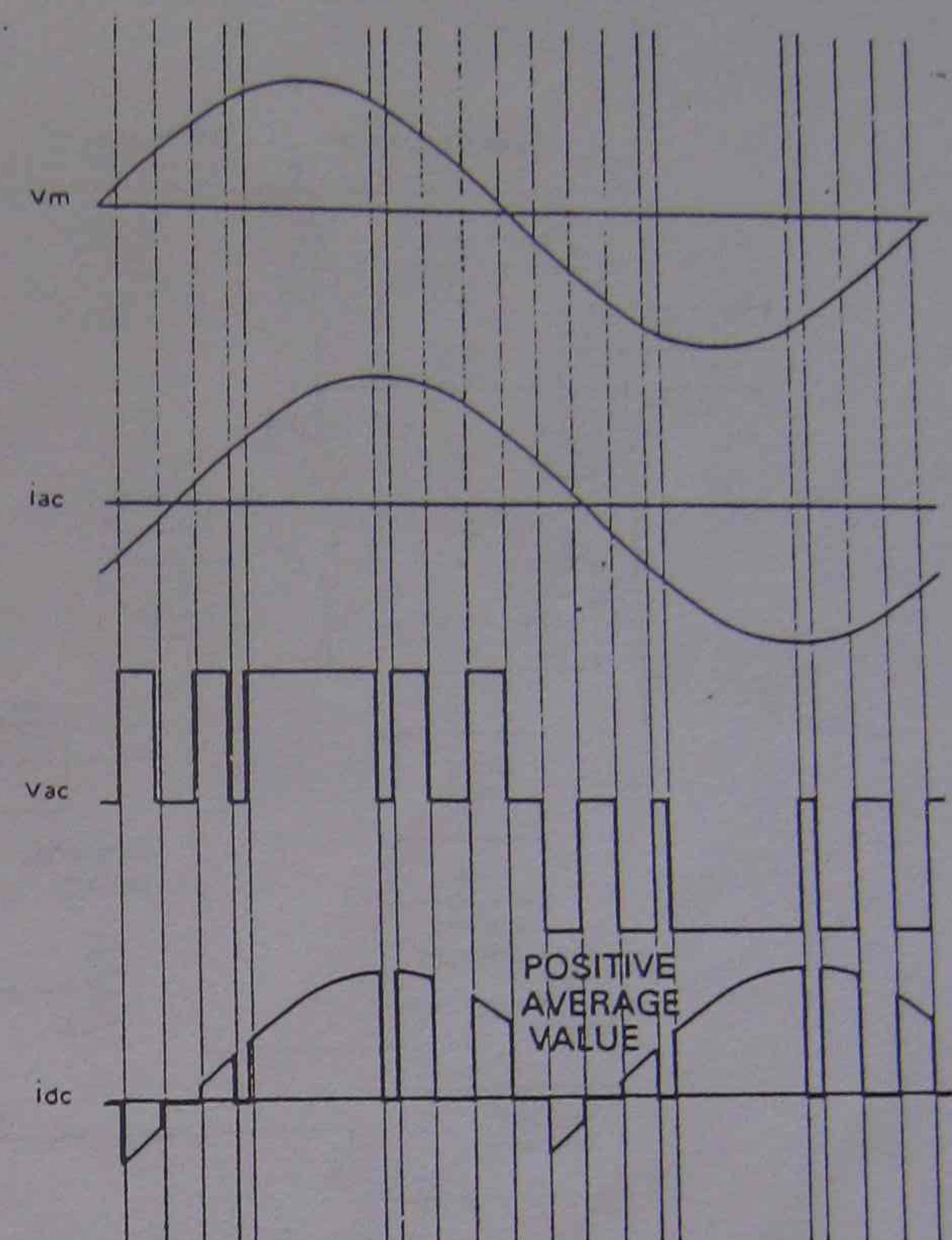


18 *Current source inverter bridge waveforms when the motor is regenerating.*

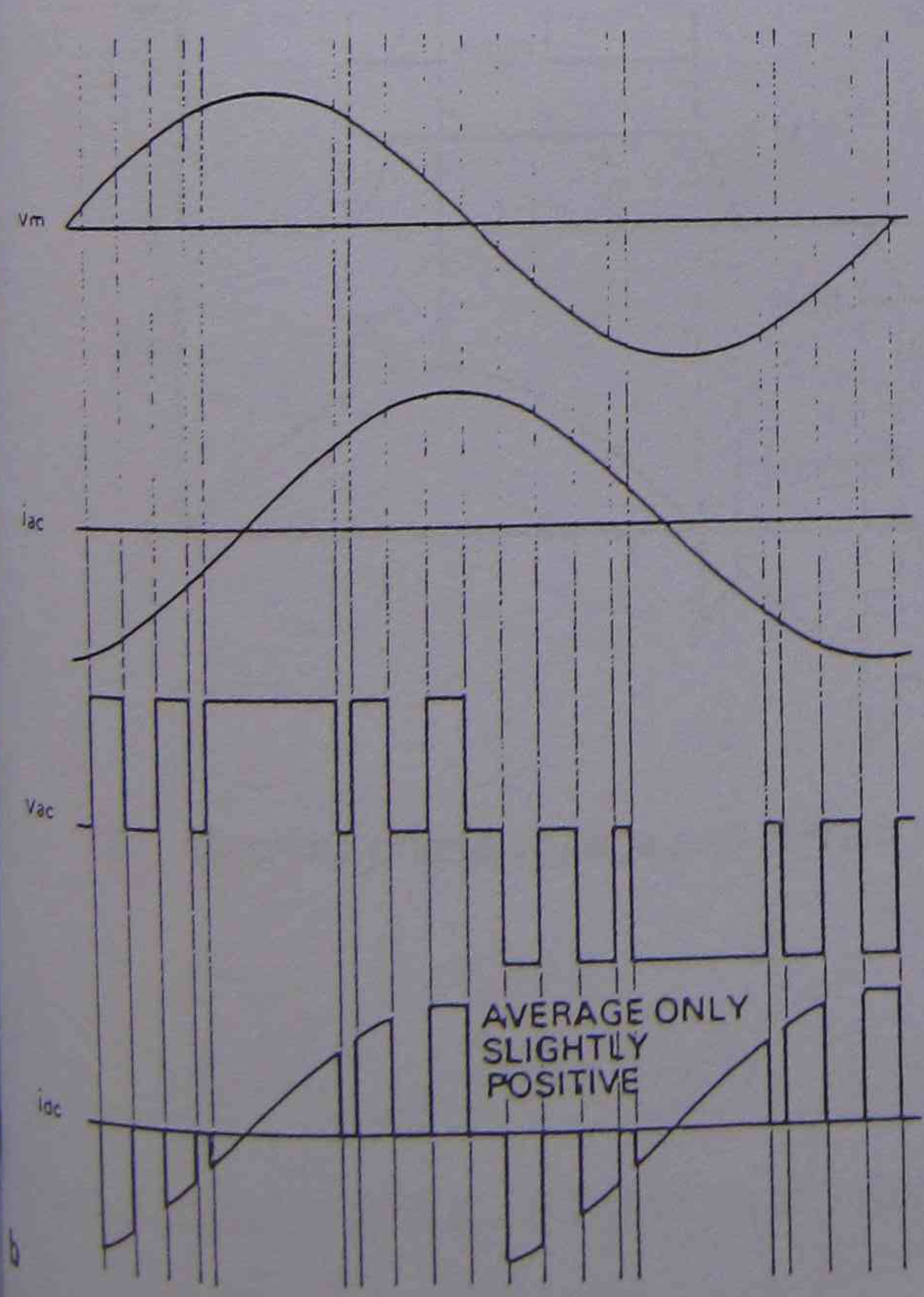


vac Actual PWM voltage applied at motor terminals
vmf Fundamental of PWM voltage
iac Idealised motor current without ripple
idc DC bus current to inverter bridge

6 *Single-phase PWM inverter bridge.*



a



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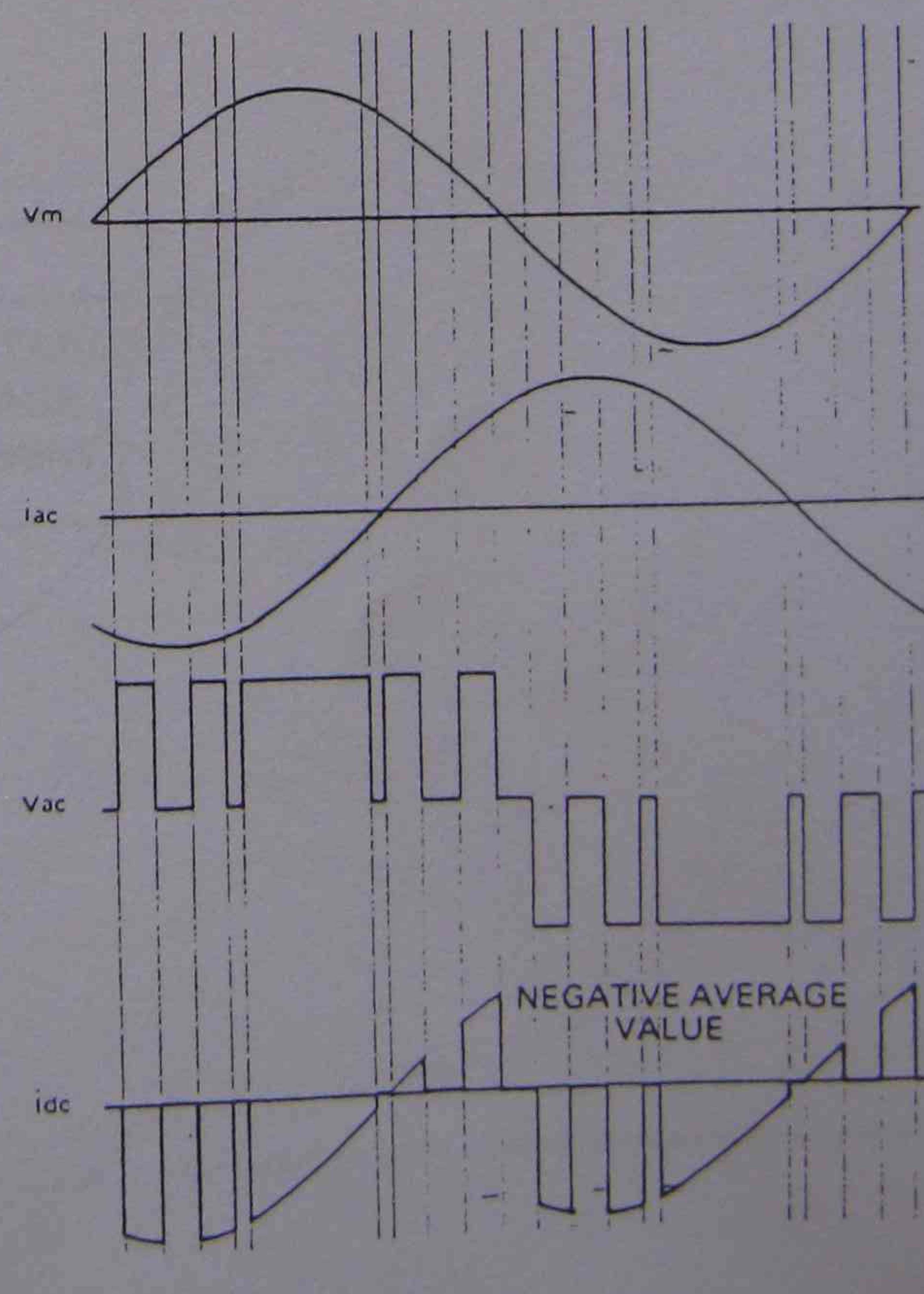

c

7 *Inverter bridge waveforms:* **a** *Motoring, full load;* **b** *Motoring, light load;* **c** *Regenerating.*

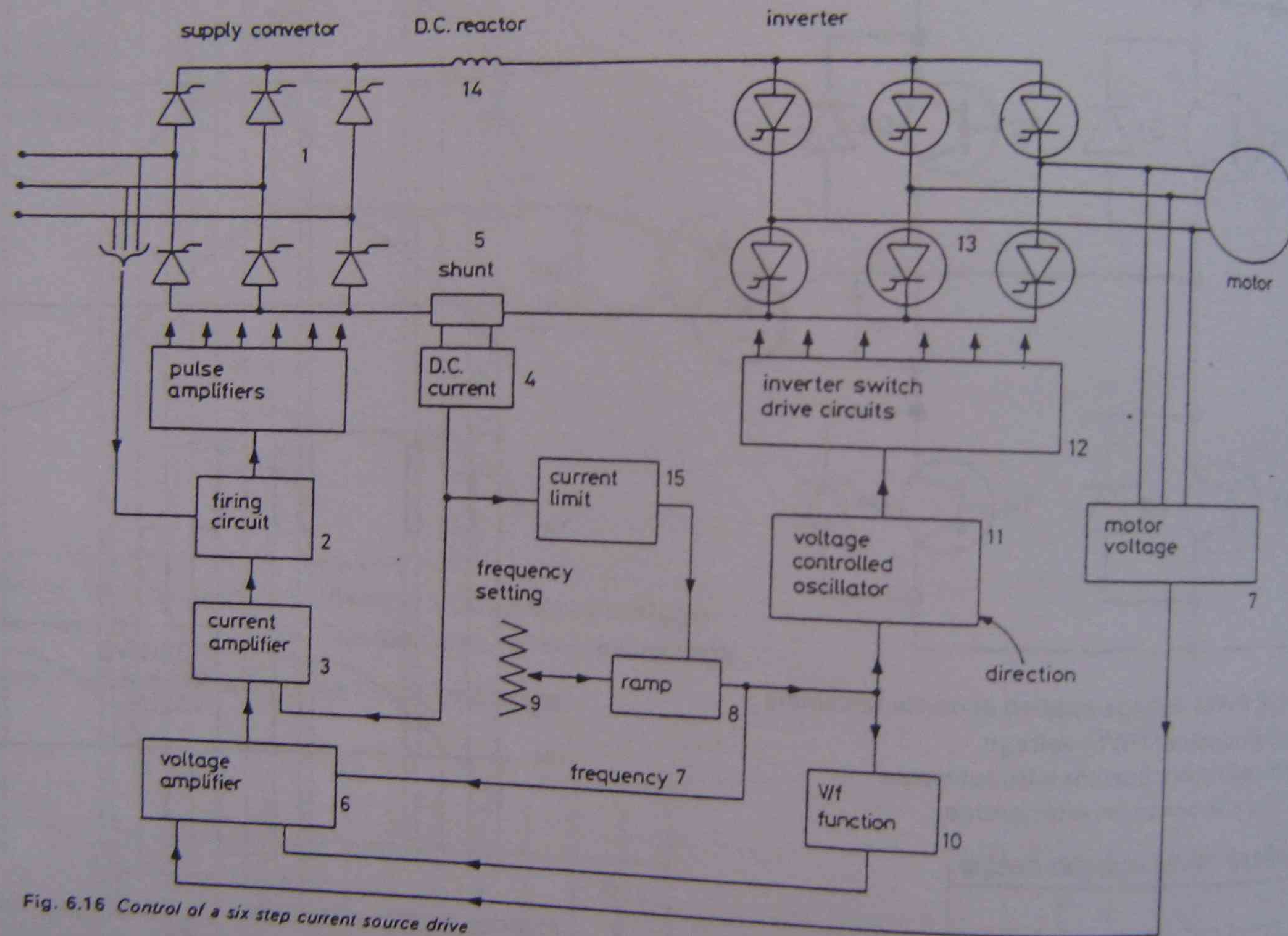

Fig. 6.16 *Control of a six step current source drive*

The six step current source inverter drive

SUPPLY

11 *Generalised p*

ia

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A.C. Motor Control.

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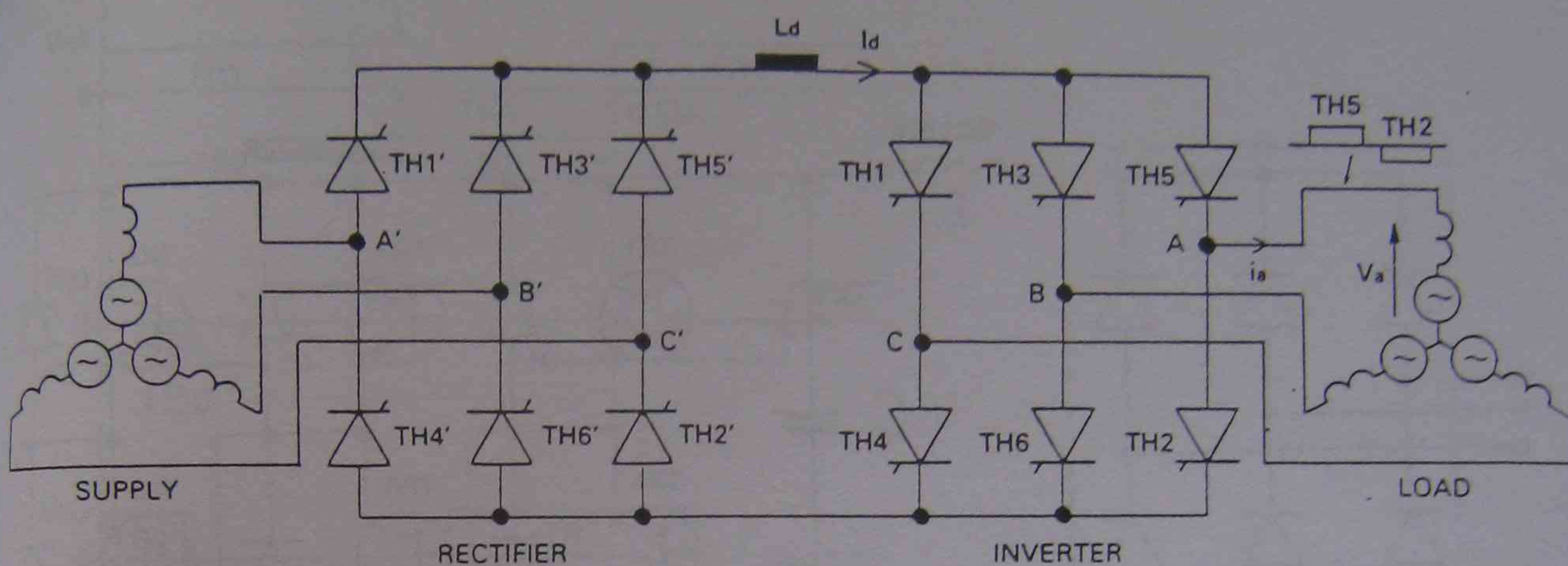
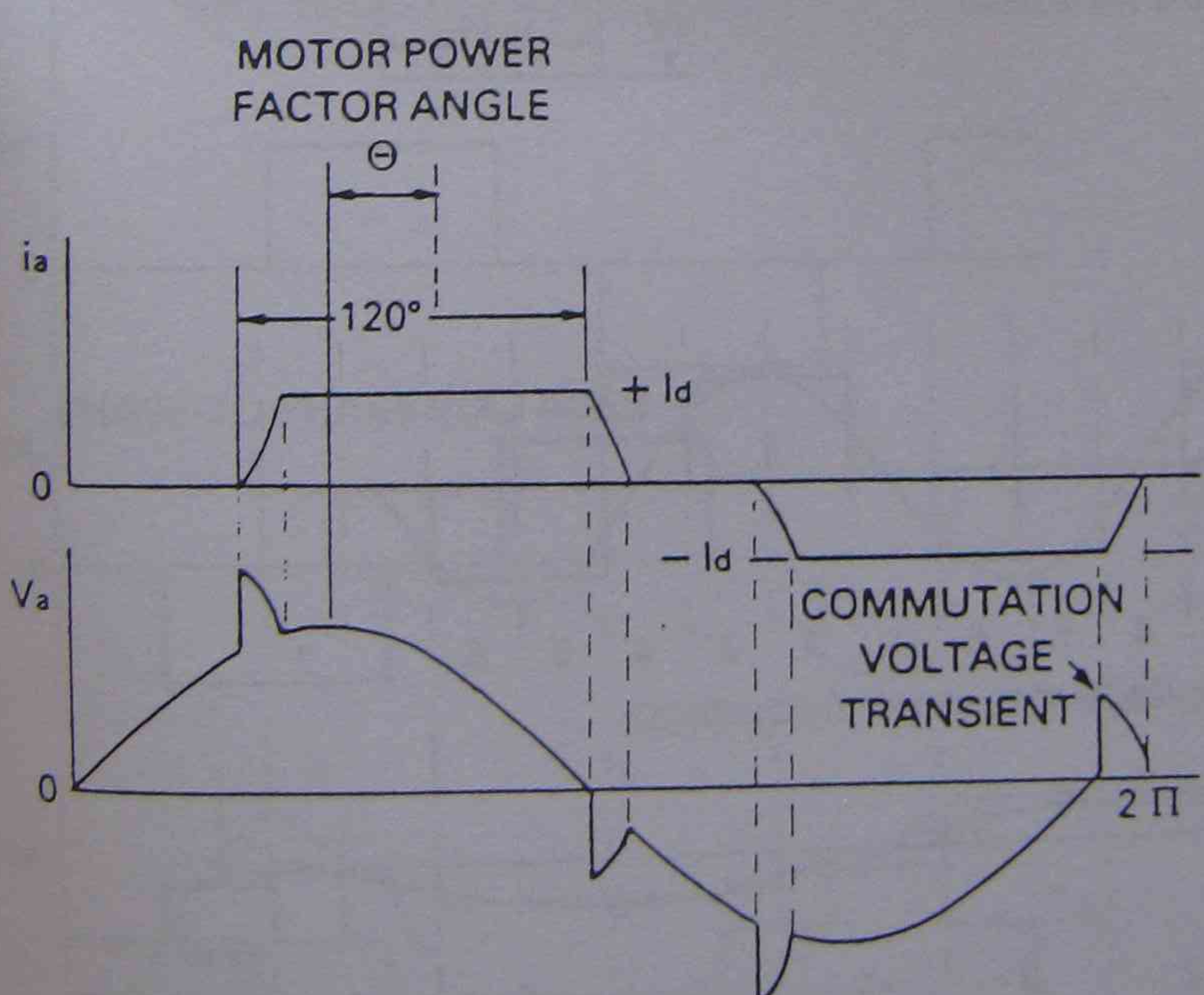


11 *Generalised power circuit of current-fed inverter.*



12 *Machine phase voltage and current waves.*

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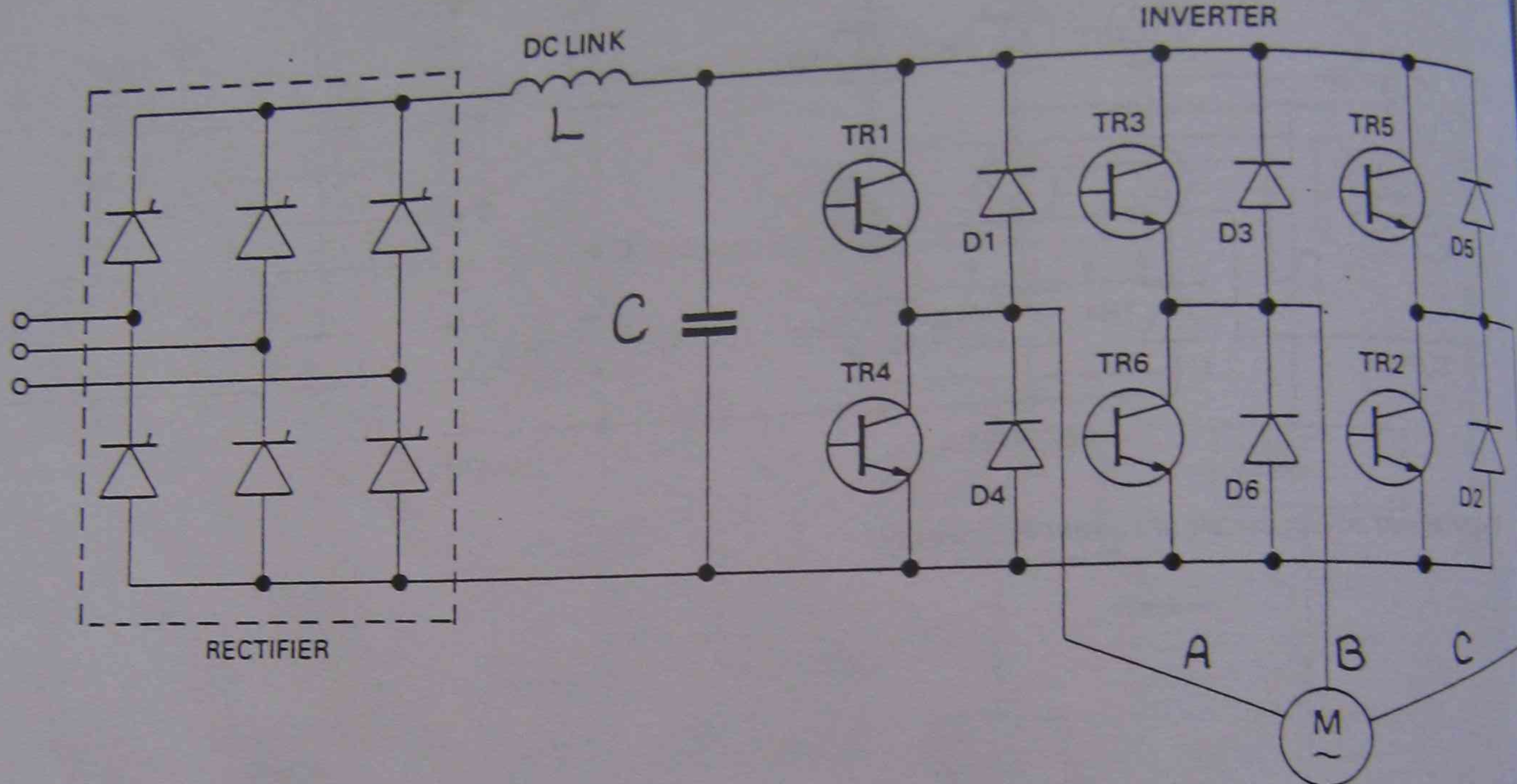
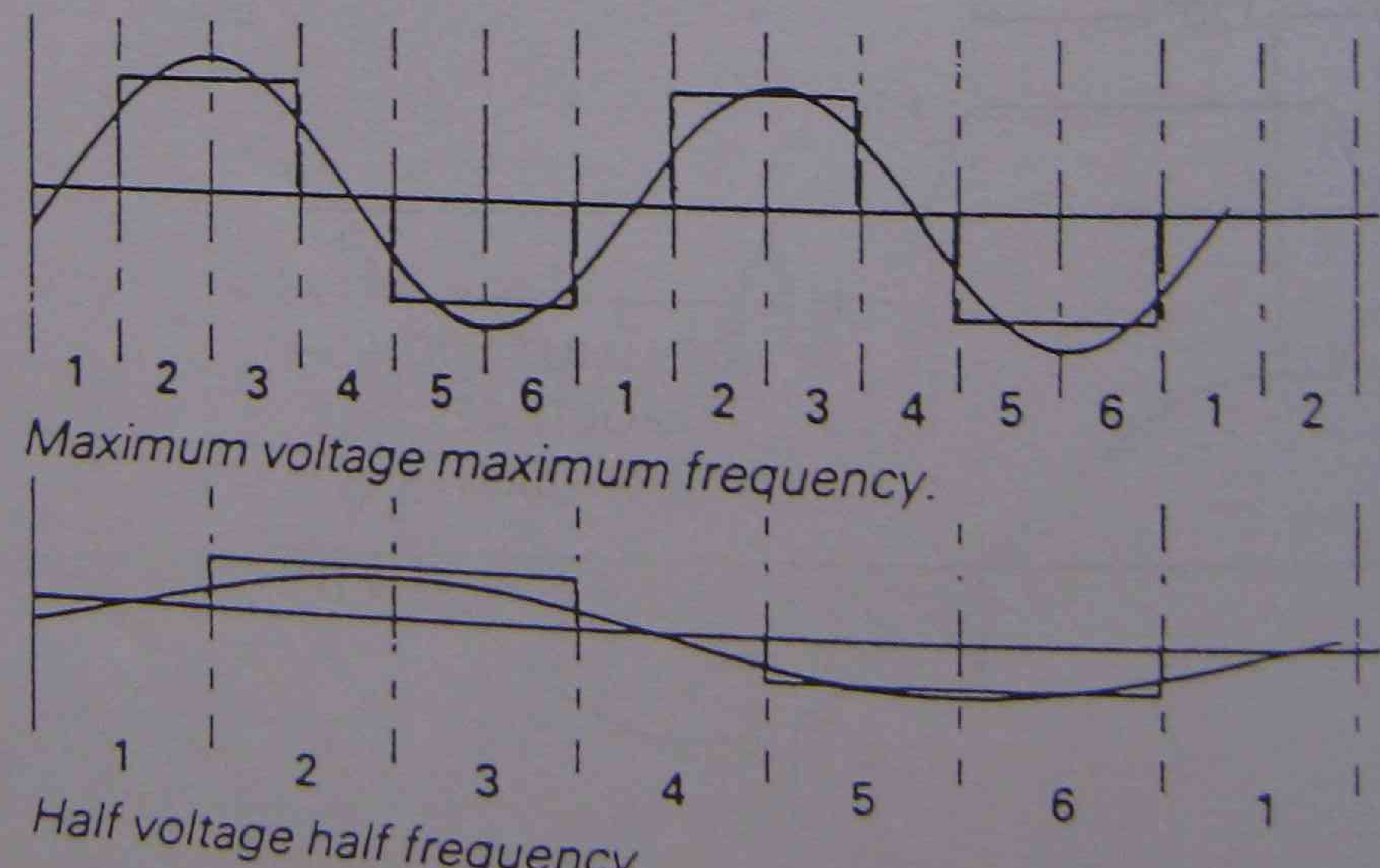
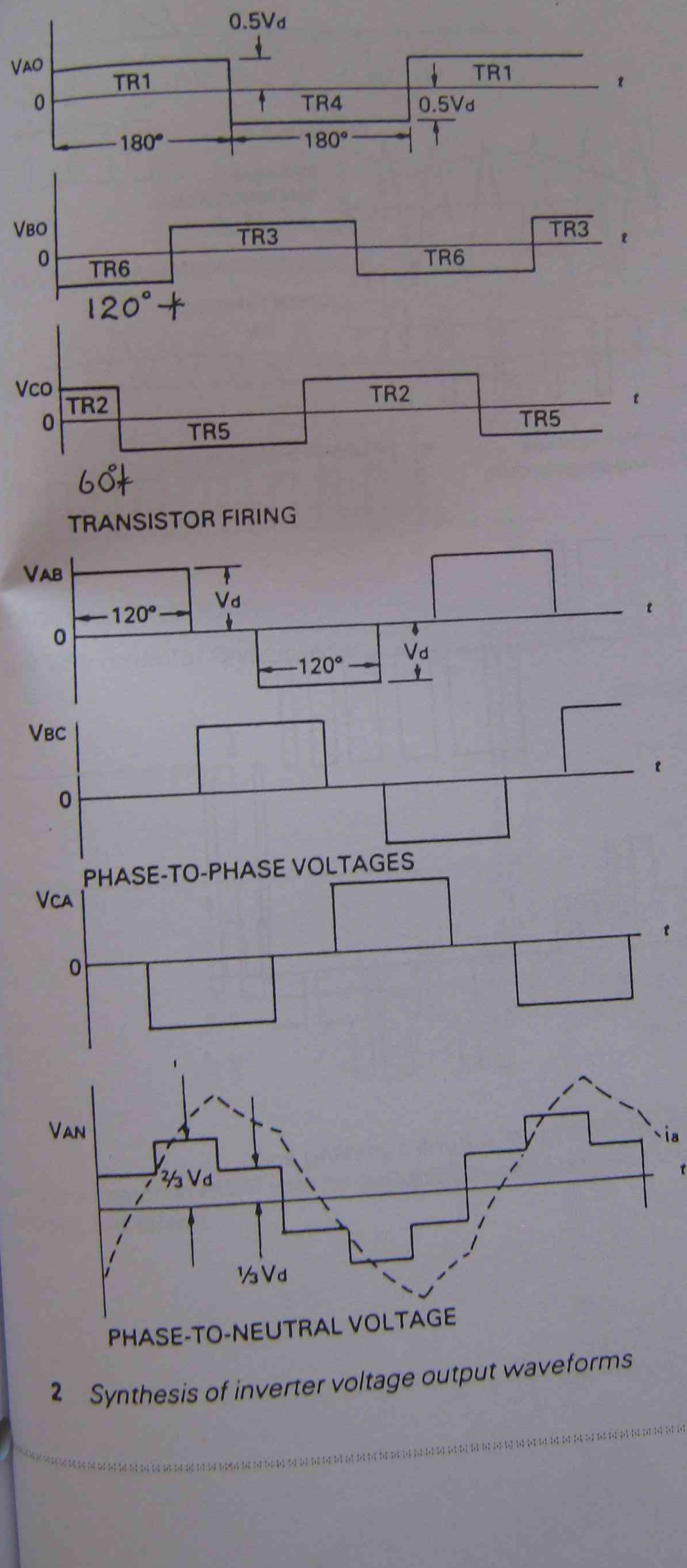


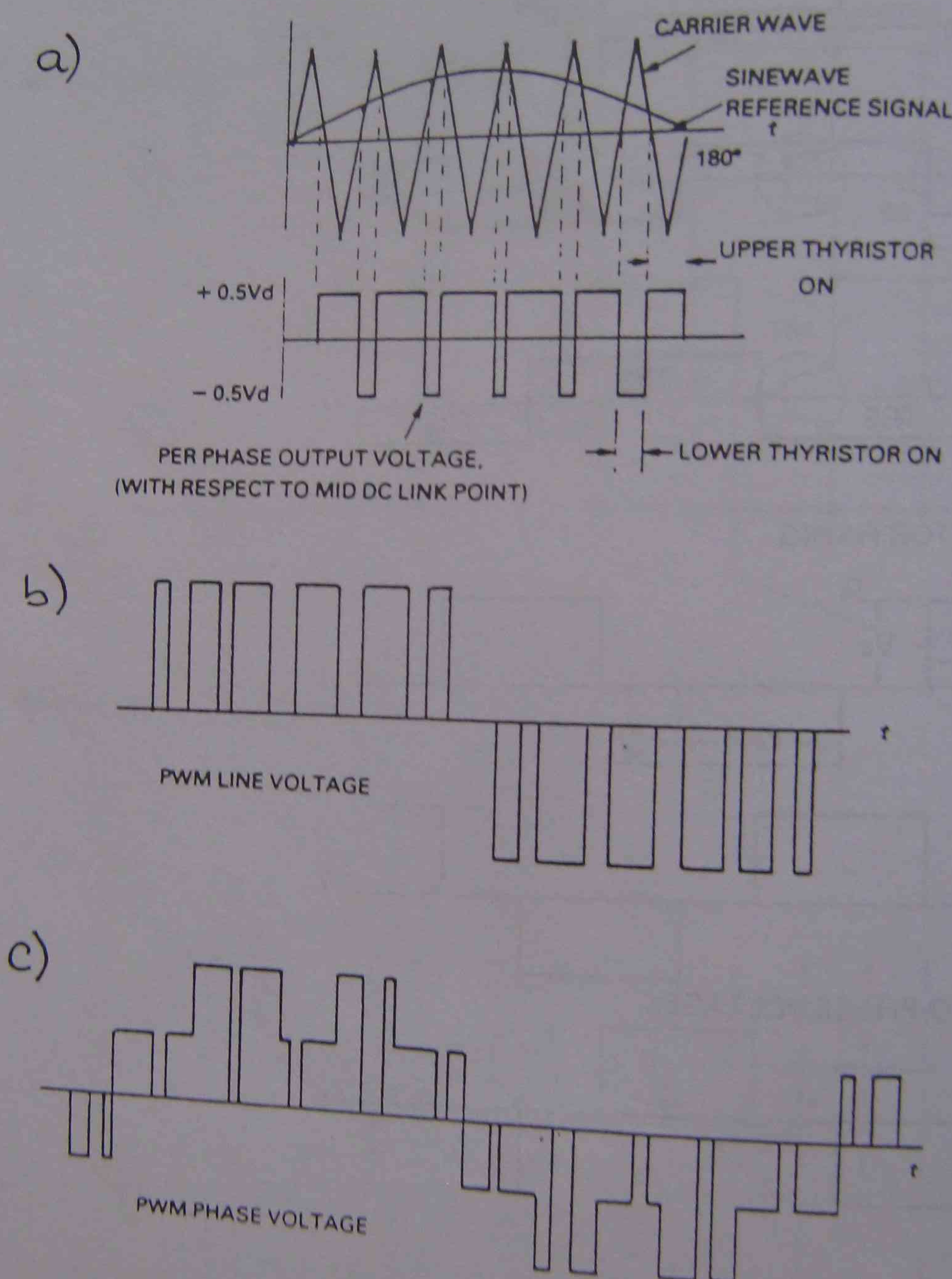
1 *Basic dc link voltage-fed invertor square wave drive.*



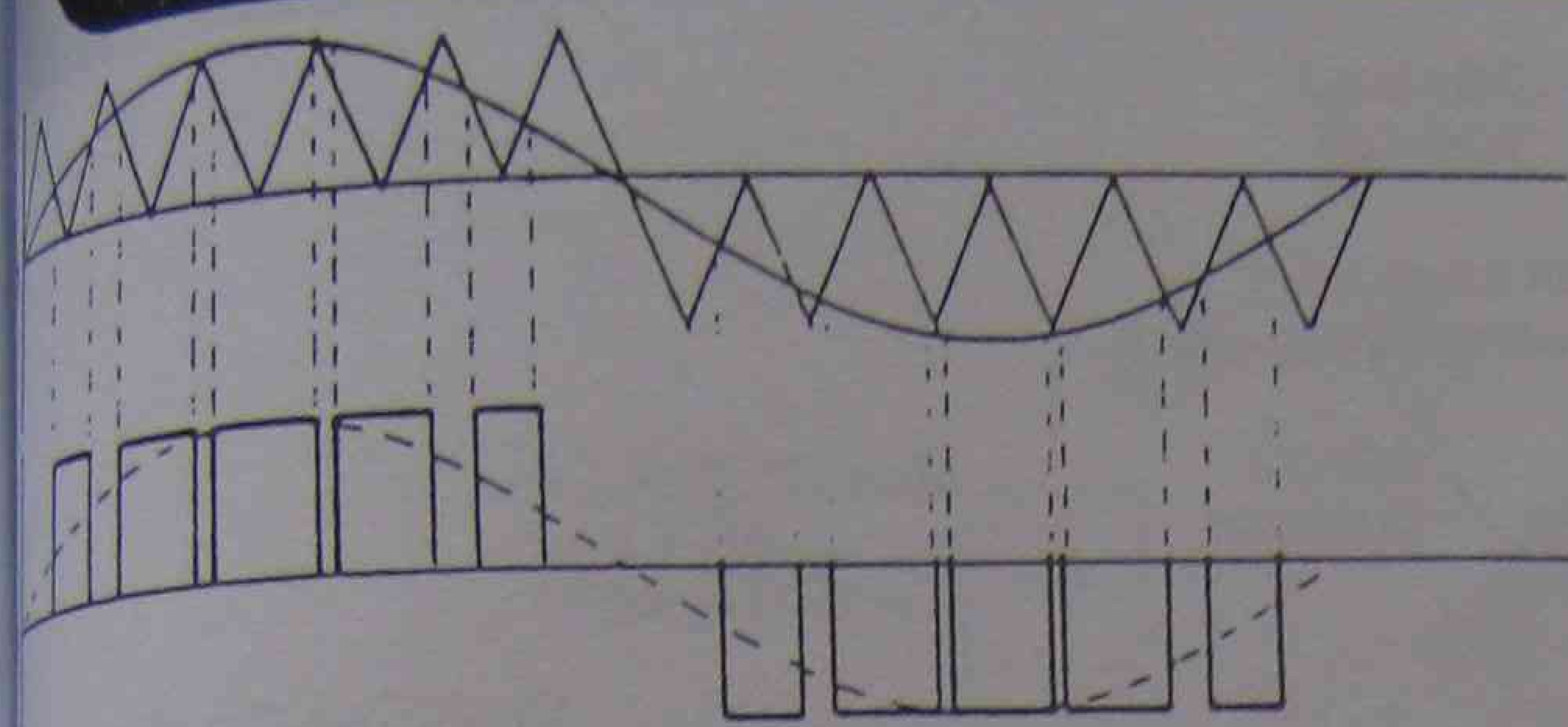
3 *Constant volt/Hz control of square sine wave inverter.*



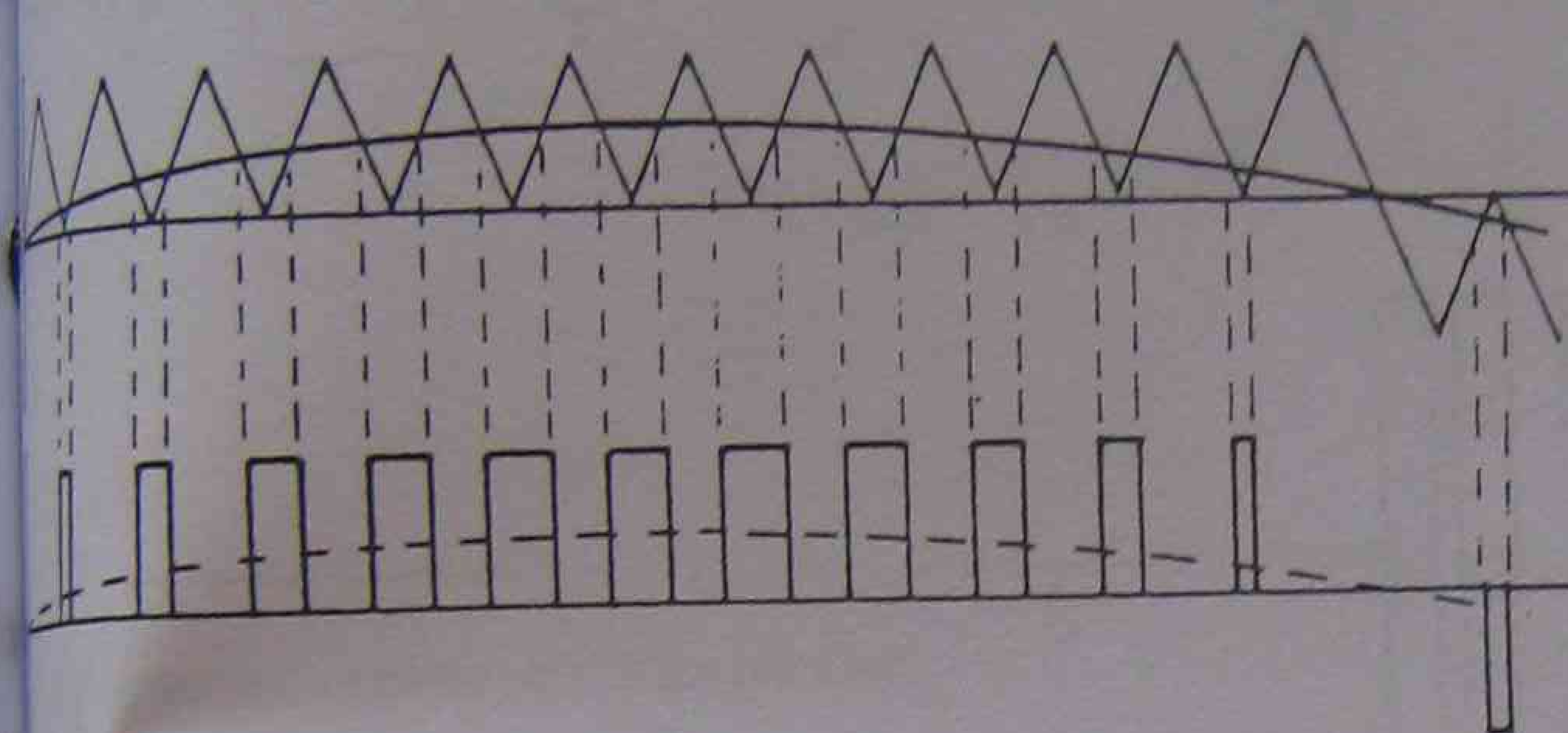
2 *Synthesis of inverter voltage output waveforms*



4 *Principle of sinusoidal PWM with natural sampling and the resulting output line and phase voltages.*

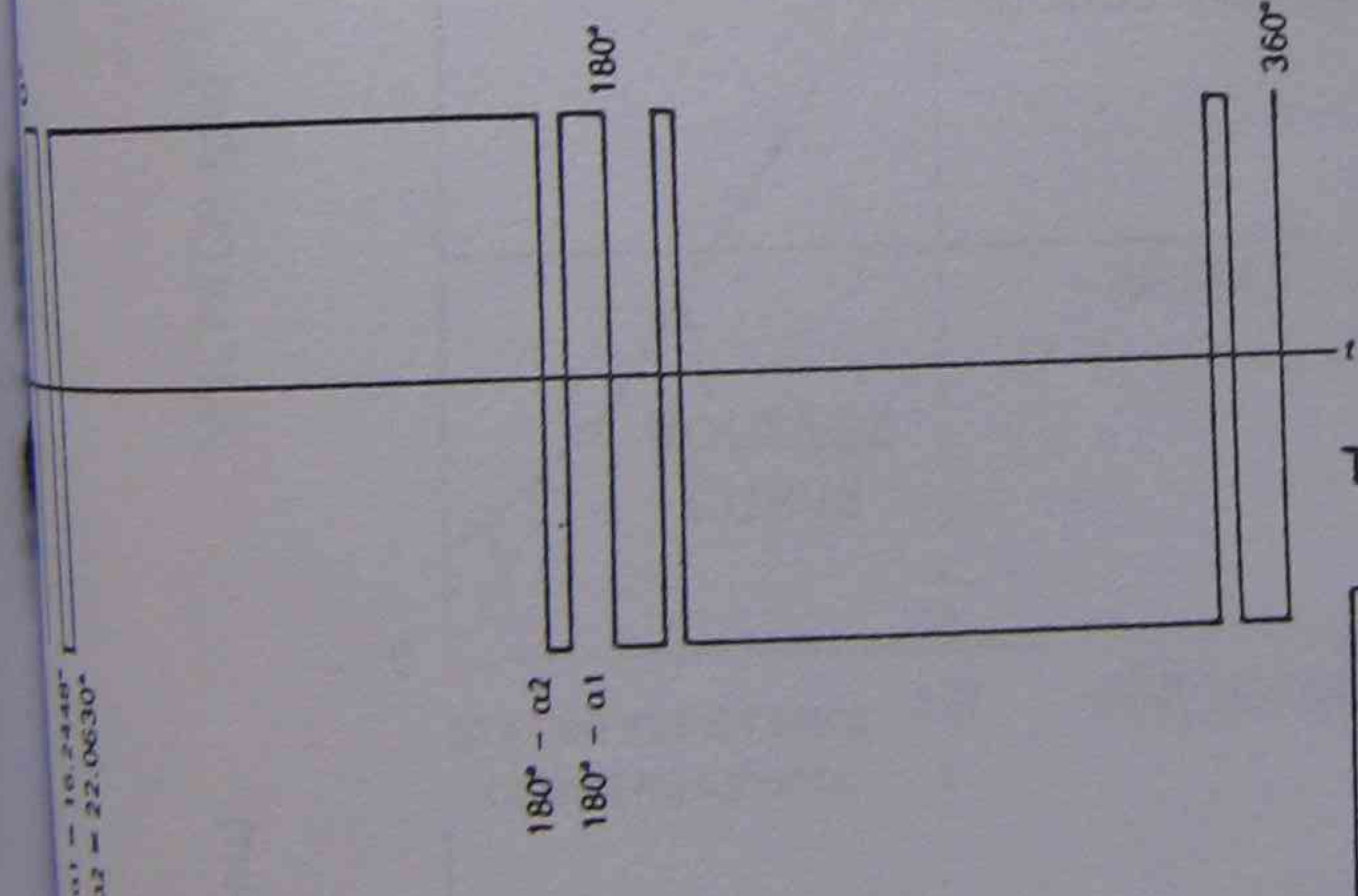


XIMUM VOLTAGE MAXIMUM FREQUENCY



F VOLTAGE HALF FREQUENCY

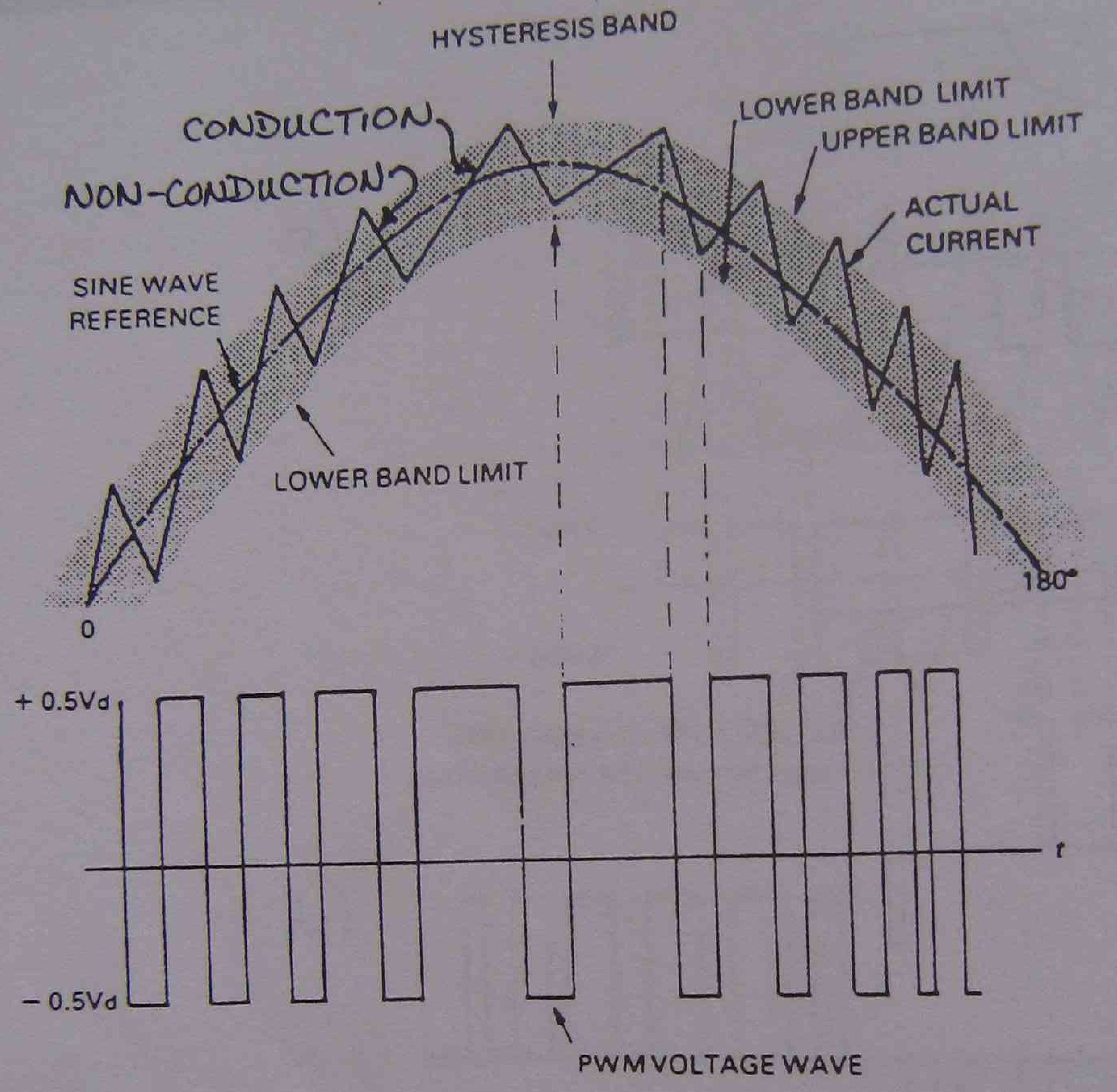
Constant V/Hz control of PWM inverter



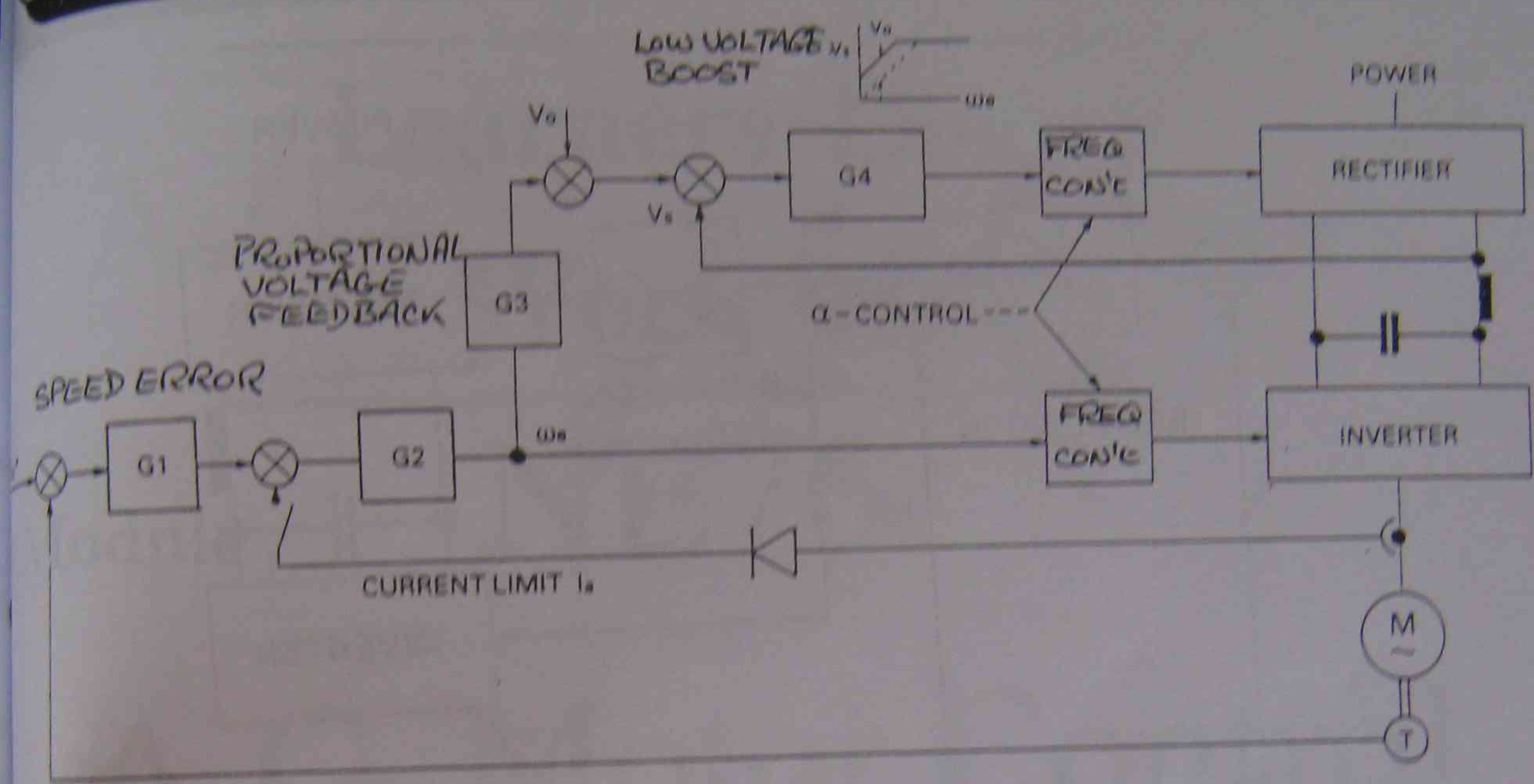
Harmonic elimination PWM with no fifth and seventh harmonics, see table 1.

TABLE 1 Analysis of waveform in Fig.5 showing estimation of 5th and 7th Harmonic.

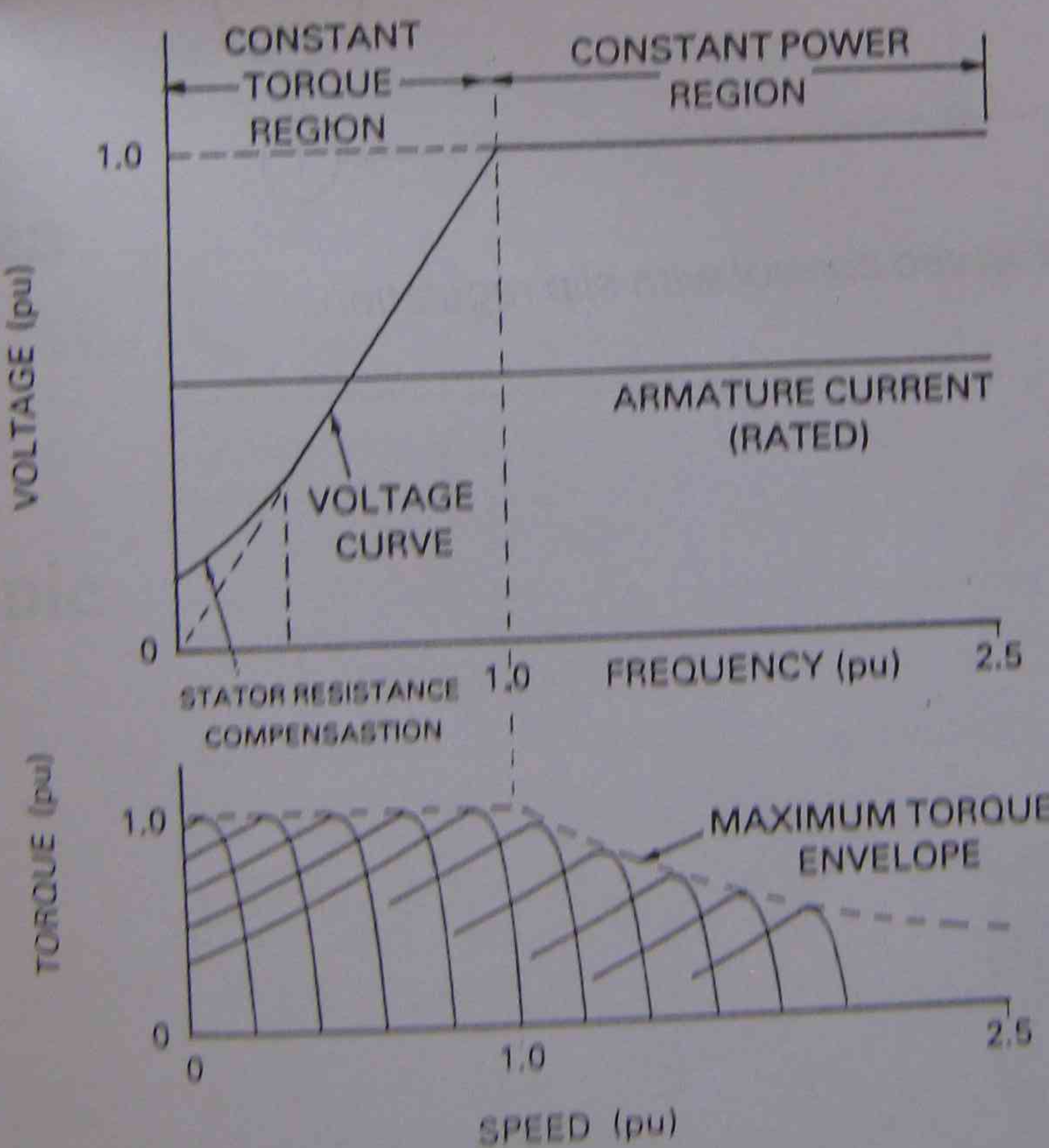
Order of Harmonic	Absolute value of Harmonic - Coefficient	Absolute value of Harmonic as Percentage of Fundamental
1	1.1897	100
3	0.2070	17.43
5	0	0
7	0.0001	0.01
9	0.1086	9.14
11	0.2421	20.31
13	0.3223	27.13
17	0.2030	17.09
19	0.0514	4.33
21	0.0825	6.94



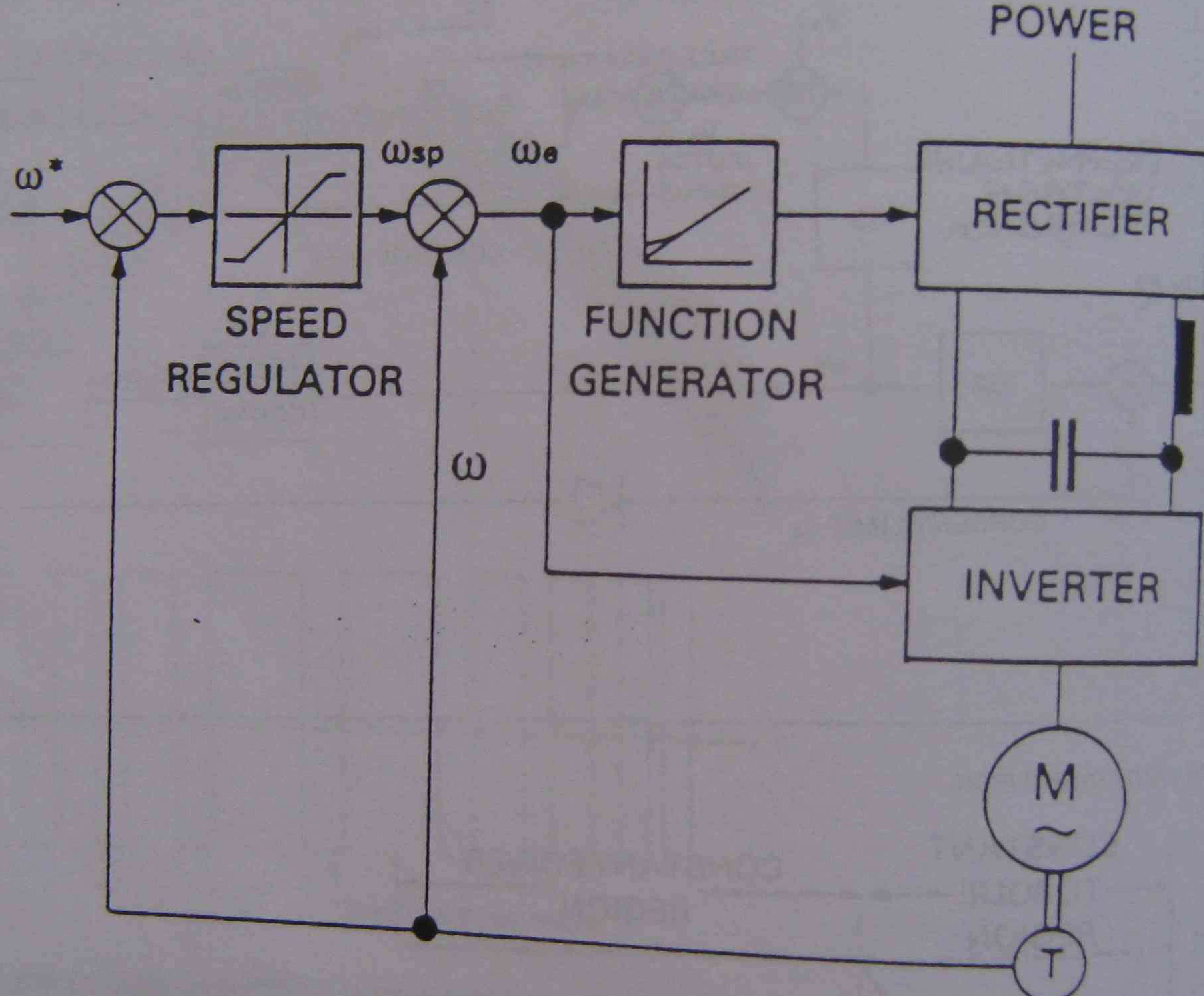
7 *Principle of adaptive PWM with bang-bang current control.*



V/Hz speed control with current limit.



9 *Torque-speed curves of induction motor with variable frequency power supply.*



10 *Constant V/Hz speed control with slip regulation.*

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A.C. Motor Control.

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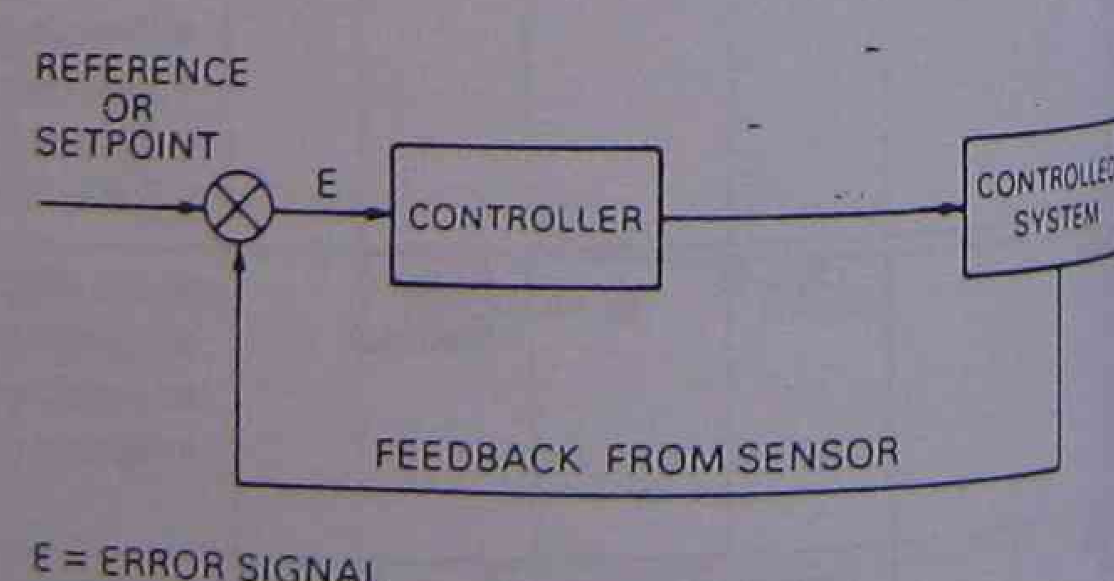
DRIVE SYSTEM	Speed Ratio	Braking Torque	MOTOR DE-RATING Continuous Use at: Full Load	Low Speed	Torque Response	SPEED HOLDING 0-100% Load Change	Speed Linearity	Starting Torque	CONNECTIONS Controller to Motor	SUMMARY Principal Advantages	Principal Disadvantages
DC Motor + Converter	1:20 (Analogue AVF) 1:100 (Analogue dc tacho) 1:400 (Temp compensated dc tacho or encoder) 1:1000 (Encoder with digital lock)	150% (with 4Q drive)	Dependent on motor rating and 6, 3 or 2-pulse bridge: no de-rating above 10kW with 6-pulse	As full load if forced air cooling. 1:5 speed ratio at 90% nominal torque without forced cooling	<10ms with 6-pulse bridge, no choke in motor supply	2·0%; AVF with IR compensation. 0·1%: Anal.tacho. 0·05%: Digital encoder	Typically 0·1% With digital speed feedback <0·01%	150% 20-30s	AVF: 4 Closed-loop: 6	• Wide speed range • Good starting torque • High efficiency • Economic cost of controller • Digital communication possible • Braking facility	• Expensive motor • Brushgear maintenance • Possible commutation failure on loss/dip of supply • Torque variation at low loading • Low/part loads reduce brush life • Low protection class (motor)
AC Motor + Inverter (VVVF or PWM)	1:20	approx 100% for voltage-driven inverters. 100% (regen) for PWM. DC braking 50-100% depending on motor: – non-linear; also high losses	5-15% dependent on quality of sine waveform output	Dependent on speed range and motor/inverter characteristics. 90% nominal torque over full speed range with forced cooling. 1:4 speed ratio at 90% nominal torque without forced cooling.	Dependent only on torque response of motor	1-2% with slip compensation	Typically 0·1%	Depends on quality of sine waveform output: for 150% FLC 20-30s, torque 75-150%	Open loop: 3	• Maintenance economy • High protection class • Motor availability ex-stock • Simple application and set-up • Economic cost of motor • Digital communication possible • Overload and fault protection • Speed range to >100% nominal • Braking facility	• Possible motor instability at low speed/ light load • Possible acoustic noise • Average speed range available
AC Motor + Flux Vector	1:400	150% dynamic or regen	5%	Forced cooling is usual: typically 95% nominal torque over full range	<1·0ms	0·05%	<0·01%	150% 30s	Power: 3 Encoder: 4-6	• Excellent torque response • High starting torque • Widest range of applications • No zero-torque deadband • Excellent stability • Maintenance economy • Overload and fault protection • Speed range to >100% nominal • High protection class • Braking facility	• Additional converter required for regeneration into supply
AC Switched Reluctance Drive	1:100	Effectively max 20% braking torque	Nil – Special motor	Nil – Special motor	Typically 40 ms	0·01%	0·3%	150% 5s	Power: 6 Feedback: 4	• High efficiency • High standard speed range • Overload and fault protection • High protection class	• Specialised motor design • Applications limited • Cogging tendency at low speed • Acoustic noise • 6 power cables required for motor
AC Eddy-Current Coupling	1:20 1:40 Depending on number of poles	Nil	Nil	Dependent on cooling. Typically lower speeds not available at >50% motor torque.	Not good	0·5%	1·0%	Dependent on coupling frame size. 150% possible	Power: 2 Feedback: 2	• Economic maintenance • Good starting torque	• Efficiency low at low speed • Poor torque response • No braking facility

4 CLOSED-LOOP CONTROL

The general principle of closed-loop control is illustrated in Fig.1. The principle applies not only to variable-speed drives but also to other electrical, mechanical, hydraulic or pneumatic systems.

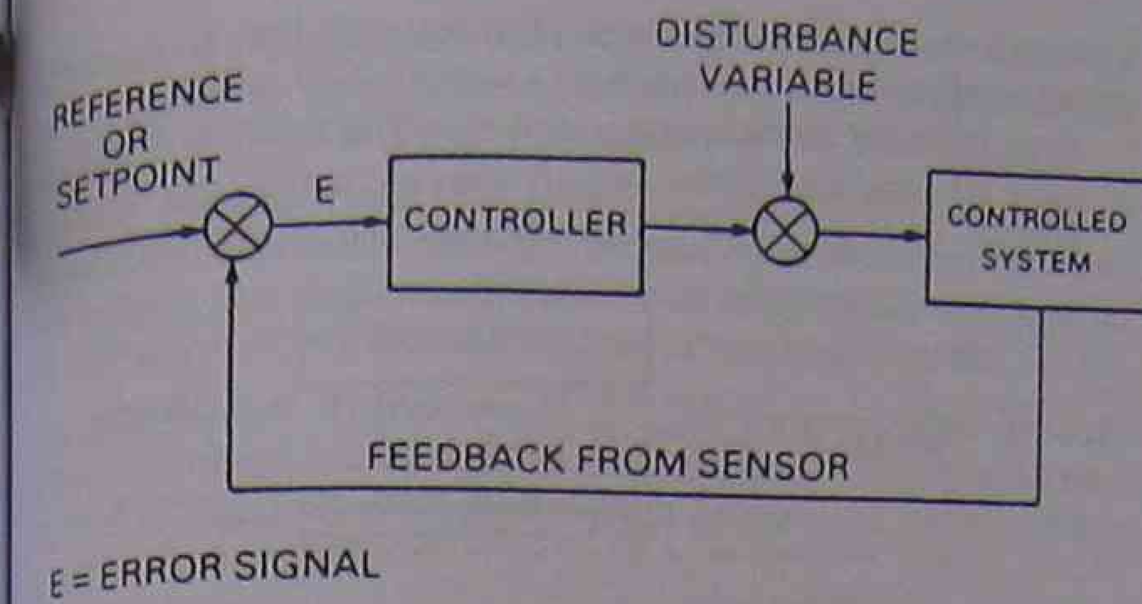
The closed-loop system is characterised by a feedback signal, derived from a sensor in the controlled system. This signal monitors the actual behaviour of the system, and is compared with (or subtracted from) the reference signal. The magnitude and polarity of the resulting error signal, E, are directly related to the difference between required and actual values of the controlled variable — which may be the speed of a motor, temperature of a furnace, level of liquid in a tank, and so on. The error signal is amplified by the controller, and the controller output makes a correction to the controlled system, reducing the error signal.

As the error signal reduces, it eventually reaches a value at



1 *Closed loop control system*

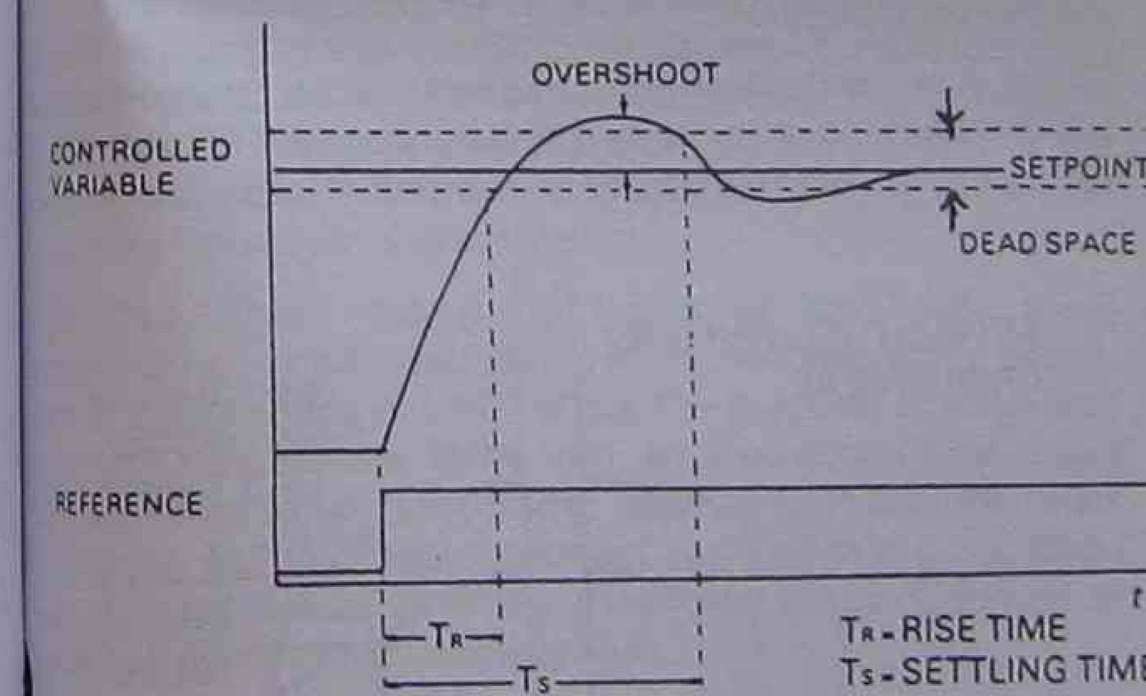
which the control system gain is insufficient to make any further correction to the controlled system, resulting in a band either side of the set point, known as 'dead space' in which no effective regulation occurs. Increasing the control



2 *Closed loop control system with disturbance variable*

system gain reduces the width of the dead space, but increases the tendency of the overall system to become unstable, ie to break into oscillation. The time-constant or rate of response of the system introduces a delay between input and output. If the delay is such that the output of the system is in antiphase with the input, the feedback will add to the error signal rather than reducing it. If the system gain is sufficiently high, oscillation instability will result. Obviously this is undesirable in a control system, and the gain must therefore be limited in practice.

A development of the basic closed-loop system is shown in Fig.2, where an external disturbance variable is introduced between controller and controlled system. In speed control systems, the disturbance variable might represent load fluctuation; in temperature control, the heat loss resulting



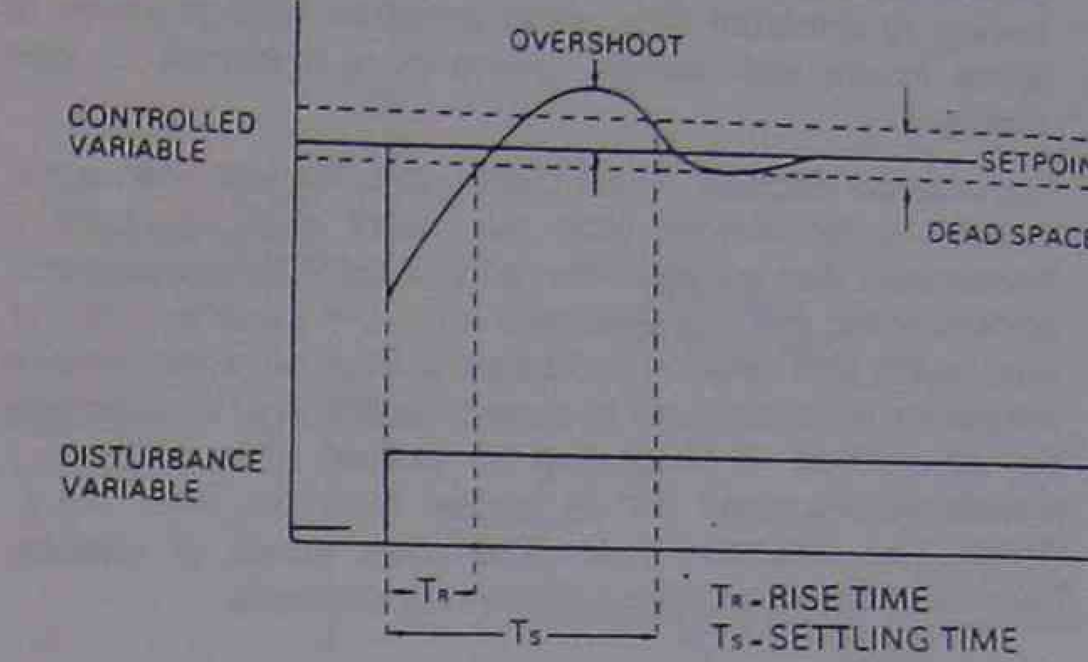
3 *Response of a closed-loop system to a step change in reference*

from opening the furnace door; in liquid level control, variations in the rate at which liquid is drawn from the tank. Therefore the controlled system is affected directly by the disturbance variable, causing a change in the feedback signal which results in compensation by the control system.

The response of a closed-loop system to step-changes in reference and in disturbance variable are illustrated in Figs.3 and 4.

The system response shows a characteristic Rise Time, T_R, which is the time that elapses between the step-change in reference or disturbance variable and the initial entry of the controlled variable into the dead space.

Typically, an overshoot then occurs, and when the controlled variable re-enters the dead space to remain within it, the system Settling Time, T_S, is considered to have elapsed.-



4 *Response of a closed-loop system to a step change in disturbance variable*

If no overshoot occurs, the system is said to be overdamped, Fig.5a, and will tend to respond in a sluggish manner, whilst multiple overshoots are characteristic of an underdamped system, Fig.5b, which is liable to instability. The ideal is the critically-damped response illustrated in Fig.5c.

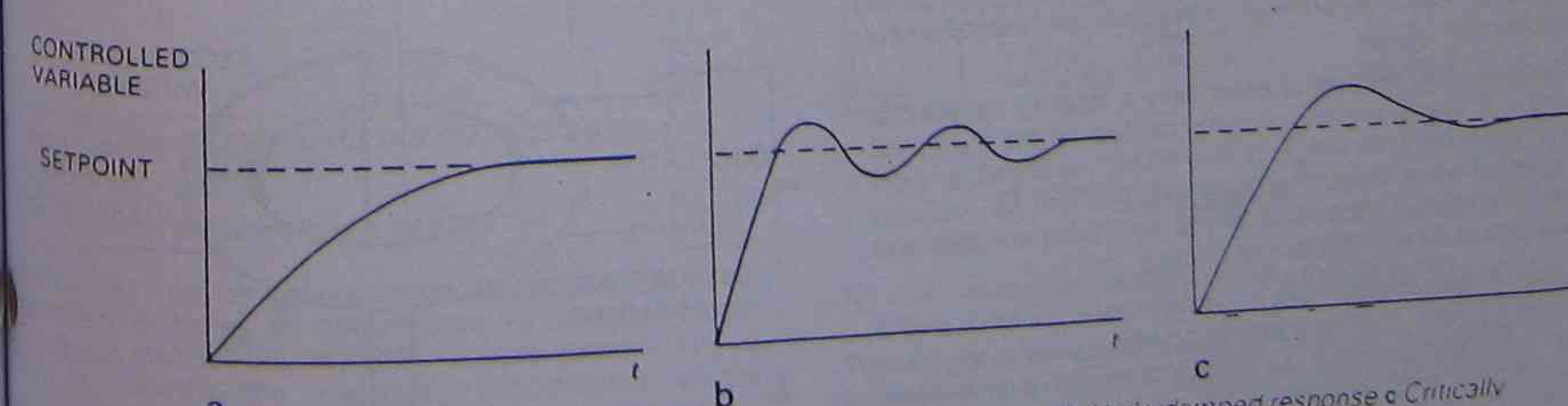
Feedback Sources

In the closed-loop control of motors by means of thyristor drives, the feedback to the control loop is from a transducer or sensor which converts a non-electrical quantity (eg speed) into an electrical quantity (eg a voltage), or converts an electrical quantity to a form which is compatible with the regulator input circuits (eg current to voltage). The following are examples of feedback sources which are commonly encountered.

Tachogenerator. This is a small permanent-magnet dc generator, usually driven directly by the motor shaft via a coupling attached to a stub shaft at the non-drive end. The output is a dc voltage which is proportional to the speed of the motor, and whose polarity is determined by the direction of rotation.

AC Tachogenerator. Mounted directly to the motor in the same way as a dc tachogenerator, the output is an alternating voltage whose magnitude and frequency are proportional to speed. Usually the output is rectified to give a dc signal. The ac tachogenerator is unsuitable for reversing applications, since its output is unipolar. Operation at low speeds is often unsatisfactory owing to the high ripple content of the signal.

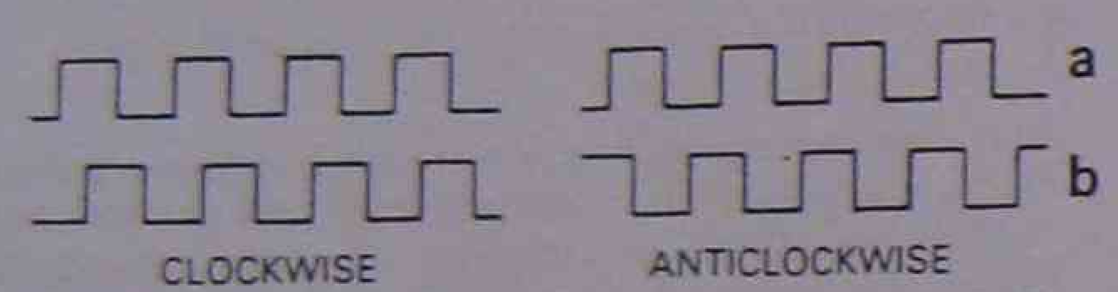
DC Voltage Transformer (DCVT). This device is used to provide an electrically-isolated armature voltage feedback



5 *Effect of system damping on response to a step input:* **a** *Overdamped respose* **b** *Underdamped response* **c** *Critically damped response*

signal as an alternative to non-isolated potential dividers. An internal oscillator modulates the primary voltage (motor armature voltage) impressing upon it an ac component which enables normal transformer action to take place. The secondary voltage, rectified and smoothed, becomes the feedback signal. Bipolar DCVTs are available for reversing applications, but armature voltage feedback is only suitable where accuracy of speed control is not critical, because (owing to armature resistance) armature voltage varies to some extent with current, giving poor response to load changes.

Incremental Encoder (Pulse Generator). The encoder, again usually driven directly from the motor shaft, contains a transparent disc marked with radial lines. A light source and photoelectric cell are arranged near the periphery of the disc, such that rotation produces a train of pulses whose frequency is proportional to speed. Direction of rotation can be determined if necessary by pulses from a second photocell, displaced 90° in phase from the first, Fig.6. Quadrature detection logic determines sense of rotation from the phase relationship of the two channels.



6 *Pulse trains corresponding to bidirectional rotation of an encoder.*

The encoder has the advantage that its output is a pulse train whose frequency is not affected by temperature or attenuation of long cable runs as is the analogue signal of a tachogenerator; therefore it is potentially capable of contributing to extremely accurate digital speed control.

Encoders are available with an additional output known as a marker pulse, which identifies a specific orientation of the disc. By counting pulses from the datum provided by the marker pulse, the angle of rotation can be accurately measured. This feature is used in angular positioning systems, eg machine tool spindle orientation.

Absolute Encoder. The absolute encoder works in the same way as the incremental encoder described above, except that multiple channels are used to give a discrete code for every position increment. By decoding the output the angular position can be deduced directly, without the need to count from a datum or marker.

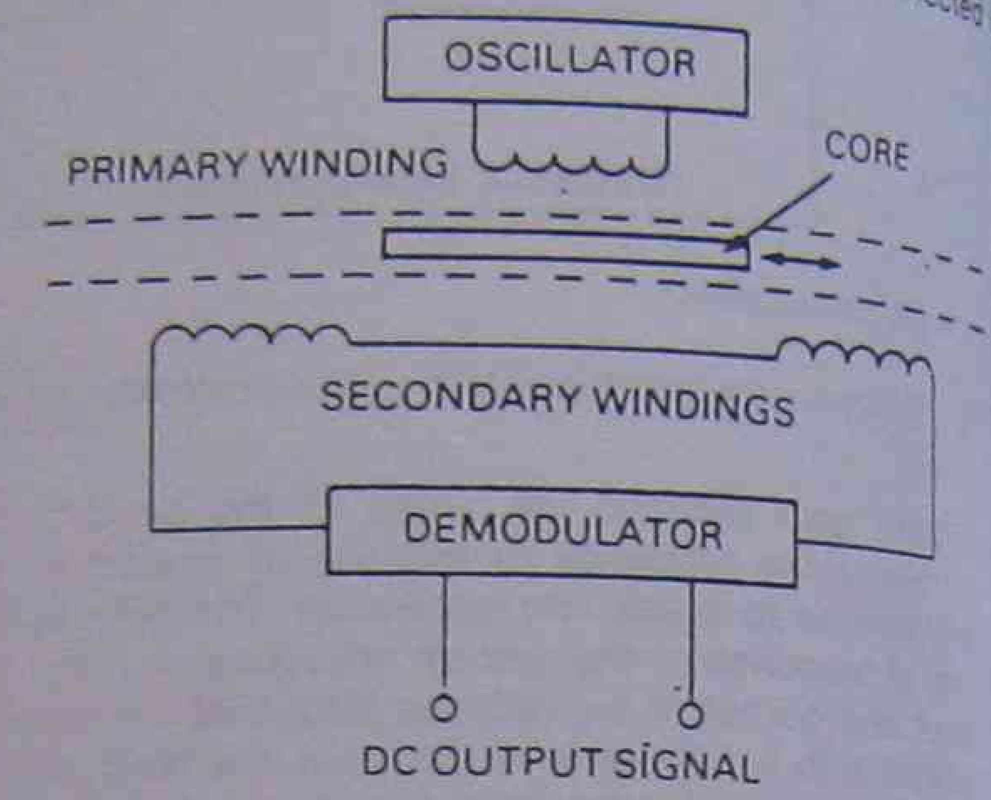
Absolute encoders are used in precision positioning systems, and are encountered more usually in conjunction with servo drives than with variable speed drives.

For the determination of linear position, linear encoders are available in both incremental and absolute configuration, having a grating in the form of a strip marked with transverse lines, which is free to move on its long axis relative to an optical sensor. They are used in precision and measurement positioning.

Resolver. The resolver is essentially a rotating transformer having a single primary winding, carried on the rotor, and two secondary windings in the stator, arranged at right angles to each other. The rotor position can be deduced from the relative magnitude of the secondary voltages and their phase relationship to the primary.

Linear Potentiometer. This is simply a resistive track with a sliding contact. The linear potentiometer is used in positioning applications which do not require the consistency, accuracy or long mechanical life of the more costly linear encoder.

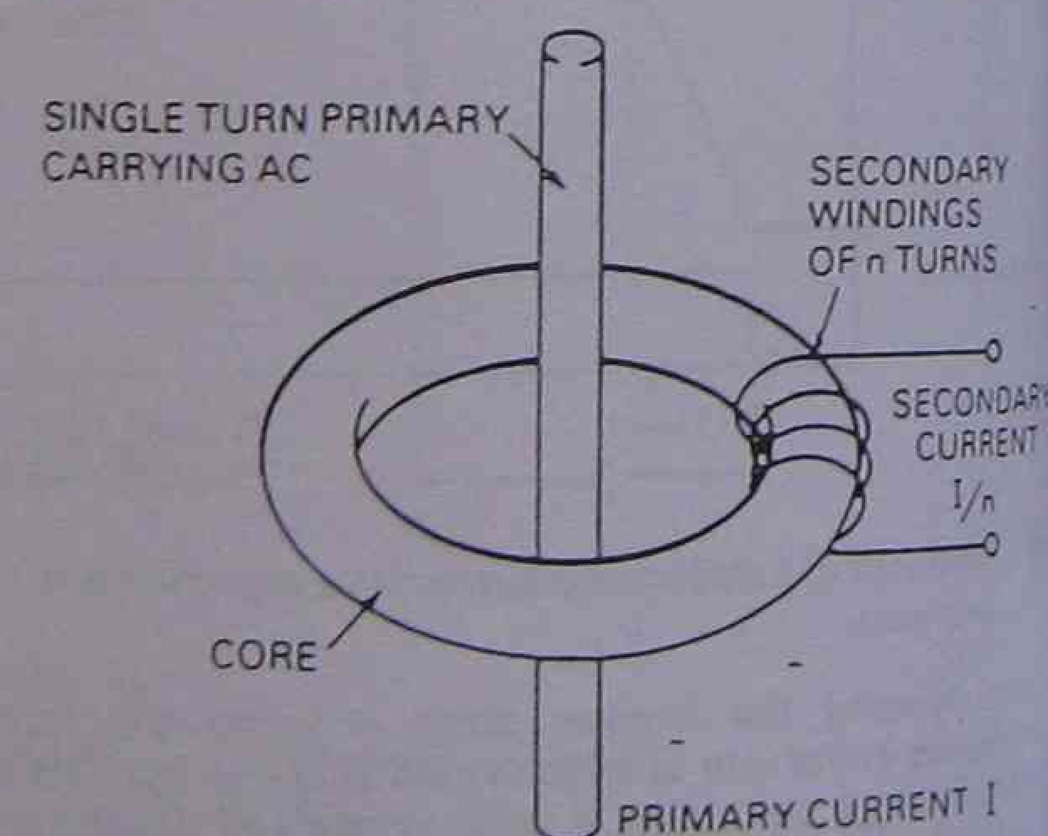
Linear Variable Differential Transformer (LVDT). The LVDT is a linear position transducer, having three windings arranged side by side on a tubular former. The core is a cylindrical slug of iron or ferrite which moves within the former, as shown in Fig.7. The secondary windings are connected in



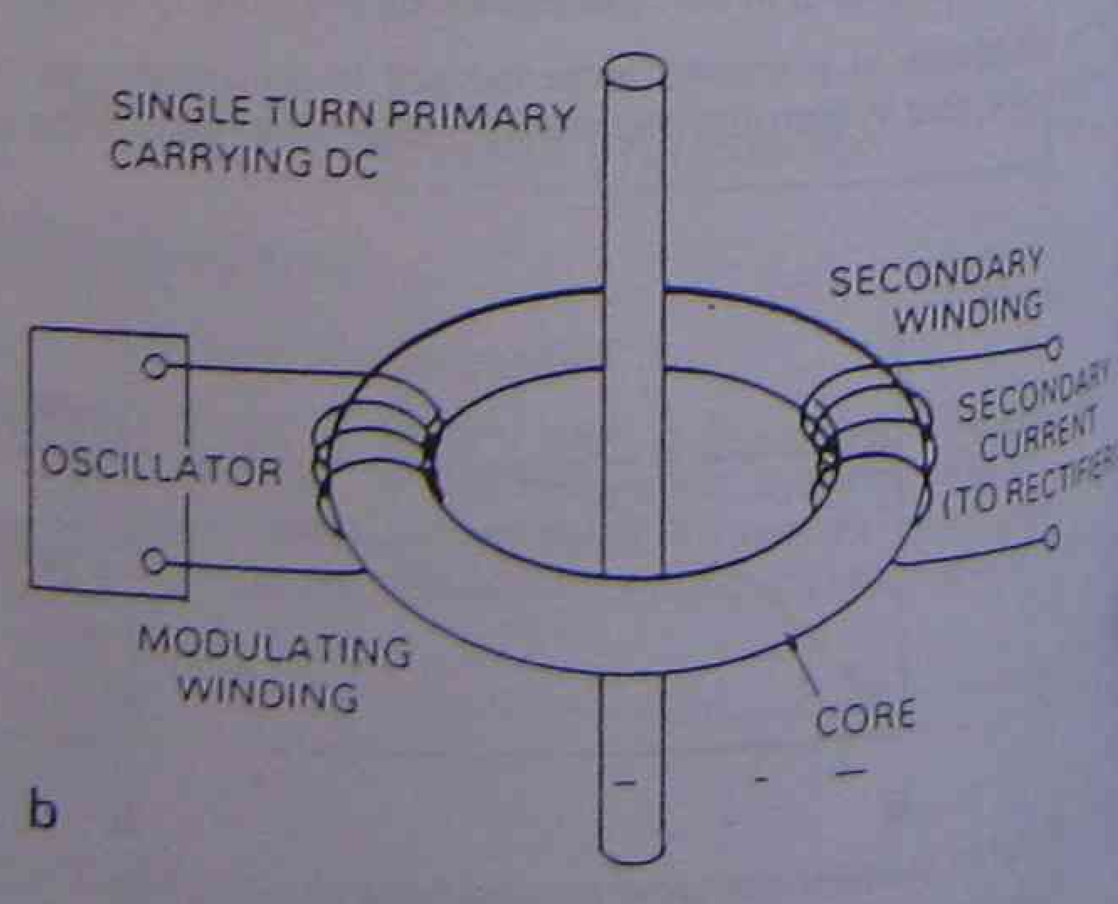
7 *Linear variable differential transformer (LVDT)*

opposition to one another, such that when the core is in the central position, the primary flux is coupled equally into both secondaries, and the output is zero. If the core is moved towards one end of the LVDT, the coupling is unequal and the secondary voltages have a resultant which is proportional to the distance the core has moved from the central (null) position.

Shunt. A shunt is a low resistance connected in series with a current-carrying circuit. In accordance with Ohm's law, a voltage is developed across the shunt whose magnitude is



a



b

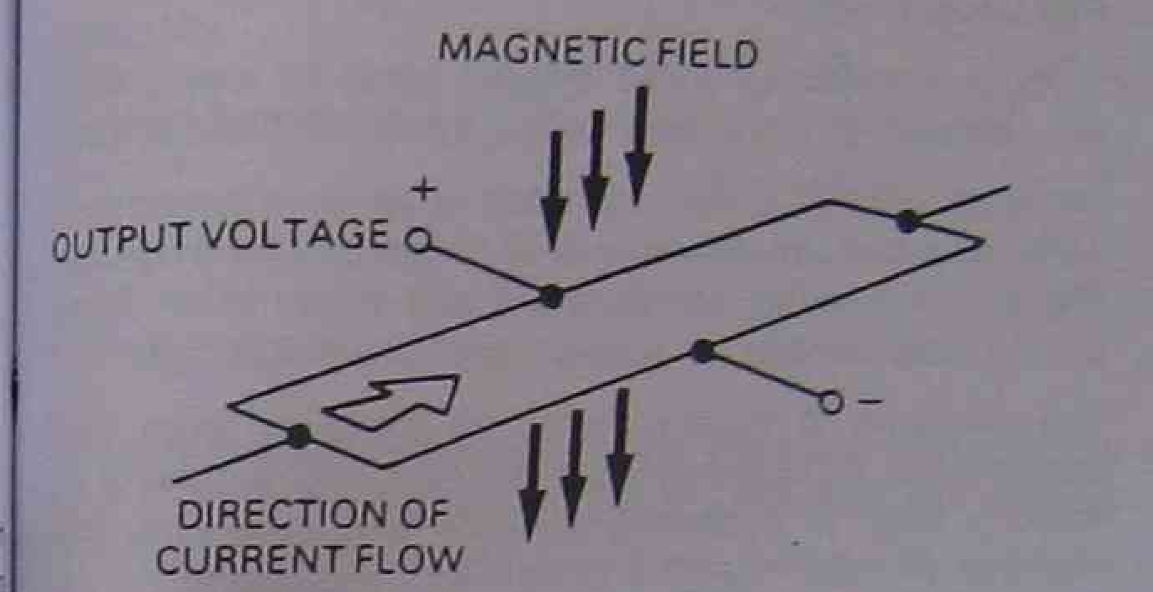
8 *Current transformers* **a** *(AC)CT* **b** *DCCT*

proportional to the current flowing, and whose polarity depends on the direction of current flow. This voltage can be used as a feedback signal in current control loops.

Current Transformers (CT and DCCT). A CT is usually a toroidal transformer, used for measuring alternating current. The output is a current signal whose magnitude is equal to the primary current divided by the turns ratio, Fig. 8a.

The DC Current Transformer (DCCT) incorporates an additional winding, connected to an oscillator, which modulates the flux in the core produced by the primary, in which direct current flows, Fig.8b.

Hall-Effect Current Transducer. The Hall Effect, in which a voltage is developed across a current-carrying conductor

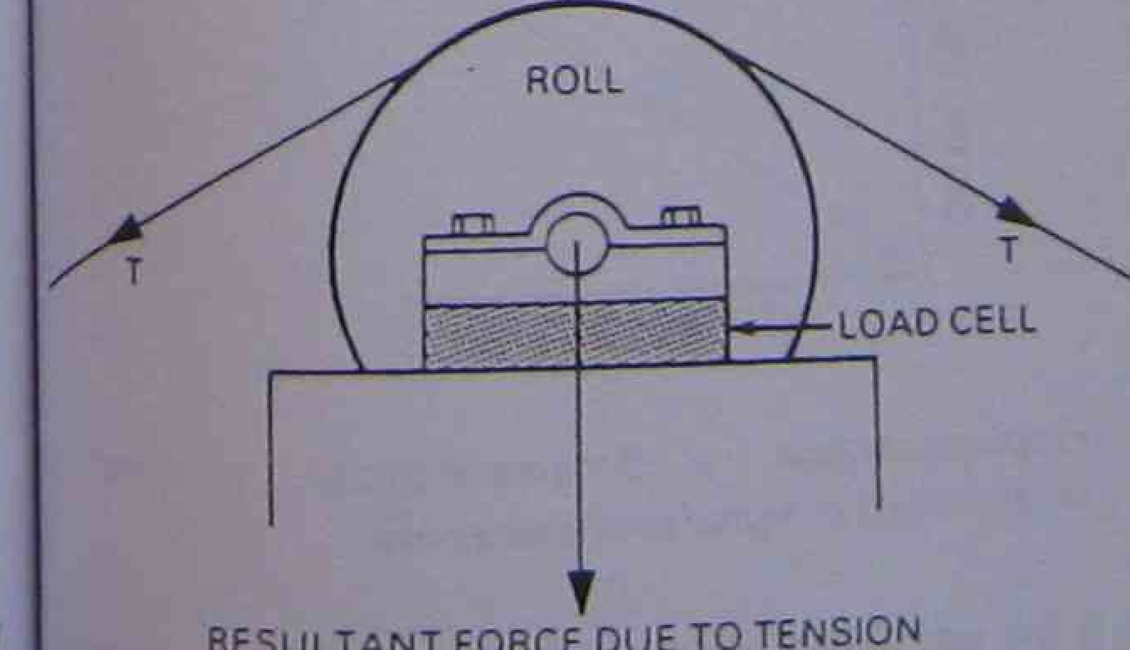


9 *The Hall effect*

placed in a magnetic field, is illustrated in Fig.9. If a Hall Effect transducer, fed by a constant-current source, is placed in a gap in a magnetic core having a current-carrying winding, an output voltage is produced which is proportional to the flux in the core and therefore to the current in the winding (provided that the core is operating in the linear part of its magnetisation characteristic).

Load Cell. There are many types of load cell, some incorporating strain gauges, others incorporating piezo-electric transducers or LVDTs, but the purpose of each is to convert a mechanical force into an electrical signal. Load cells are often used in weighing, especially of bulk materials in hoppers, but the most important application in conjunction with thyristor drives is in the measurement and control of tension in continuous process lines.

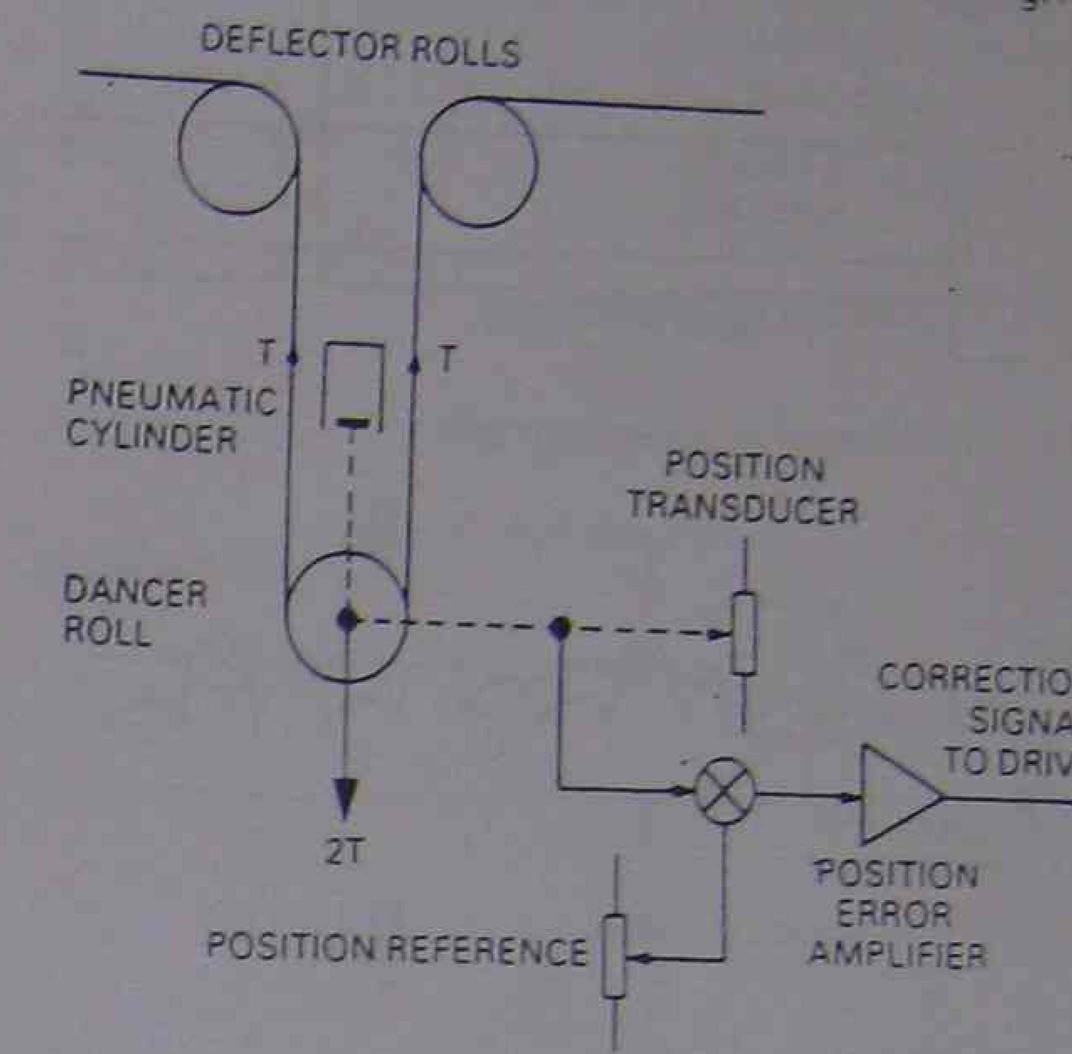
A typical arrangement is shown in Fig.10, in which the material passes over a roll supported on load cells (often



10 *Tension measurement by load cell*

incorporated into the bearing pillow blocks); two are used, connected in series to compensate for uneven tension distribution across the material). Simple trigonometry is used to calculate the magnitude and direction of the resultant force on the load cell due to tension, and in most cases it is necessary to compensate for the tare weight of the roll and its bearings.

Dancer. The dancer is itself not a feedback transducer, but is worth mentioning here because it is an example of indirect control — using position control as a means of controlling tension. A typical dancer arrangement is shown in Fig.11.

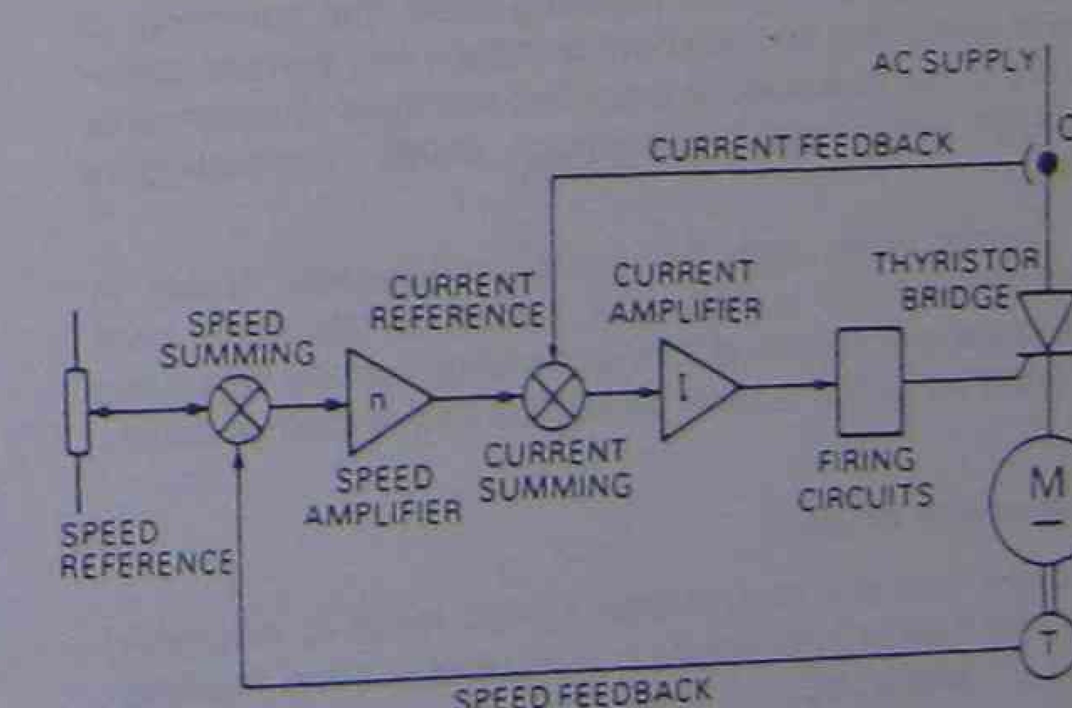


11 *Dancer tension control*

the material passing over a deflector roll, around the dancer roll which is free to move vertically, and returning to the original passline via a second deflector roll. The dancer is loaded (usually by a pneumatic cylinder) with a force which determines the tension in the material. Attached to the dancer is a position feedback transducer (often a linear potentiometer) and the position of the dancer is controlled via the line drives by means of a position loop. If the tension alters, the dancer rises or falls, causing a position error which is used to restore tension, and therefore the position of the dancer.

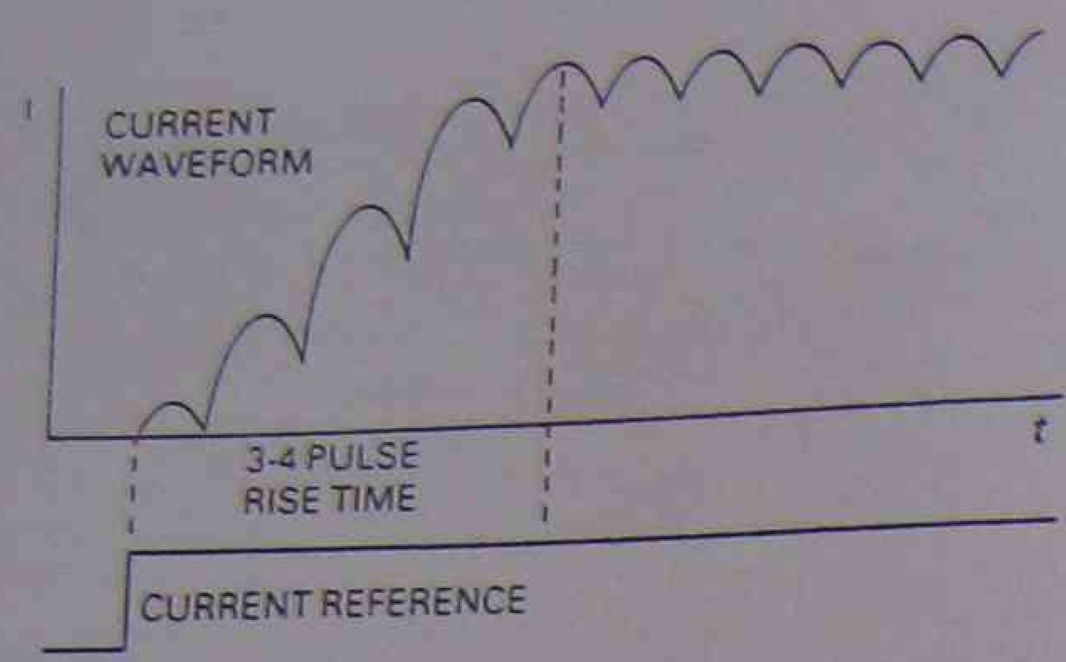
Cascaded Closed-Loop Control

Whilst the function of a variable speed drive in a closed-loop control system can be considered as the block labelled 'CONTROLLER' in Figs. 1 and 2, this is of necessity an oversimplification, and there are often two or more closed loops within the control system. For example, a drive in speed control, as illustrated by Fig.12, has not only a speed loop but also an inner current loop.

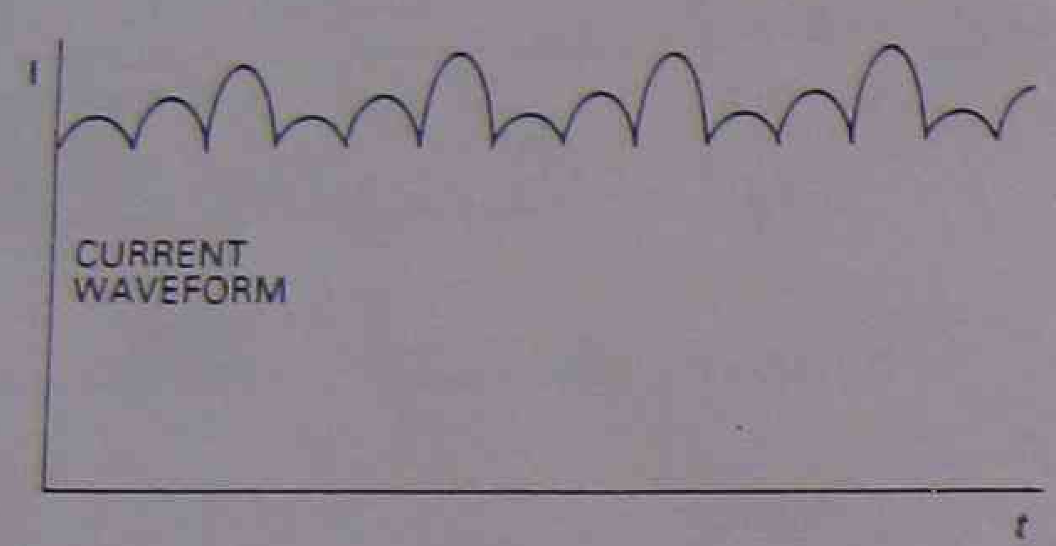


12 *Cascaded closed loop control of a thyristor drive*

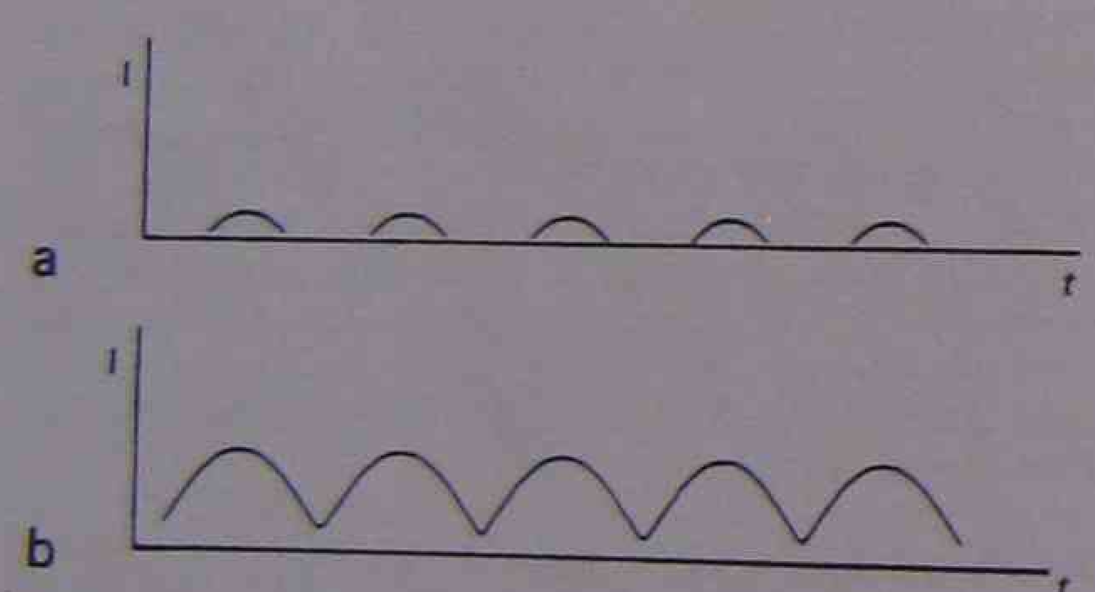
The speed error signal, resulting from the summing of reference and feedback, is amplified by the speed amplifier, and becomes the reference to the current loop. It is normal for limits to be imposed upon the magnitude of the current



13 *Optimisation of current loop gain*



14 *Current loop gain too high*



15 *Current waveforms* **a** *Discontinuous* **b** *Continuous current*

reference to prevent excessive current being delivered to the motor.

The current error signal, resulting from the summing of current reference with current feedback (via current transformers in this example), is amplified and used to advance or retard the firing angle of the bridge, thereby controlling its output.

The current loop can be made considerably faster in response than the speed loop, (which is limited by both mechanical and electrical time constants) thereby improving the response of the system to fluctuations in load or supply voltage.

Optimisation of gains

Excessive gain in a closed-loop system leads to instability, whilst insufficient gain results in poor response and 'hunting', as already explained.

In a drive having cascaded speed and current feedback loops, the inner current loop is the more critical and must be optimised before the speed loop is adjusted if the best performance is to be obtained. The actual gain required in the current loop depends on the electrical time-constant (L/R) of the motor armature circuit, and therefore varies from motor to motor. Customarily, the gain is adjusted by disconnecting the motor field supply and mechanically locking the shaft to prevent rotation, then applying a step input to the current loop whilst observing the current waveform by means of an oscilloscope. The current should rise to its final value after three to five pulses, Fig.13, although if an uneven waveform is seen, as in Fig.14, the gain is too high and should be reduced somewhat. The procedure is easier when dealing with modern, digital drives, since the gain is a precise digital quantity which can be calculated once the value of current reference required for continuous conduction has been ascertained. This is usually achieved by adjusting current limit with the motor stalled as above, until the desired waveform is obtained, Fig.15.

PID Loop Control

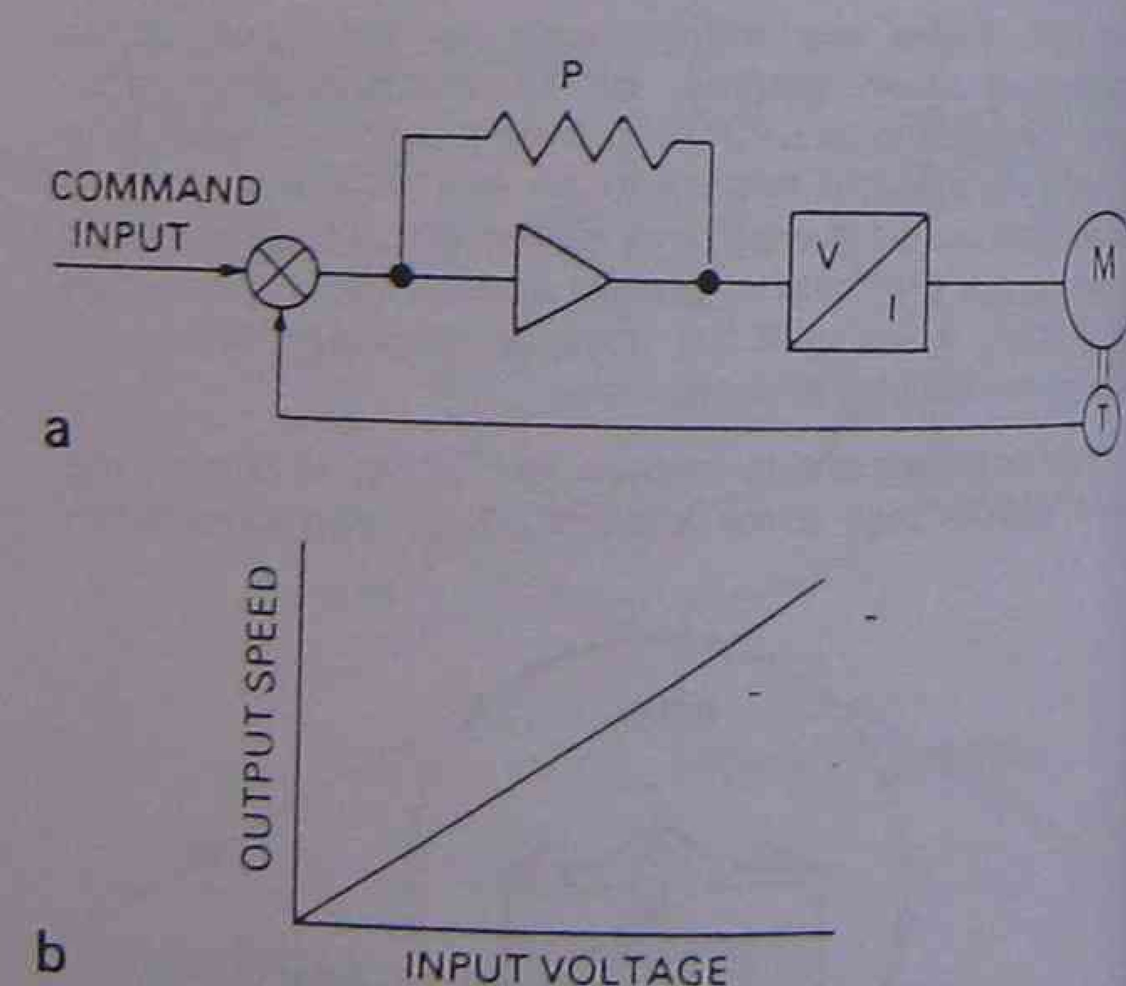
Two, or sometimes three distinct types of gain are to be encountered in the speed loop of variable speed drives.

PID loop control is not restricted to variable speed drive or servodrive control. Any one of all of the functions can also be found in hydraulic, temperature and many other forms of closed loop control.

The principle is illustrated by an example from variable speed drive technology to show how PID functions in the velocity loop of a servodrive, and how it can be used to improve and optimise the control of the speed of the motor. PID is a series of signal gains, each making a different adjustment to the feedback.

Proportional

Proportional gain is the factor by which the speed error is multiplied to produce the proportional speed correction term. Increasing proportional gain gives faster transient response and increased system damping, but leads to instability if carried to excess.



16 *Proportional gain:* **a** *Schematic circuit;* **b** *Linear relationships of signal to output speed.*

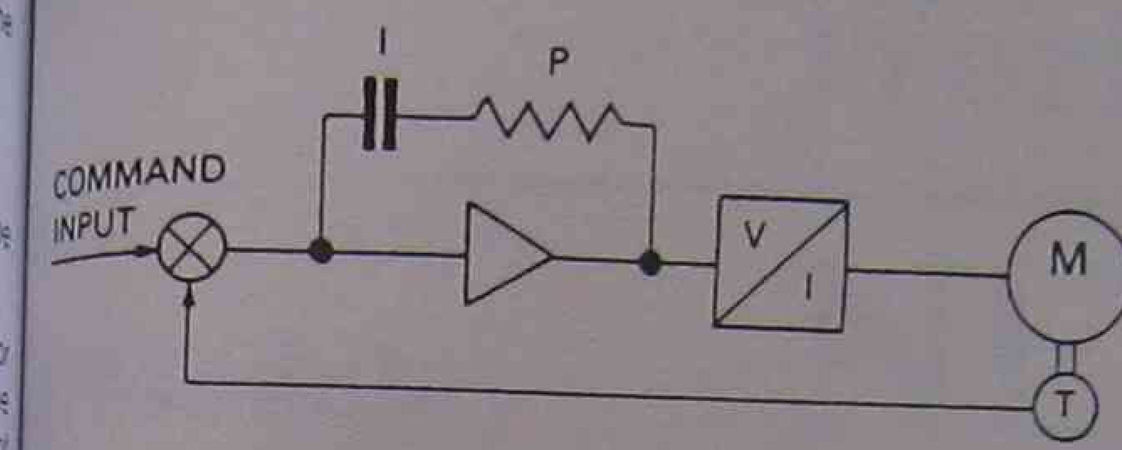
This is the simplest of the three functions. The output from the system, ie the speed, is made proportional to the external command signal input into the system. The electrical schematic for this function is shown in Fig.16a.

The relationship between the input signal and the output signal is linear, as shown in Fig.16b.

Integral

Integral gain is necessary to eliminate the speed error which would otherwise exist due to the fact that the proportional gain is finite. By integrating the speed error with respect to time, a correction term is produced which compensates for the initial speed error during steady-state operation. Increasing integral gain results in more rapid recovery after a transient disturbance (eg sudden load change) but again, instability is the result of excessive gain.

This function is incorporated to give the system good position-stiffness. In other words, when the drive is at standstill, the integral function provides the control necessary to prevent rotation being induced by outside loads. This is achieved by incorporating a capacitor in the feedback of the velocity loop amplifier, Fig.17.



17 *Integral gain schematic circuit.*

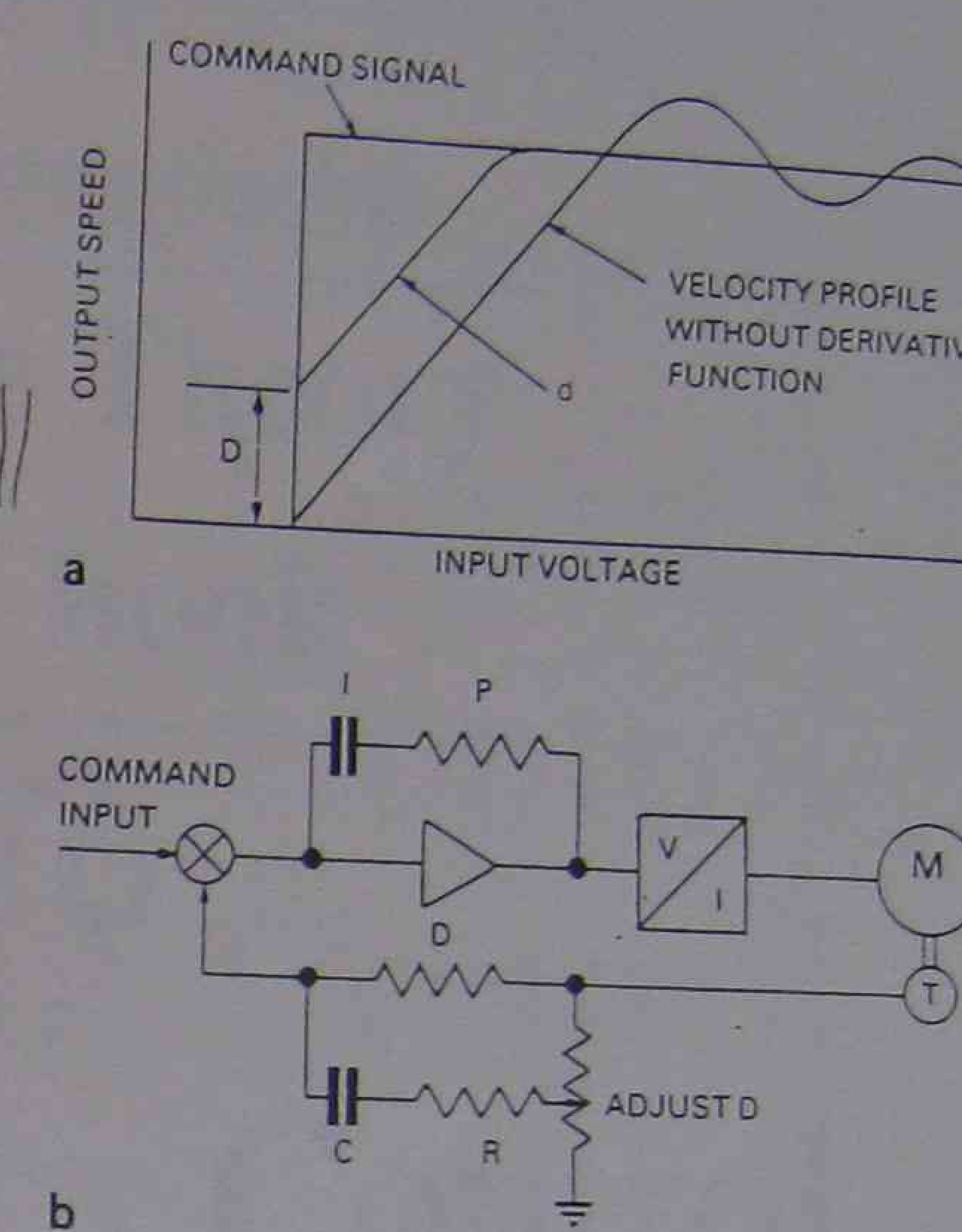
At low speeds the reactance of the integrator capacitor is high. It therefore has more effect at zero and low speeds than at high speeds. i.e. almost open loop gain of the OP-AMP.

Derivative

Derivative gain, also known as forcing, is sometimes encountered. The error signal is differentiated to obtain its rate of change, which is then multiplied by the derivative gain to give a term which corrects for sudden transient disturbances. However, modern drives respond so rapidly that derivative gain is seldom necessary, and in addition, it has the undesirable effect of amplifying noise and ripple in the feedback signal, often contributing to instability.

The derivative function of the feedback loop helps to prevent overshoot when reaching the required speed, including zero speed. This is achieved by introducing as kind of feed-forward, which "predicts" the approach of the desired speed. (velocity feedback.)

Profile D, Fig.18a, is the sum of the derivative induced current plus the tacho feedback induced current.



18 *Derivative gain:* **a** *Effect on control stability;* **b** *Schematic circuit.*

The electrical schematic for this function is shown in Fig.18b. In practice, the derivative function is adjustable so that the system can be optimized and incorporates the filter circuit as shown.

A simpler way to understand the derivative function is to imagine the temperature control of an electric oven. If the control of the oven were left until the desired temperature had been reached, then the temperature would rise above the set point. If however a derivative offset were introduced, then the control can be turned off before the set point is reached and the temperature will rise only to the required level.

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Module **NE76**

A.C. Motor Control

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Topic

Session No. 8

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Principles of vector control

The first part of a two-part article which discusses the steady-state and dynamic operating characteristics of vector-controlled induction motors compared with dc motors for variable speed applications.

By Dr Dal Y Ohm

The induction motor is the most widely used electrical machine in industrial applications, mainly for constant-speed operations directly from the powerline. Induction motors have many advantages over dc motors, such as a simple and rugged structure, low cost, and reliability. However, for variable speed applications, induction motors have only recently found favour. Instead, dc motors have dominated because of relatively simple dc voltage control. For example, permanent magnet (PM) dc motors have been widely used for servo drives, and separately excited dc motors have been used in wide-speed-range applications, like machine tool spindles.

The popularity of dc motors in variable speed applications is not because the motor itself is inherently superior to ac motors. It is simply because the voltage and current of an ac power source is difficult to control, and proper control methods had not been developed.

With proper ac power control, ie, vector control, the induction motor can be as good as, or better than dc motors in high-performance, variable speed applications. For example, the ac motor has higher peak torque capability. The rapid evolution of power semiconductor and microprocessor technology has made induction motor with proper drives economically feasible. They can be applied in many applications, including machine-tool spindles, steel mills, etc. They can now challenge servo drives and traction motors.

Usually, high-performance drives use feedback control for fast dynamic response and to obtain accurate position or velocity. The motor and drive set in a motion control system serves as a torque amplifier. High-performance motion control can only be achieved if the torque characteristics of the motor and drive are stable and linear. Before discussing vector control, we'll compare the operational characteristics of dc and induction motors.

Dc motor

Figure 1 is a schematic of a PM dc motor connected to a load. Upon injection of voltage, V, armature current, Ia, flows in the rotating armature coil through the commutator and brush assembly. Mutual reaction between the stator's permanent magnet flux (F) and the rotor's armature current, Ia produces torque. Here:

$$T(t) = Ke\, F\, Ia(t) \qquad (1)$$

Back EMF, Vb, is produced as a load to the electrical system as:

$$Vb = Ke\, F\, \omega \qquad (2)$$

Where:

Ke = Constant determined by the motor structure

ω = Angular speed of the motor

The relationship between V and Ia is:

$$V(t) = L\, dIa(t)/dt + RIa(t) + Vb(t) \qquad (3)$$

Where:

L = Motor inductance

R = Armature resistance

From Equation (1), torque is proportional to armature current if flux stays constant. When supply voltage, V, is controlled, Ia has a time delay of L/R, and its magnitude is dependent on speed (due to back EMF term). If Ia is directly controlled, these problems can be eliminated. Therefore, most high-performance drives use a current amplifier that is either a current source or PWM amplifier with high gain current feedback.

From Equation (2), Vb is proportional to motor speed. If this voltage approaches the supply voltage, current (and torque) can no longer be controlled because of the small potential difference available to the amplifier. Usually this is the operational speed limit of a PM dc drive; it is called "base speed".

Next, consider a separately excited dc motor whose flux is supplied from field current connected from the independent power source, instead of a permanent magnet. Here, flux is proportional to field current, If. Equation (1) can then be expressed, with a different constant:

$$T(t) = Kd\, If\, Ia(t) \qquad (4)$$

When field current is fixed at the highest designed value, its operational characteristics are identical with that of a PM motor, and speed is limited by supply voltage. But, if field current is allowed to change, higher speed operation is possible with a reduction in field current. For example, if field current (and flux F)

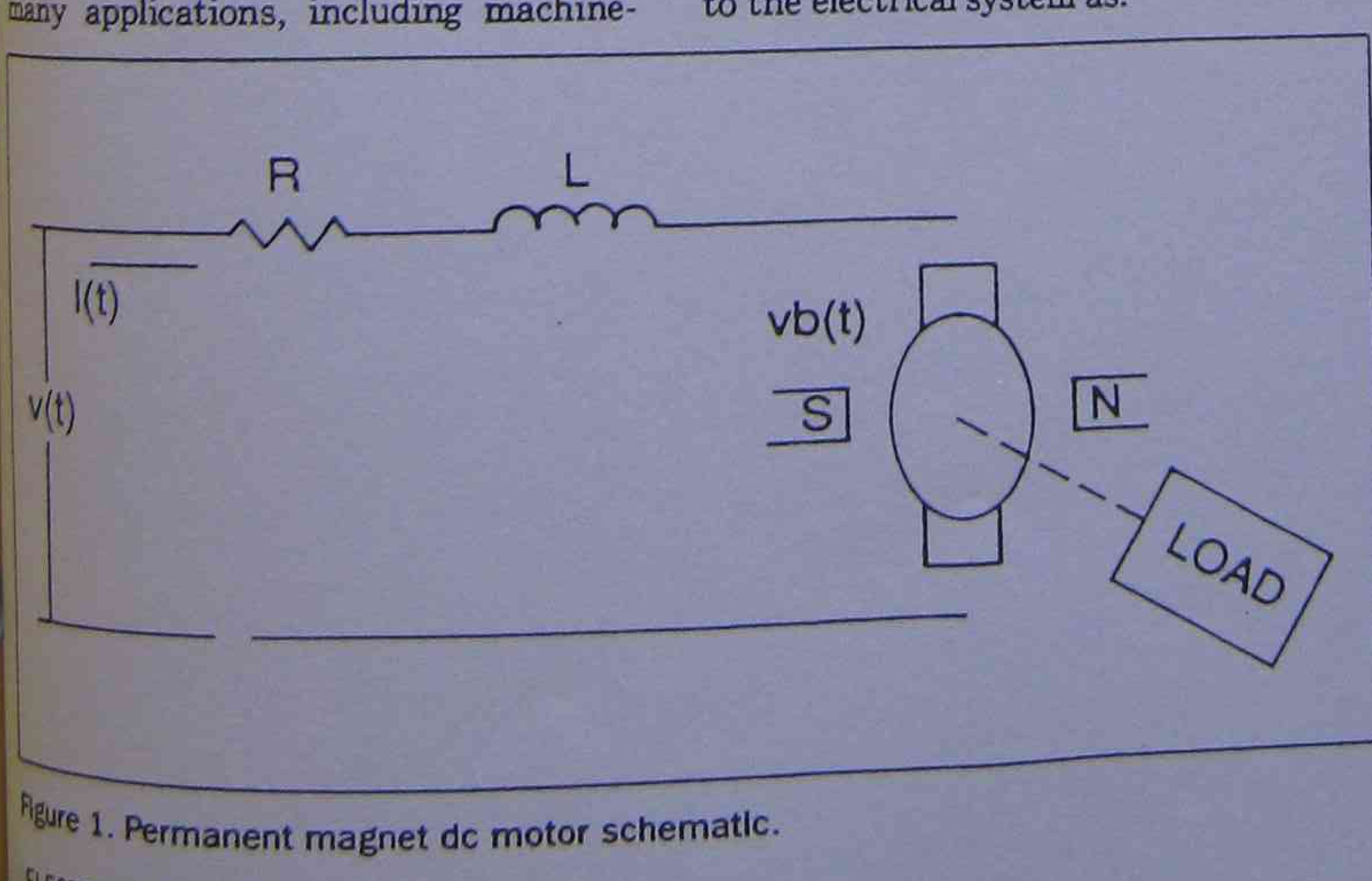

Figure 1. Permanent magnet dc motor schematic.

1

are cut in half, back EMF is also reduced by half (Equation (2)). Therefore, the motor can run up to twice the previous speed because of the additional voltage available for armature current control. Here, torque constant, Ke, is reduced in half.

One popular method is to control field current inversely proportional to the speed above base speed. Operational speed range above base speed is called the "constant power region" because available power $(T(t)^{*} \omega(t))$ is constant in this region. Figure 2 shows torque and power characteristics of a separately excited dc motor. Theoretically, speed can be increased indefinitely, but in practice speed is usually limited by the commutator and brush design, system frictions etc. A special motor must be designed for high-speed operation. Loads like machine tool spindles, rolling mills or traction applications require low torque at higher speed, and this field-weakening method has been widely used.

Dc motors are still widely used in industry, but their commutators require periodic maintenance; they also have low reliability and are dangerous in explosive environments. Another disadvantage of the dc motor is that its commutator or demagnetisation limits its peak torque. Besides these drawbacks, high-power dc motors are much more expensive than induction motors.

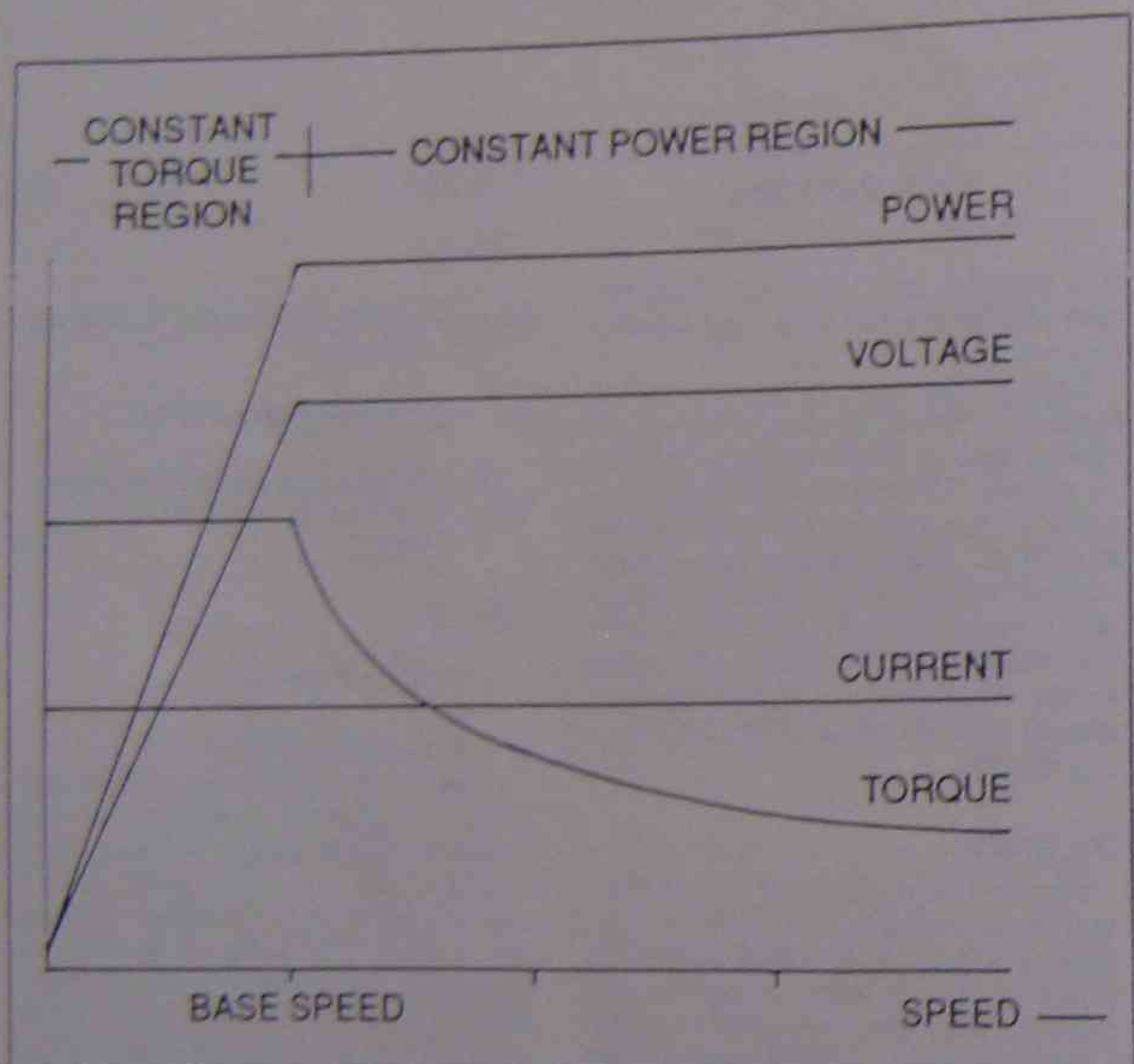

Figure 2. Separately excited dc motor characteristics.

Three-phase Induction motor

Three-phase induction motors have an ac winding on the stator so that spatially distributed magnetic flux rotating around the airgap is generated from the supplied ac voltage. For single-phase motors magnetic flux is not rotating but stationary and pulsating. Poor performance of single-phase induction motors, especially at low speed, precludes their use in most variable speed applications. From now on, only polyphase (three-phase in particular) motors will be discussed. If ac voltage (with constant frequency, f_o) is supplied to the stator winding of an induction motor, the stator generates rotating magnetic flux, revolving at a speed, *no*, (RPM) determined by:

$$no = \frac{60 f_o}{P} \ [\text{RPM}] \qquad (5)$$

where:

P = Number of motor pole pairs

This speed is called synchronous speed, and induction motor speed at no load is very close to this speed. Equation (5) also is a general equation relating electrical frequency to mechanical speed.

In cage-type polyphase induction motors, the rotor coil is simply several conductor bars connected at both ends, and transformer action induces rotor current from the stator. Mutual reaction between the rotating magnetic flux and rotor current produces torque. Consider that the rotor is turning at a speed *nr*, which is less than *no* during normal motoring operation. Frequency fs (slip frequency) of the rotor circuit is determined by:

$$f_o = f_r + f_s \qquad (6)$$

where:

f_r = Speed *nr* converted to frequency using Equation (5). We can define angular frequencies ω_o, ω_r and ω_s that correspond to f_o, f_r and f_s multiplied by 2π. Sometimes per-unit slip, s, may be used as defined by:

$$s = \frac{fs}{fo} = \frac{no - nr}{no} \qquad (7)$$

Steady-state characteristics of an induction motor are best described by its per-phase equivalent circuit shown in Figure 3. In this equivalent circuit, rotor

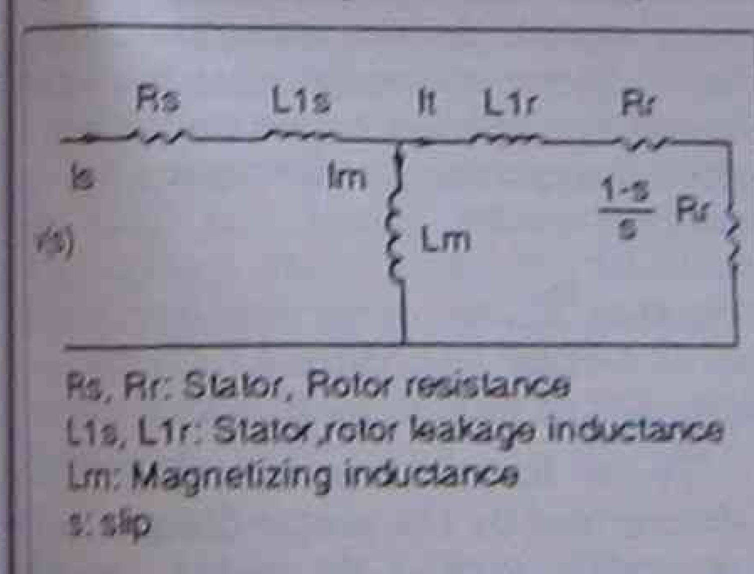

Figure 3. Steady-state equivalent circuit of induction motor.

circuit parameters are referred to as stator side via tranformation. Produced torque can be expressed by:

$$T = Ka \, lm(t) \, lt(t) \sin \alpha \qquad (8)$$

where:

α = Phase difference between lm(t) and 1q(t)

From Equation (7), maximum torque is produced when α is almost 90° (slip s is close to zero and the effect of leakage inductance is small). When the motor starts (s = 1), the phase difference between two current components is very small because leakage inductance is dominant in the rotor circuit. The angle is small, and large rotor current (inrush current) flows in the motor to produce the require torque.

Torque characteristics of an induction motor operating directly from the power line (constant voltage, constant frequency ac source) is shown as Curve A in Figure 4. Stable operation is between the synchronous speed to maximum torque point (marked as "M") and the rated operating point marked with an "R". As shown in the figure, the stable operating speed is about 90% to 100% of synchronous speed. If the power source frequency is allowed to change, this stable operating range can be moved up and down. Flux current lm(t) is roughly determined from:

$$lm(t) = \frac{V(t)}{(\omega_o Lm)} \qquad (9)$$

Constant flux can be maintained if the ratio of supply voltage per frequency (known as V/H) is preserved, and the

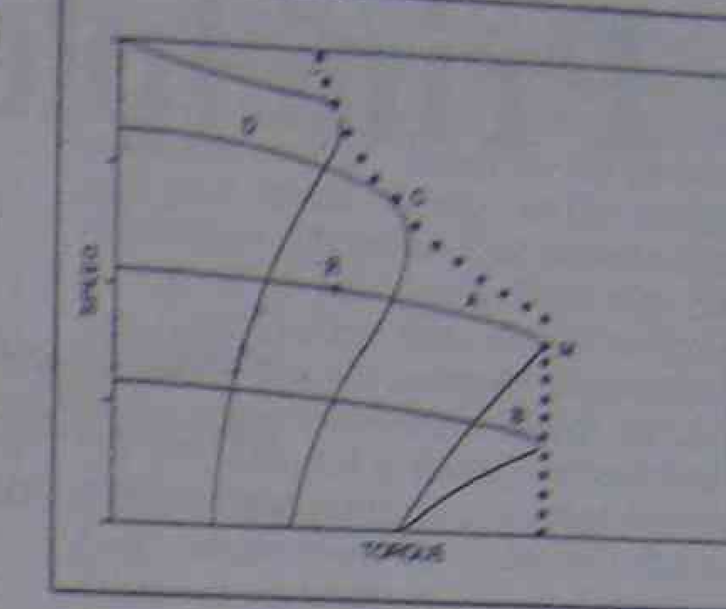

Figure 4. Torque-Speed curves of inverter-driven induction motor.

rated and maximum torque values stay the same. Curve B represents the torque characteristics when both voltage and frequency are reduced in half. "Inverter" is a variable frequency, variable voltage power supply that maintains the V/Hz ratio. If the supply frequency increases supply slowly to a desired value from a very low frequency, the induction motor always starts and runs at a stable operating speed. Here, inrush current does not flow because slip is always small. As in a separately excited dc motor, high-speed, constant-power operation is possible with increasing frequency while maintaining voltage at the rated voltage above base speed. Curve C and D in Figure 4 illustrates torque curve above base speed. Steady state torque characteristics of an inverter driven induction motor is very similar to Figure 2. With inverter operation, unstable operation might result if acceleration or deceleration is too fast, and motor speed cannot track the frequency within a stable slip value. Therefore, an inverter driven induction motor is used only in applications where fast dynamic performance is not important.

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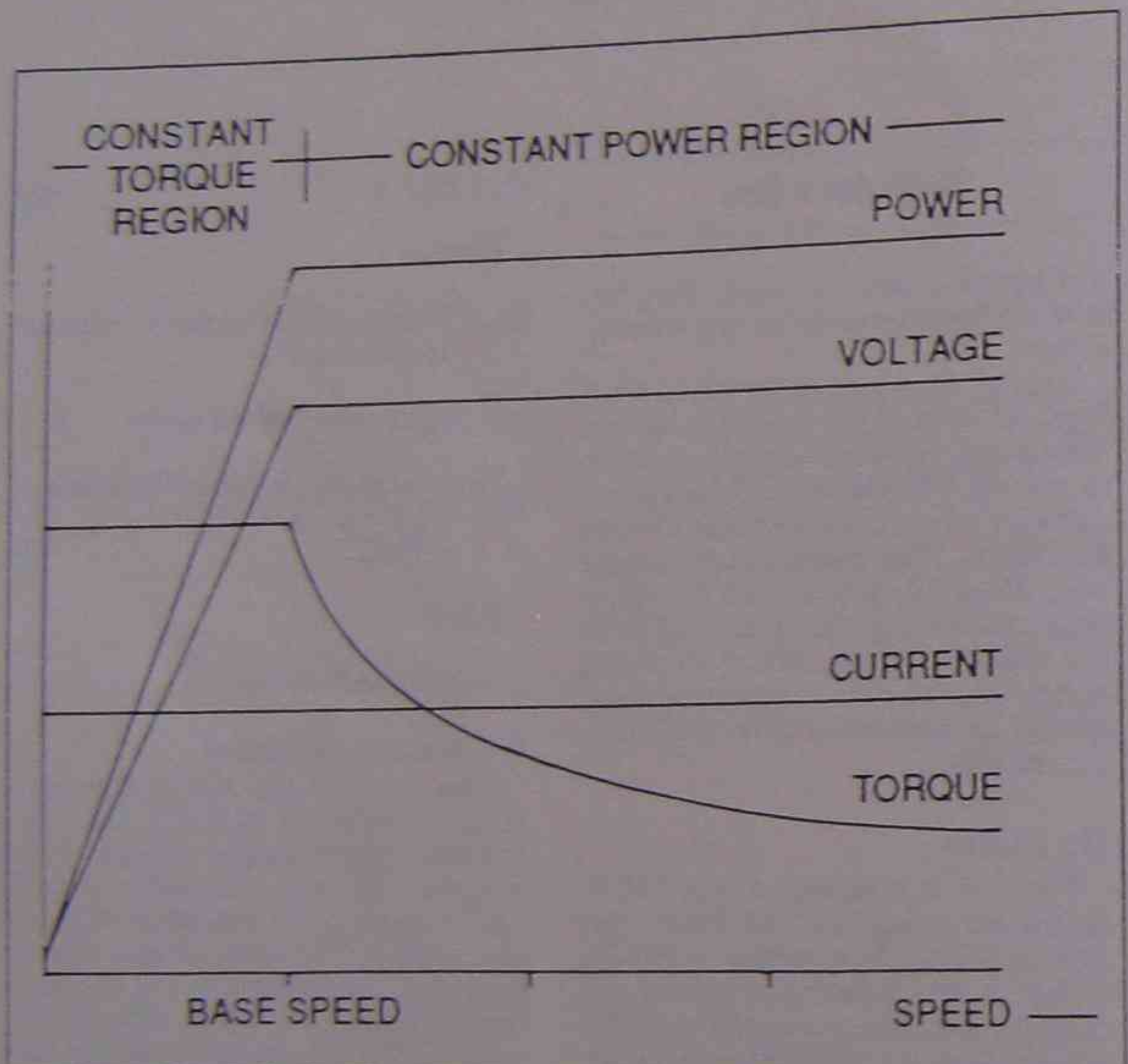

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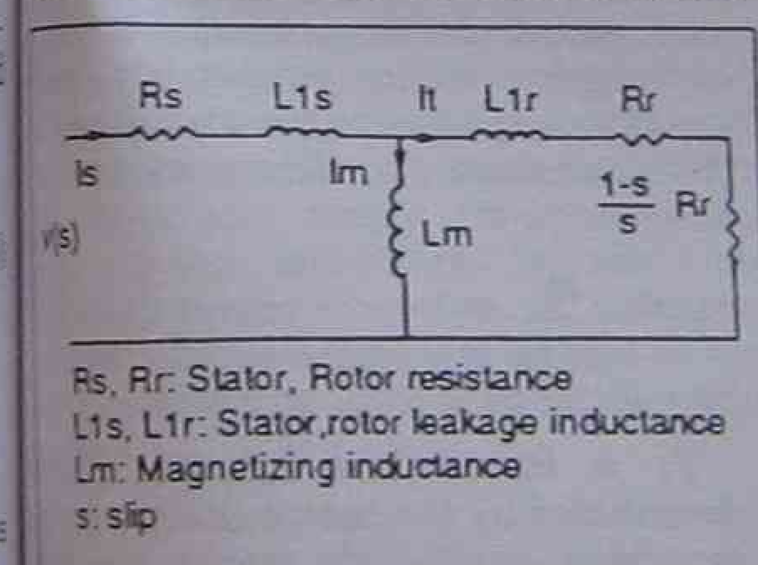

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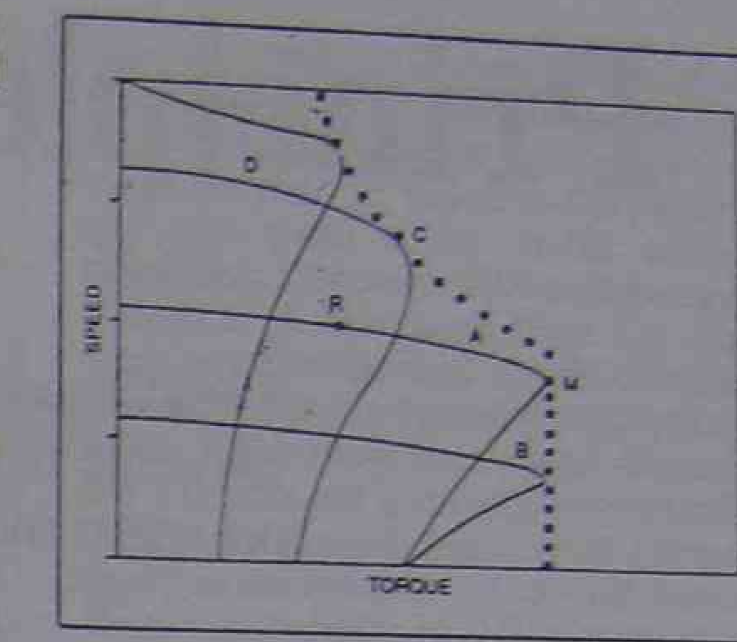


Figure 4. Torque-Speed curves of inverter-driven induction motor.

Principles of vector control

Part two of an article discussing steady-state and dynamic operating characteristics of vector controlled induction motors compared with dc motors for variable speed applications.

By Dr Dal Y Ohm

Vector control principles are based on the synthesis of ac induction motor current. Consider equations (4) and (8):

$T(t) = Kd\,lf\,la(t)$ (dc Motor) (4)
$T = Ka\,lm(t)\,lt(t)\sin\alpha$ (Induction)(8)

where:

α = Phase difference between lm(t) and lq(t)

For two different types of motors, torque equations are very similar except the term sin α. In the dc motor, this angular relationship is still present but is fixed to 90° by the motor design. If the angular position of brushes is allowed to vary, corresponding sinusoidal terms can be applicable in a dc motor, too. The principle of vector control is to synthesise stator current so that these two component currents maintain orthogonality and are controlled independently in all dynamic situations. Decoupling these two current components maximises the efficiency of the produced torque, and provides operational characteristics similar to the dc motor.

The difference between the dc motor and the induction motor is that in the induction motor the airgap flux rotates whereas it is stationary in the dc motor. Because rotor current, or rotor mmf, produced from this current travels past the rotor at slip speed, and slip frequency EMF is generated in the rotor circuit by the transformer action, the relative angular position of rotor mmf is stationary relative to the stator mmf.

If we use a synchronously rotating reference frame as a reference coordinate system, both the stator and rotor fluxes are stationary and their mutual interaction generates continuous torque.

A mathematical linear transformation is possible between a three phase stationary reference frame and a two phase rotating reference frame with d and q axes. In the rotating reference frame, variables like voltages or currents are purely real quantities (like dc quantities) without modulation. In this synchronous frame, we can define ld and lq, which correspond to rms values of lm(t) and lt(t) if leakage inductances are neglected. Thus, equation (8) can be written as:

$$T = K\,ld\,lq\sin\alpha \quad (10)$$

Here, an analogy to the dc motor is possible, where ld corresponds to field current, and lq corresponds to armature current. Because the two current components are orthogonal to each other (ld lags lq by 90°), stator current is the vector sum, ie:

$$I_s = \sqrt{ld^2 + lq^2} \quad (11)$$

These vector relationships are shown in Figure 5. In the induction motor, ld and slip are mutually dependent quantities. Once lq is set by the torque requirement, angular slip frequency ω_s must satisfy:

$$\omega_s = \frac{lq}{Tr\,ld} \quad (12)$$

where

Tr = Rotor time constant (Lr/Rr) determined by the motor design. As in a separately excited dc motor, the magnitude of magnetising current, ld, is fixed to a constant value below base speed and reduced inversely proportional to speed above base speed. Torque producing current lq is controlled to meet the torque requirement of the load.

To supply synthesised stator current to the motor, ld and lq must be transformed back to three phase sinusoidal phase currents. This inverse transformation requires information on the instantaneous angular position of the flux. Two methods can be considered in obtaining this airgap flux position. "Direct vector control" actually measures by using flux sensors. The "indirect method" estimates it by integrating rotor speed and generated slip. The indirect method is more popular because measurement of flux requires additional hardware and complex signal processing. From now on, discussions will be limited to the indirect method. Here, the instantaneous phase of stator current is calculated by:

$$\varphi = \int (\omega_r + \omega_s)\,dt + \theta \quad (13)$$

where: (14)

$\theta = \mathrm{Atan}\,(lqs/lds)$

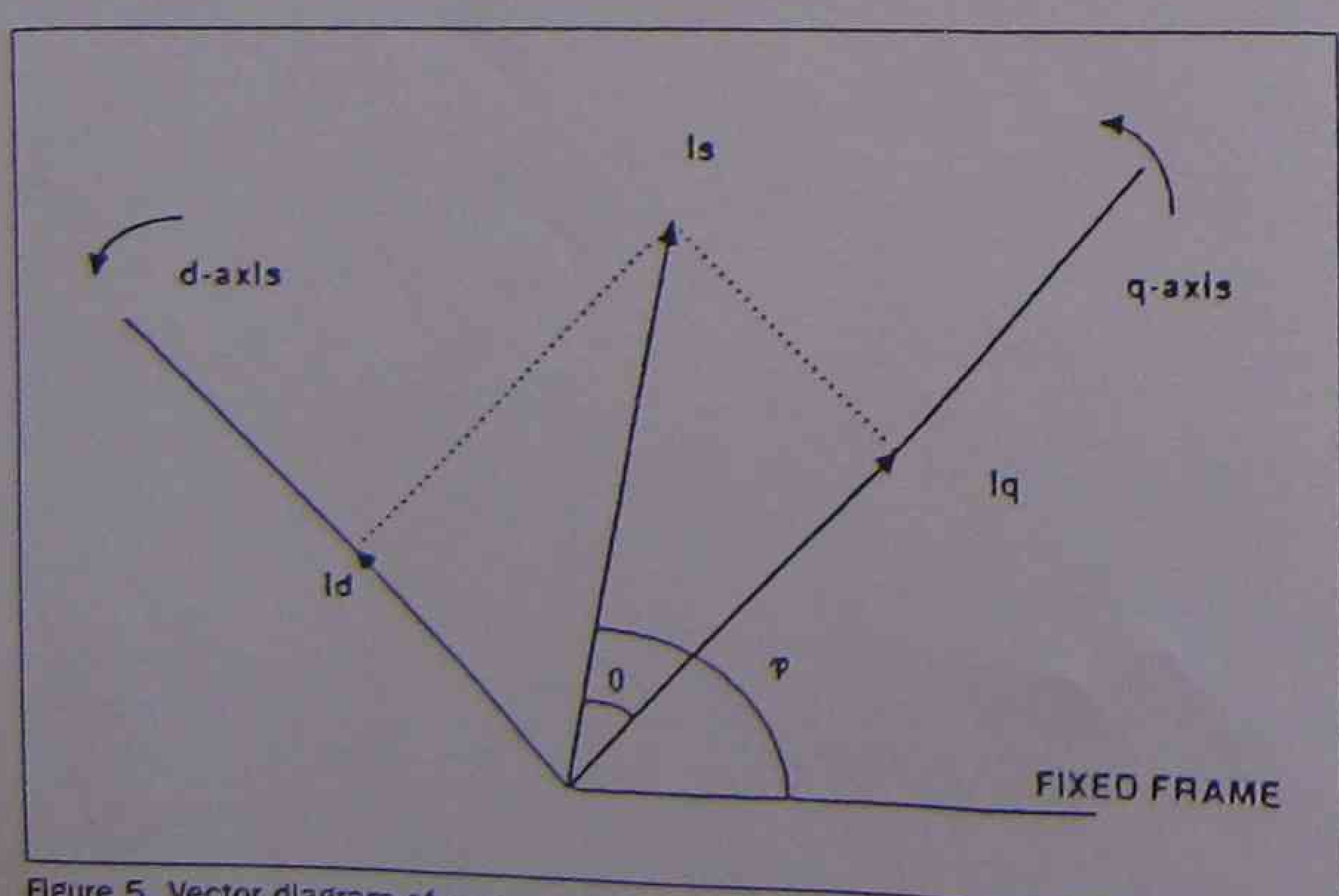


Figure 5. Vector diagram of sector current components

Note that stator current phase current is dependent upon slip, which is based on the knowledge of Tr in Equation (12). If the estimated Tr is not matched to the actual Tr, the two current components are not orthogonal. Therefore, the produced torque will be less than expected, resulting in poor efficiency and the inability to produce maximum torque. So, in vector control, correct tuning of parameter Tr is very important. With correctly tuned Tr, produced torque is:

$$T = Kv\,ld\,lq \quad (15)$$

where:

Kv = (3/2)P(Lm/Lr). Clearly, the above equation is analogous to the dc machine equation (equation (4)). Torque characteristic curves are depicted in Figure 6. Note that the stator current is slightly reduced as speed increases above base speed. This is due to the vector relationship in equation (11). The major difference between an inverter-driven motor and a vector-controlled motor is that vector control characteristics are not limited to steady-state, but applicable in a dynamic situation like the dc motor.

With vector control, you can obtain dynamic operating characteristics comparable to a dc motor. The major advantage of the vector-driven induction motor is its rugged construction, reliability, low cost and simple construction for high-speed machines. In addition, constant-power operation is somewhat simpler than a separately excited dc motor because it is embedded in the vector control.

Vector control system implementation

We can present a practical vector control design with Baldor's ASBTS-20 series spindle drive. This system uses indirect vector control to get very accurate speed and positional controllability throughout its wide speed range. Often, this is required in high-performance machine tool spindle applications. Figure 7 shows a functional block diagram of the vector control used in the drive. Except the motor and mounted encoder, all electronics are packaged inside the drive. The drive includes many other functions — handshake logic with NC machine, protective functions and the operator interface etc — but discussions will be limited to vector control.

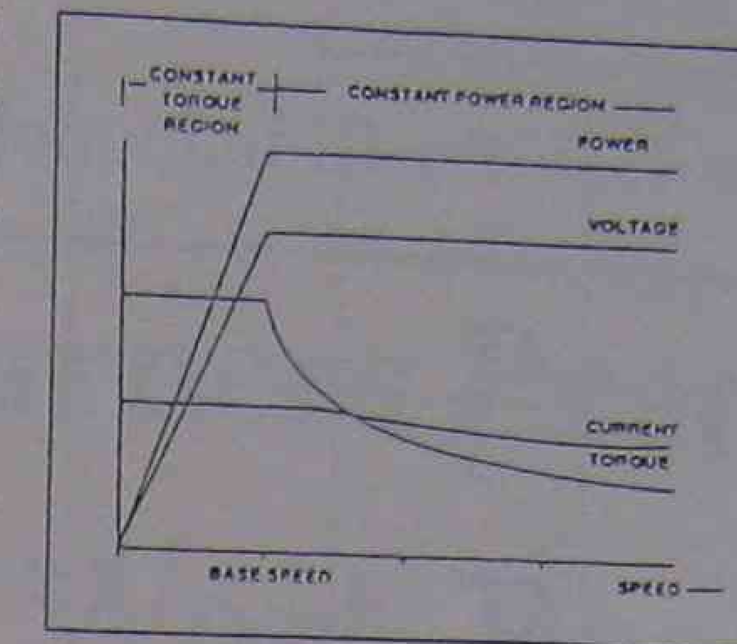


Figure 6. Vector controlled motor characteristics

For vector control, which involves many arithmetic calculations of extended resolution, at least a 16-bit microprocessor, or signal processor is required. The ASBTS-20 uses a NEC 78312 16-bit microcontroller with many functions handled by hardware, either through built-in microcontroller logic or on-board logic.

This effectively relieves software burdens required with fast sampling time.

From the speed command Vc from a host (either CNC or operator), velocity profile, Vr, is generated for every control interrupt cycle. The rate of change in the profile velocity depends on acceleration rate and speed. Vr is then compared to the actual speed of the motor, and the closed-loop compensator determines torque command, Tc, based on the present and past speed errors. Vector control starts from this point. Flux current component ld is calculated from the flux calculator process that simply modifies command flux ldc inversely proportional to the speed above base speed. Because the Tc command is directly proportional to lq (torque-producing current component), we are ready for vector calculation. From two variables ld and lq, magnitude and phase of stator current vector can be calculated from equations (11) and (14), and produced slip from equation (12). Rotor flux angle can be estimated by equation (13), so the appropriate arithmetic and digital integration process results in a rotor flux angle of the current interrupt cycle. Based on the magnitude and flux angle, the frame transformation process can be done via a combination of hardware and software. The resulting three phase stator current commands are transformed to an analogue format, filtered and amplified to feed motor current. To eliminate current phase lag due to inductance, a PWM amplifier with high gain current feedback is used.

There are two open-loop parameters that must be tuned properly. These are ldc and Tr (rotor time constant). To optimise performance, these must be tuned correctly with a load test. Because motor parameter Tr varies as motor temperature changes, peak torque capability may be deteriorated as temperature varies. Fortunately, for sizes of most spindle motors, its effect is not so critical in performance as in much larger size motors.

Dr Ohm is with the Baldor motion products group.

For further information contact Australian Baldor, 6 Stanton Rd, Seven Hills NSW 2147.

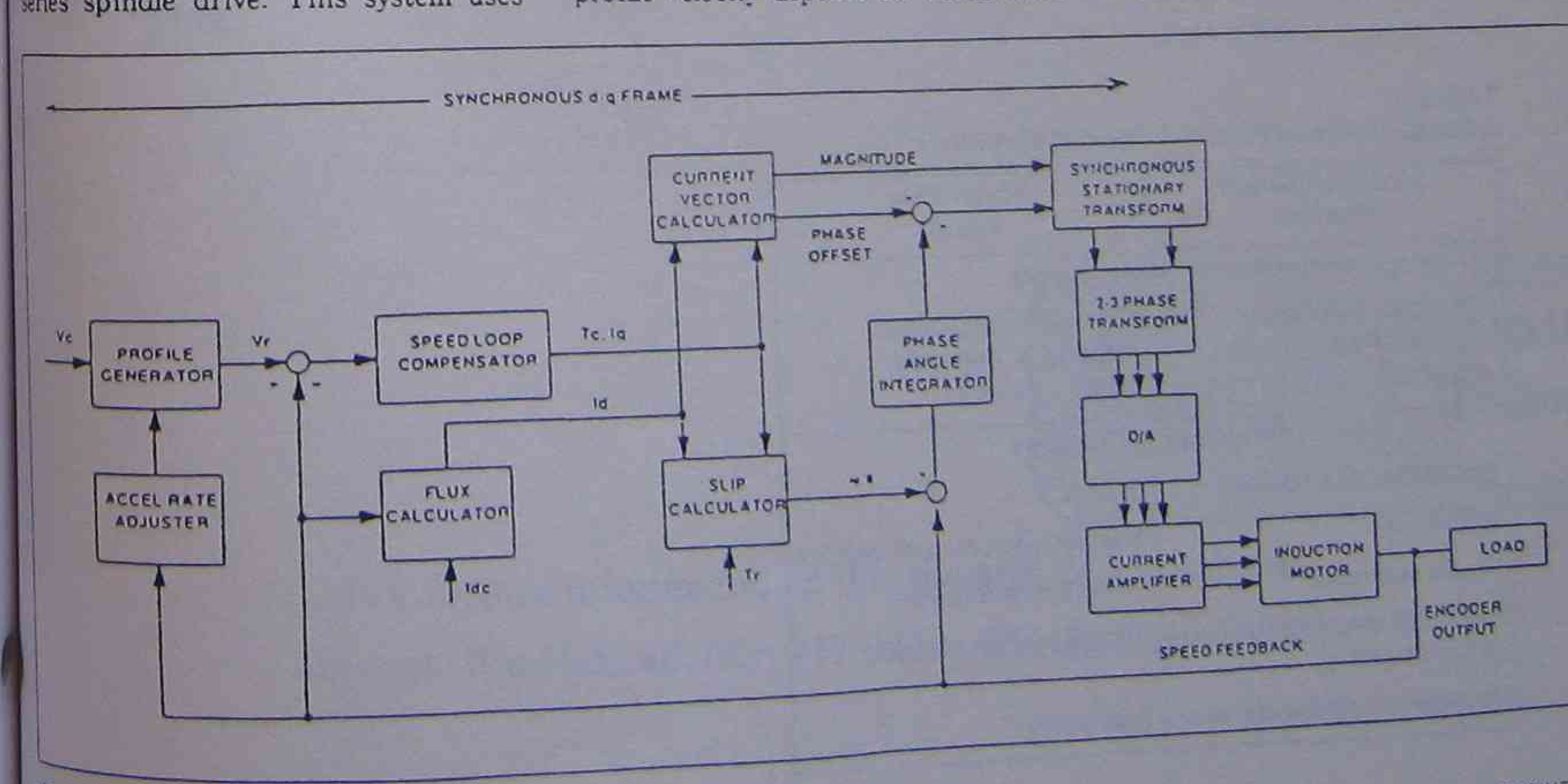


Figure 7. Vector controlled motor drive

The difference between the dc motor and the induction motor is that in the induction motor the airgap flux rotates

It(t) if leakage inductances are neglected. Thus, equation (8) can be written as:

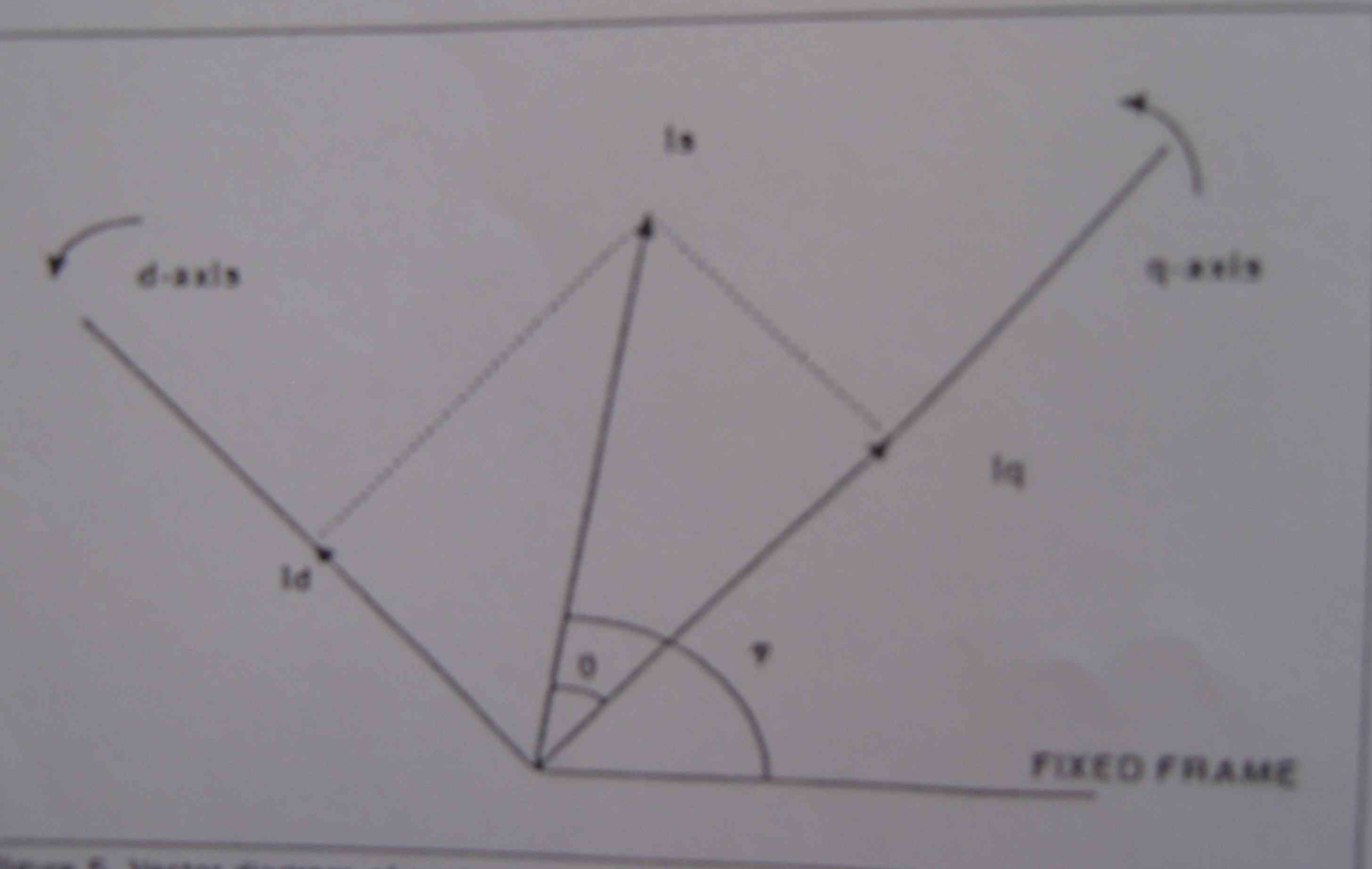
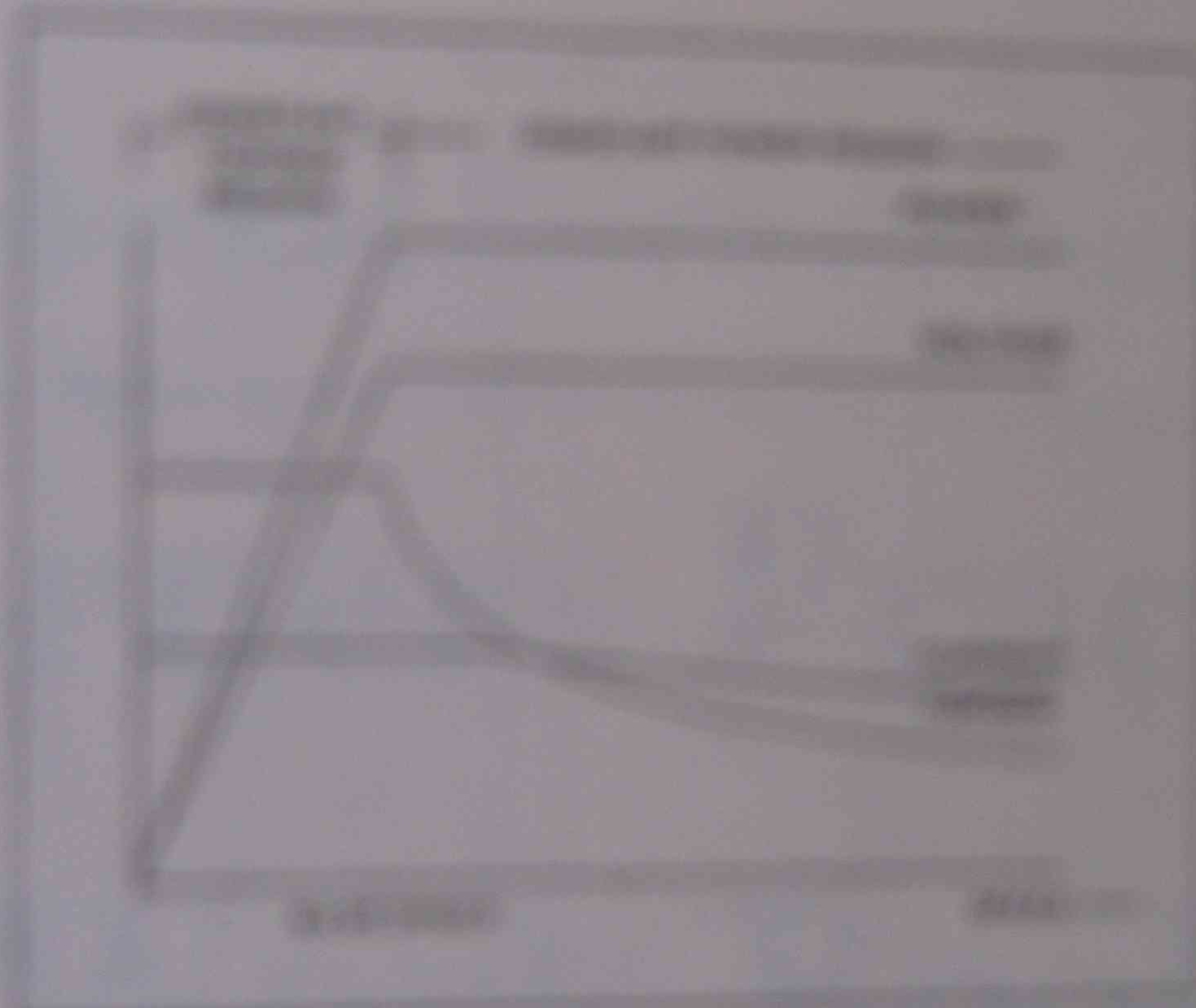


Figure 5. Vector diagram of sector current components



because it is embedded in the vector control.

Vector control system implementation

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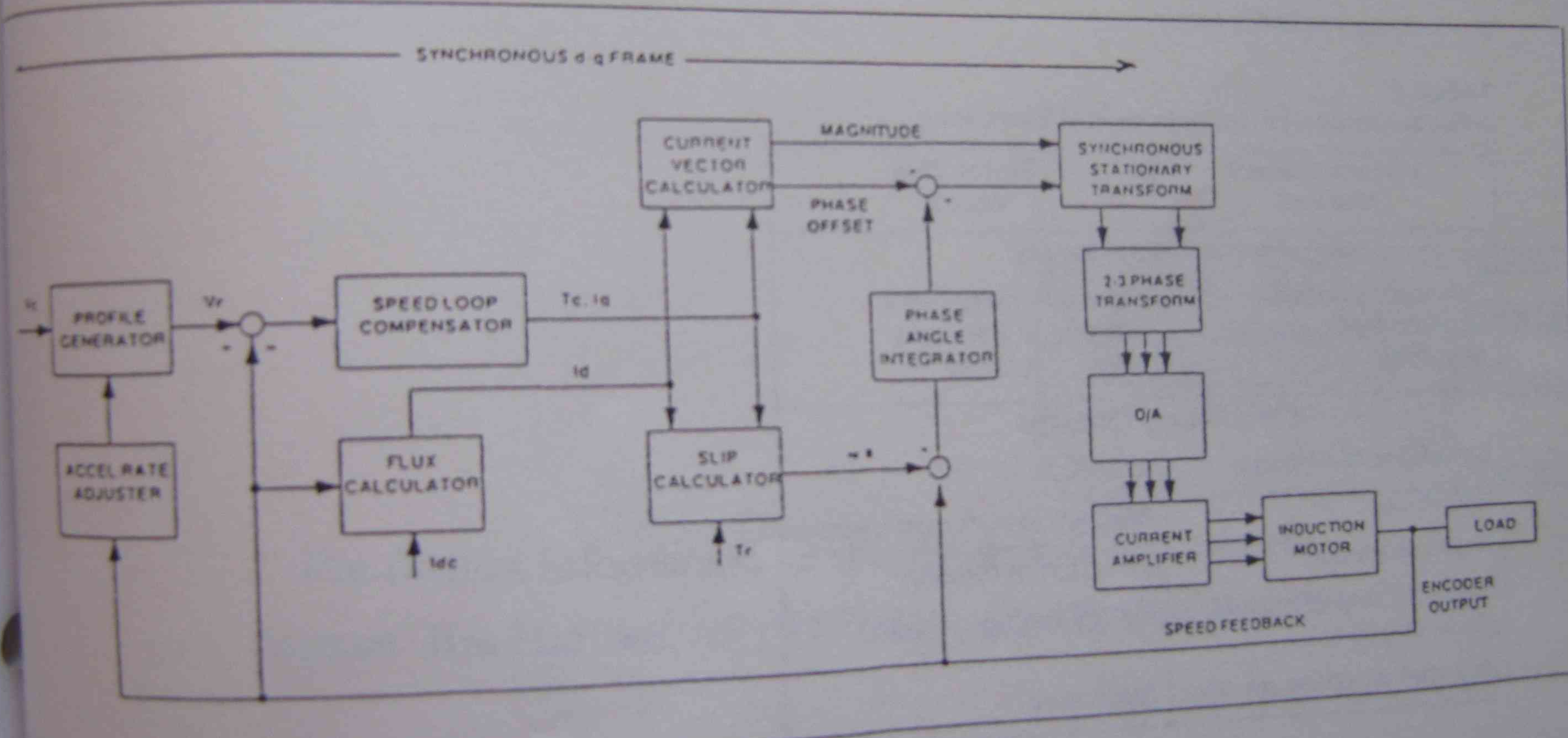

Figure 7. Vector controlled motor drive