VARIABLE SPEED OPERATION OF WIND TURBINES

by

D. Goodfellow

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MEMORANDUM

The accompanying thesis submitted for the degree of Ph.D. entitled "Variable speed operation of wind turbines" is based on work conducted by the author in the Department of Engineering of the University of Leicester mainly during the period between October 1983 and September 1986.

All the work recorded in this thesis is original unless otherwise acknowledged in the text or by references.

None of the work has been submitted for another degree in this or any other University.

The main contributions the author claims to have made to the subject of variable speed operation of wind turbines using a cycloconverter include:

1. A secondary emf signal generator has been designed which enables the cycloconverter to control the induction machine smoothly above and below synchronous speed in an asynchronous mode.

2. The firing angle requirements for the production of secondary current in phase with the induced secondary emf have been calculated by computer, and a modified cosine crossing technique used to ensure operation of the equipment with these firing angles.

3. A cycloconverter using six effective phases of mains supply has been designed and successfully operated over a limited speed range above and below synchronous speed in both generating and motoring modes.

4. Results have shown the ability of the cycloconverter to drive an induction machine smoothly from standstill to just below the operating range of the system as a generator.

5. An assessment of the cycloconverter as a variable speed wind energy converter has been achieved using an on-line computer simulation.

D. Goodfellow
Department of Engineering
University of Leicester

LIST OF PRINCIPAL SYMBOLS

V	Wind speed	m/s
p(V)	Probability that windspeed exceeds V	
Vm	Mean wind speed	m/s
V_o	Cut-in wind speed	m/s
V_1	Cut-out wind speed	m/s
P	Power	W
Pm	Mechanical power	W
Pe	Electrical power	W
P1	Primary power	W
P2	Secondary power	W
ρ	Air density	kg/m^3
Cp	Power coefficient	
Cpm	Maximum power coefficient	
A	Swept area of turbine blades	m^2
λ	Tip speed ratio	
ω	Rotational speed of blades	rad/s
ω_{max}	Maximum rotational speed	rad/s
R	Radius of blades	m
T	Torque	Nm
LS	Low speed shaft torque	Nm
HS	High speed shaft torque	Nm
s	Slip	
Ns	Synchronous speed	rev/min
N	Rotational speed	rev/min
ω_o	Normal fixed turbine speed	rad/s
T_o	Normal torque rating	Nm
P_o	Normal power rating	W
J	Blade inertia	kgm^2
E	Energy	Whrs

Fs	Secondary emf frequency	Hz
Fm	Mains supply frequency	Hz
MSB	Most significant bit	
LSB	Least significant bit	
EPROM	Electrically programmable read only memory	
ϕ	Magnetic flux	Wb
B	Magnetic flux density	Wb/m^3
H	Magnetic field strength	A/m

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ABSTRACT

This work describes a control system in which a cycloconverter is connected between the secondary windings of a three phase induction machine and the a.c. mains supply to give variable speed sub- and super-synchronously

In order to control the system smoothly in an asynchronous mode a secondary emf signal generator has been designed, which enables the cyclo-converter to operate in synchronism with the emf induced in the secondary windings of the machine.

A computer programme has been written which calculates the required firing angles for the cycloconverter to produce secondary current in phase with the secondary emf in the machine. An electronic system has been built which ensures that these firing angles are used by the cycloconverter during actual operation.

A cycloconverter has been built, using an effective six phases of mains supply, and has been successfully operated over a range of 20% about synchronous speed in both generating and motoring modes.

Results show the ability of the cycloconverter to drive the machine up from standstill as a motor to just below 20% subsynchronous speed.

An on-line computer simulation of a wind turbine has been developed which enables an assessment of variable speed generation applied to wind turbines to be achieved. This simulation, in connection with a d.c. machin and thyristor controller, can be used to drive the shaft of the induction machine and assess operation of the cycloconverter control scheme under actual wind turbine operating conditions.

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CHAPTER 1

1.0 Introduction

This thesis is entitled "The variable speed operation of wind turbines" and investigates the use of a doubly fed induction machine as an asynchronous generator, using slip energy recovery, to generate into an established grid. Generators connected to the grid are normally either synchronous fixed speed generators, or limited slip induction generators. The system proposed here uses slip energy recovery to enable an induction generator to operate over a variable speed range. Variable speed generation can be used to operate a wind turbine as a variable speed constant frequency wind energy converter, supplying the power to an existing grid system. Variable speed wind energy conversion has the advantages of greater energy capture and the removal of some of the structural problems which may result from the large fluctuations in torque with fixed speed turbine systems.

The system uses a cycloconverter as a frequency changer which controls the power flow to and from the secondary windings of the generator by controlling the secondary current. If the secondary current produced by the cycloconverter is to be maintained reasonably sinusoidal then the secondary frequency should be limited to approximately 10 Hz, which corresponds to an operating speed range of $\pm$ 20% about synchronous speed. The secondary current is controlled to be in phase with the secondary emf and so shaft torque will be directly proportional to secondary current. The secondary current, and therefore torque, is controlled according to a torque-speed characteristic which will enable the generator to operate as a load on a variable speed wind turbine. This characteristic is designed to operate the turbine at its maximum efficiency over the greater part of its operating range, and then automatically limit the speed at each end of the operating speed range.

This work has concentrated exclusively on doubly fed generation in an asynchronous mode for wind energy recovery but the principles involved are directly applicable to motoring.

1.1 Wind Energy

Although the wind is not reliable as a source of energy from day to day, it is reliable on a year by year basis. It is now generally agreed that wind energy is most viable in conjunction with existing energy supplies, cutting down the cost of energy in a future in which fuel will become scarce and/or increasingly expensive (ref.1).

That the wind is a variable source of energy is well known, its speed varies, and as the power available is proportional to the cube of the wind speed, so the power available varies greatly.

The variation of wind speed can be expressed as a velocity distribution in the form of a Weibull Function:

$$p(V) = \exp\left[-\left(\frac{V}{c}\right)^{k}\right]$$

p(V) = probability that the wind speed exceeds V

c = scale parameter

k = shape parameter

It has been found that the "Rayleigh" distribution is a good approximation to wind conditions in W. Europe (ref.2)

$$p(V) = \exp\left[-\frac{\pi}{4}\left(\frac{V}{Vm}\right)^{2}\right]$$

Vm = mean wind speed.

Typical mean wind speeds in the U.K. are approximately 6.5 - 7.5 m/s (ref.3).

A useful characteristic is the potential energy capture for each wind speed, which is the probability of a particular wind speed occurring in hrs/ann, multiplied by the power available at that speed. The wind speed at which the turbine must operate at maximum efficiency should be the wind speed with the greatest potential energy capture.

The type of turbine being considered is the horizontal axis type. The power available using such a turbine is given by

$$P = 0.5.\rho.Cp.V^3.A$$

ρ = air density

A = swept area of blades

V = wind speed

Cp is the "power coefficient", most usefully described in relation to the tip speed ratio λ ;

$$\lambda = \omega R/V$$

ω = rotational speed of blades (rad/s)

R = radius of blades .

The power coefficient is a measure of the aerodynamic efficiency of the blade, and can be plotted against λ as in Fig.1.1. The theoretical maximum (Betz limit) for Cp is 0.59. Altering the pitch of the blade produces some variation in the characteristic, see Fig.1.2. The Cp maximum is achieved at one value of λ , so, for a fixed speed machine, the turbine operates at maximum efficiency at only one windspeed. It should be possible, for a variable speed generator, to control the speed of the rotor blades in order to maintain the optimum Cp point over a range of wind speeds.

From the Cp characteristic it is possible to produce torque curves, plotted against rotational speed, for each wind speed, as in Fig.1.3. The torque curves can be derived as follows:

$$P = 0.5.\rho.Cp.A.V^3 \qquad (i)$$

where A = swept area of rotor blades: πR^2

But $\lambda = \omega.R/V$

$V = \omega.R/\lambda$.

Substituting this for a V^2 in the expression in (i) gives

$$P = 0.5.\rho.Cp.A.V.\omega^2.R^2/\lambda^2 \qquad \text{(ii)}$$

and $$T = P/\omega \quad ,$$

so $$T = 0.5.\rho.Cp.A.V.\omega.R^2/\lambda^2 \quad , \qquad \text{(iii)}$$

which gives torque vs ω for varying V .

If the remaining V term is replaced by $\omega.R/\lambda$ then this becomes

$$T = 0.5.\rho.Cp.A.\omega^2.R^3/\lambda^3 \quad , \qquad \text{(iv)}$$

which can be written

$$T = 0.5.\rho.A.R^3.(Cp/\lambda^3).\omega^2 \quad .$$

For any given Cp and its associated λ this equation becomes of the form

$$T = K.\omega^2 \quad ,$$

so for $Cp = Cp_{max}$ this square law torque-speed curve can be drawn, and is shown in Fig.1.3 as the "Max Cp" curve.

From the torque curves derived it is possible to decide upon an operating strategy for loading of the blades by the generator. In this system the incident wind speed is not required as an input to the control system. The loading torque is controlled as a function of rotational speed only.

In a fixed speed mode the generator load torque would simply move up and down a vertical line as shown in Fig.1.4, reaching its optimum Cp at point a , corresponding to a wind speed of $\simeq 8$ m/s , its maximum power (in this case 2.5 MW) and torque would be reached at point b (16 m/s), and for further increasing wind speed the torque decreases, e.g. down to c at 21 m/s. Note that sudden increases of wind velocity produce sudden fluctuations in load torque, which may produce dynamic stability problems.

For absolute optimization of efficiency in the variable speed mode the turbine could be controlled to operate exclusively upon the torque curve corresponding to max Cp (line xy). For example, at a wind speed of 5 m/s the operating point is s , at a wind speed 7 m/s it is point t . At both these points maximum Cp is being achieved. However for large wind speeds the turbine must be prevented from exceeding its rotational speed limit.

The control method used in this thesis is a combination of the two schemes outlined above. The turbine operates on the max Cp torque curve until the rotational speed limit is nearly reached, at which point the torque-speed control scheme forces the turbine to operate in a virtually fixed speed mode, see Fig.1.5. The steep torque speed characteristic over this period corresponds to operation with a low slip induction generator, a mode of operation which has been found to remove the dynamic stability problems associated with fixed speed operation (ref.4). The reasons for the use of this strategy are discussed more fully in Chapter 2 of this thesis.

There are a number of techniques that may be used to recover wind energy to a constant frequency grid system using variable speed turbine operation.

1.2 Alternative Variable Speed Generation Techniques

1.2.1. An alternator with line commutated inverter

In this scheme as shown in Fig.1.6a the output of the alternator is rectified to give a d.c. link, and power transferred to the grid system by a line commutated inverter. Such a system is being operated at 250 kW in the Orkney Islands, (ref.5). A wide speed range is possible, and the Orkney system has a 50% speed range. This technique requires an expensive d.c. link choke to maintain continuous current and commutation failure in the inverter can occur during transient disturbances in the mains supply. The power electronic devices must be rated at the alternator power ratings, i.e. the total output power of the turbine.

1.2.2. Supersynchronous slip recovery induction generator

A cage induction machine generates when driven supersynchronously. However, the speed range is limited. An extended speed range is possible using the Kramer system of slip energy recovery shown in Fig.1.6b. This

requires a slip ring machine with the slip energy being recovered by the same technique as in 1.2.1. above. However in this case only the slip power is controlled by the electronics. The system suffers from the same disadvantages as the system 1.2.1. above, i.e. commutation failure and the need for a choke. The system controls the torque by producing quasi-square wave currents in the secondary of the generator. These waveforms have a high harmonic content and so reduce the rating of the machine, also they are reflected back into the stator and produce harmonics in the power fed back into the supply. The diode bridge will only allow power flow in one direction, which limits the system to only supersynchronous generation. At twice synchronous speed the rotor voltages equal the rated voltage and further increase in speed will be limited by the winding breakdown voltage, (ref.6).

1.2.3. Sub- and super-synchronous operation of slip recovery induction generators

For operation both sub- and super-synchronously a slip energy recovery scheme must be able to control power flow both to and from the secondary windings. This is the Scherbius scheme and can be implemented statically in two ways:

(i) Current source inverter and line commutated inverter.

The diode bridge in system 1.2.2. is replaced by a current source inverter, as shown in Fig.1.6c, which enables power to flow to or from the secondary windings. The speed range is from standstill to twice synchronous speed. The inverter requires 6 extra thyristors and the associated commutating capacitors. As in scheme 1.2.2. above, the inverter produces quasi-square wave currents in the secondary of the generator, and also requires the d.c. choke to smooth the link current, (ref.7).

(ii) Cycloconverter

In this method, shown in Fig.1.6d, the two converters are replaced

by a cycloconverter which produces near sinusoidal currents in the secondary of the generator. The frequency ratio across the cycloconverter will determine the quality of waveform produced. The speed range of the generator is limited by the maximum frequency that can be supplied by the cycloconverter into the secondary windings without too great deterioration of the waveform quality. This quality can be improved by using more effective phases of mains supply. In this system six phases of supply are derived from the grid, and the operating speed range is $\pm$ 20% about synchronous speed, corresponding to a maximum frequency of 10 Hz , (ref.8).

1.3 Comparison of Scherbius Systems

Although the current source inverter can operate the generator from standstill to approximately twice synchronous speed, this may not lead to a significantly greater energy capture than a $\pm$ 20% limited range, and it may be impossible to fully utilise the range due to wind turbine dynamic instability problems.

The inverter produces quasi-square wave currents in the secondary circuit, with a high harmonic content, whereas the cycloconverter will produce a more sinusoidal current.

The inverter is a more complex system, requiring a force commutated inverter, with its associated capacitors, and also a large choke to smooth the D.C. link current, and problems occur during a possible mains outage.

The cycloconverter demands more power thyristors but these individually have a lower rating than those required for an inverter. The control scheme for the inverter is relatively complex, as there are two different control schemes, one for each inverter, whereas the cycloconverter merely requires one simple control system applied to a large number of devices. The cycloconverter is also naturally commutated, but a failure to commutate does not result in high fault currents and therefore no failure in the power circuits. Obviously an orderly restart procedure should be

designed into the equipment. Cycloconverters for use with variable speed wind turbines have been proposed and built (ref.9), and certain features analysed (ref.10).

These slip recovery techniques demand the use of induction machines. Up to the present most wind turbines have used synchronous generators. However, it would appear (ref.11) this is only due to the lack of experience of induction machine operation applied to wind turbines.

This thesis investigates the use of a six-phase cycloconverter static Scherbius system with a $\pm$ 20% speed range.

1.4 Cycloconverter Control System

For smooth control of the cycloconverter knowledge of the frequency and phase of the secondary emf induced in the windings is needed. Previous work (ref.7) developed an electronic secondary emf signal generator, which produced a signal of the same frequency and phase as the secondary emf. This was achieved by counting pulses scanned by an optical device on a slotted disc fitted to the rotor of the machine, and comparing this frequency with a frequency derived from the mains supply. However, the system was only initially synchronised, and an accumulation of errors due to losing or misreading pulses could occur, which produced a signal no longer in phase with the induced emf. Also, the signal generator only produced square waves at the slip frequency, which only allowed the cycloconverter to operate at a fixed firing angle. The amplitude of the square wave could be altered, which would advance or retard the firing angles, but as the firing angles were all equal, the system could only attempt to produce square waves of current. The actual current output was distorted due to the secondary emf present in the winding. The problem of a short circuit occurring between two phases of mains supply, to which cycloconverters are prone, was avoided by electronic current blanking techniques. This was complex and subject to mal-operation, and introduced a delay due to the need for

detection of zero current. Slip energy recovery techniques using cyclo-converters are not designed to have any mode of operation beyond their limited speed range, i.e. they normally do not start the machine from standstill as a motor.

1.5 Aims of the Research Programme

The main aim of this research work is to investigate the Scherbius system for operation as a variable speed wind energy converter. The various control strategies for variable speed wind energy conversion are assessed. The disadvantages of previous variable speed induction generator control schemes are overcome by use of the following techniques:

(i) By using a divided layer winding on the motor secondary, first proposed by Holmes (ref.12), and firing the p-group and n-group thyristors into separate windings, a short circuit between voltage supplies is prevented.

(ii) A new secondary emf signal generator has been developed which produces waveforms locked in phase with the actual secondary emf. The problem of lost or misreading pulses has been overcome by a technique of resynchronising twice per rotor shaft revolution. The waveforms are obtained from an EPROM which can be programmed to contain the waveforms required to produce sinusoidal current in phase with the secondary emf.

(iii) A 36 element cycloconverter, with six phases of mains supply is used to provide smoother current waveforms into the secondary, and a "modified cosine crossing" technique used to fire the thyristors in order to produce sinusoidal current in phase with the secondary emf, and also to operate the system as a generator in such a way as to optimise the energy capture for a variable speed wind energy converter.

(iv) The use of a divided winding secondary enables the system to start up as a motor, from standstill, providing the thyristors are rated to accept the starting current.

(v) An assessment of the control strategies possible for variable speed wind energy conversion has been achieved with a computer simulation programme. A control strategy was devised which would provide the most useful idea of the problems which may have to be overcome for future designs, and this was implemented in the cycloconverter control scheme.

CHAPTER 2

2.0 Variable Speed Wind Energy Recovery

The recovery of wind energy into the grid system, which is investigated here, generally implies a fixed generator speed, due to the constant 50 Hz grid frequency. From the reasons outlined above (Section 1.1), it may be advantageous to vary the rotational speed of a wind turbine.

The systems being investigated here concern the use of a variable rotational speed wind turbine connected to the grid system. There are electronic techniques which allow the speed to vary between standstill and twice normal running speed, but the system being investigated here is restricted to approximately $\pm$ 20% about normal operating speed. The relative advantages and disadvantages of several different operating strategies using this system applied to existing wind turbines are assessed.

The existing wind turbines will have limits set of maximum torque and rotational speed. This investigation will in general restrict itself to a rotational speed limit comparable to that of the turbine in its fixed speed mode. This may necessarily limit the advantages which the variable speed system will produce. A small overspeed has been allowed to counteract gusting, but the turbine will have been designed to overspeed under certain conditions (e.g. loss of grid connection). There have been variable speed systems proposed in which the rotor is allowed to increase its rotational speed to approximately twice its normal operating speed (refs. 15,16) but such investigations involve structural considerations of wear and stress which are beyond the scope of this work. Similarly the turbine rotor parameters will have been optimised for a fixed speed system, which may also limit the advantages of variable speed. Nevertheless the control schemes outlined will be applicable to any rotor characteristic and individually may be optimised by variation of the Cp curve. The relative energy captures and complexities of each system will give some idea of the methods of control which could be useful to utilise or investigate further.

Some benefits of variable speed operation are generally assumed to be:

(i) increased energy capture,

(ii) reduced stressing of components,

(iii) greater operational flexibility.

These benefits are assessed for five operating strategies for a variable speed system which will allow $\pm$ 20% variation about synchronous speed.

2.1 Outline of the control strategies

When turbines operate with variable rotational speed the effect of system inertia must be taken into account when considering the dynamic behaviour. Further, the variable speed slip energy systems control torque as a function of speed. Therefore it is necessary to consider the operation of the system with reference to the torque speed characteristics of the turbine. These characteristics can be derived from the Cp curve (shown in Fig.2.1).

The torque curves for a range of wind speeds are shown in Fig.2.2,with the maximum Cp curve indicated.

The control strategies can be considered in two groups:

(i) Power limitation by pitch angle control.

Three methods are considered and shown in Fig.2.3.

(a) Fixed speed variable pitch (FSVP)

(b) Variable speed variable pitch (VSVP)

(c) Variable speed at max Cp to power rating (MaxCp)

Note that mode (c) exceeds the speed rating of the other systems.

(ii) Power limitation by stalling.

Three methods are considered and shown in Fig.2.4.

(a) Fixed speed fixed pitch (FSFP)

(b) Variable speed with speed reduction at constant torque (CTSR)

(c) Variable speed with speed reduction at constant power (CPSR)

Note that (c) exceeds the continuous torque limit of the other systems.

2.2 Theoretical Basis for Performance Comparisons

2.2.1 Steady state energy capture calculations

The energy capture figures have been calculated under steady state conditions, assuming that the turbine instantly achieves its operating point for any particular wind speed. The results are obtained by calculating the number of hours a particular wind speed occurs, and multiplying this value by the power in Watts obtained at that wind speed. Summing the results over the range of operating wind speeds gives the number of Watt hours obtained by the turbine. The wind model is a Rayleigh distribution:

$$p(>V) = \exp\left[-\frac{\pi}{4}\left(\frac{V}{Vm}\right)^2\right]$$

where $p(>V)$ is the probability that the wind speed exceeds V and $Vm = Vmean$.

The $Vmean$ used in this thesis is $8.94\,m/s$ (20 mph). The mechanical power output is given by the torque x rotational speed for each wind speed in the mode of operation being considered. These comparisons have been made for a $40\,m$ radius turbine with an electrical rating of $2.5\,MW$. The electrical output of the turbine is calculated with the following equation, given as the efficiency of the MOD-2 system (which is rated at $2.5\,MW$):

$$Pe(V) = 0.97.Pm(V) - 55 \times 10^3$$

where

Pe(V) = electrical power at wind speed V

Pm(V) = mechanical power at wind speed V .

The total energy captured per annum is given by the following

$$E = \int_{V_i}^{V_o} Pe(V).p(V).8766\ d(V) \quad \text{Whrs/annum}$$

V_i = cut-in wind speed (5 m/s)

V_o = cut-out wind speed (30 m/s)

8766 = number of hours/year.

The energy capture calculations were based on Cp curves derived from the Nibe system. Curves for -1 and -4 degrees pitch angle (as shown in Fig.2.5) were used.

Most wind turbines are fixed speed variable pitch machines and so this mode of operation was used as the datum for comparison with other modes. The fixed speed for this case was chosen to optimise the energy capture for this wind regime (see above), Cp curve, and power rating. The calculations showed this speed to be 1.8 rad/s .

2.2.2 Torque rating consideration for variable speed operation

In addition to consideration of the energy recovery it is important to determine the torques developed at the generator for different operating modes.

The torque rating under normal operating conditions is calculated, and also a figure for the maximum intermittent torque seen due to gusting or rapid ramping wind conditions occurring at rated power. For the variable speed systems a figure for the inertia of the blade system is required, in this analysis an inertia of 22.5×10^6 kgm^2 is used (c.f. Boeing MOD2, R = 45 m, J = 28.2×10^6 kgm^2).

The gust parameters have been obtained from ref.(14), recommended as an estimation of discrete gust patterns. The gusts are modelled as "1-cosine" excursions in wind speed, and the amplitudes are calculated from the equation given in the reference. If a system can suppress long period gusts then a gust of 2 seconds duration was used in the analysis; if this was not possible a gust of 10 seconds period was used.

This analysis uses the data for the Nibe turbine operating at a pitch angle of -1 degree.

2.3 The Control Strategies

The steady state energy capture figures and torque ratings for each of the following control strategies are given in Tables 2.1 and 2.2.

2.3.1 Fixed speed variable pitch (FSVP)

This type of wind generator operates with a synchronous or low slip induction generator. The power limitation is achieved by altering the pitch of either the whole blade or part of the blade, see Fig.2.6a. Compared with the fixed pitch system this can operate at a higher rotational speed, (compare Figs.2.3 and 2.4) which will bring the Cp_{max} point up to a higher wind speed. The extra available power at even higher wind speeds is limited to 2.5 MW by the pitch control mechanism (point r on the figure). This technique increases the energy capture for this method over the fixed pitch system.

The control strategy for the pitch operation can either have power, torque, or incident wind speed as its input. The pitch mechanism is usually a hydraulic system requiring connections along the blade itself and through the shaft hub. Partial blade angle control also implies a mechanical weakness at the pivoted connection. There will be a maximum operating rate at which the pitch mechanism can deploy. During operation at rated power there is a possibility of both torque and power exceeding their continuous rating due to gusting. The pitch mechanism may be fast enough to

limit the excess torque fluctuations produced by low ramp rate gusting, but not to limit the effects of rapid gusting. Blade angle control to limit gusting will greatly increase the wear on the control mechanism.

The load torque rating is obtained from the effect of a 2 second time period gust occurring at rated power. It is assumed that for longer period gusts the variable pitch mechanism will be able to smooth the torque pulsations seen by the blades. Operation with a synchronous generator, in which the speed is not allowed to rise, implies that the torque developed by the generator measured at the low speed shaft must equal the torque developed by the wind. Operation with high slip and low slip induction generators will allow limited amounts of speed increase which will limit the torque excursion seen by the blades to a greater or lesser degree. These generators have been modelled simply as loads which operate upon steep torque-speed curves. The gradients used are 70 and 50 MNm/rads^{-1} for the low and high slip generators respectively, both with a rated running torque of 2.5 MNm .

2.3.2 Variable speed variable pitch (VSVP)

In this mode of operation the maximum rotational speed is set at the speed of the fixed speed system above. The torque-speed characteristic is shown in Fig.2.6b, and shows that this system achieves maximum Cp over a range of wind speeds up to the wind speed at which the fixed speed system also attains max Cp (point s). Thereafter the control scheme will produce an almost vertical torque gradient which will mimic the action of a fixed speed machine. The gradient allows speed increase to occur and so provides for some torque damping at the generator. However, inevitably, gusting will produce torque and power fluctuations for this steep torque operating region just below rated wind speed.

The control system can maintain the steep torque curve above the rated operating point and so some of the torque produced by gusting wind conditions

can be absorbed as an increase in rotational stored energy as the speed increases. During this time the pitch mechanism which has a limited speed of response is also operating. The gradient of this torque line can be set electronically to give either a large torque increase with small increase in speed or vice-versa. In the case presented here, the inertia of the turbine is so large that the torque can simply be held at the rated value and for a 2 second gust the speed does not increase excessively, as can be seen in Table 2.2. If the variable pitch were not to be used for suppression of long period gusts then this electronically controlled torque characteristic would have to be of some definite gradient in order to prevent excessive speed increase.

2.3.3 Variable speed at max Cp to rated power (MaxCp)

Figure 2.6b shows the variable speed variable pitch scheme outlined previously, which was limited, for the purposes of this thesis to 1.8 rad/s maximum rotational speed. As can be seen, the torque speed characteristic upon which the generator would have to operate has abrupt changes, due to the requirement of not exceeding the maximum speed limit. A much simpler control scheme would be to allow the turbine to continue increasing speed on the maximum Cp line until it reached maximum power (see Fig.2.6c). This would not require the pseudo-fixed speed range at 1.8 rad/s and the torque speed characteristic is greatly simplified. Gust limitation could be achieved by merely extending this curve beyond the new speed limit.

This system would therefore need to have its maximum speed set at the speed where the blades are operating at maximum Cp and the power reaches its limit, point P on the diagram. For the energy capture calculations the system is assumed to produce power at maximum Cp until rated power is reached, and then to maintain rated power until the blade stalls completely, in this case corresponding to $V > 30\,m/s$. High wind speeds again require aerodynamic action to restrict a further increase in speed. As the generator control system continues to provide operation

along the Cp_{max} curve then the increase in speed can be used to initiate and control the aerodynamic braking method. As long as the speed is limited, the electronic control will ensure that the torque produced maintains power at 2.5 MW .

This method of power limitation could be a simpler form of control than the previously mentioned techniques, and possibilities are tip spoiling and centrifugally operated flaps (which may already be used to prevent over-speeding in emergency cases). These simpler techniques may now be available as the rotational speed of the turbine can be used as an input variable to the control system. This would be a much more effective criterion for power limiting than the more conventional measurement of wind speed or power in fixed speed systems.

If we assume that there is no method of limiting the gusting torque fluctuations aerodynamically then the load torque rating must be calculated for a 10 s gust. However the speed governing system may be able to suppress these gusts and so a 2 s gust figure is shown for comparison. The torque-speed characteristic for the gusting region is simply an extension of the square law Cp_{max} curve.

2.3.4 Fixed speed fixed pitch (FSFP)

In this mode of operation the turbine is either connected to a synchronous generator, or a low slip induction generator. These essentially hold the speed constant, operating at Cp_{max} at only one wind speed. The power rating is reached as the blade naturally stalls and so rated power occurs at only one wind speed. The torque-speed characteristic for this system is shown in Fig.2.7a. Due to the broad Cp characteristic used in these systems there is a large range of wind speeds between the Cp_{max} point and the stalling point (the distance s-r on the figure). This means that for a particular rated wind speed, the Cp_{max} is achieved at a low wind speed. This limits the energy capture of this system. This system is widely used on small turbines due to its simplicity, requiring

no control scheme.

In this study the rotational speed was set at 1.45 rad/s to provide stall regulation at rated power. The load torque limit is then the torque at rated power (point r). Extra torque may be produced during rapid gusting at rated power, due to the time taken for the blade to stall. The evaluation of this phenomenon is, however, beyond the scope of this thesis.

2.3.5 Variable speed with speed reduction

It is possible that by a suitable electrical operating scheme a variable speed system could avoid the need for blade angle control, with consequent saving in the cost of the blades. This must be achieved by reducing the rotational speed for high wind speeds.

Below rated wind speed the control system for this method is the same as for the variable speed variable pitch system described in Section 2.3.2. When the maximum speed is reached and the power limit is detected, either by measurement of power or torque, the control scheme must try to obtain an operating point at reduced rotor speed. Two systems are investigated here; speed reduction with constant torque, and speed reduction with constant power.

2.3.5.1 Speed reduction at constant torque (CTSR)

From Fig.2.7b it can be seen that the power limit is reached at a wind speed of 12.5 m/s (point x). For an increase in wind speed to 14 m/s, a reduced speed operating point could be obtained at rated torque, corresponding to point y . In order to make the turbine slow down, the generator must provide a greater (loading) torque than the blade (accelerating) torque. When the wind speed is at 14 m/s and the turbine is still operating at its maximum rotational speed, i.e. 1.8 rad/s , the torque produced on the shaft by the wind is shown at t_g . The generator must provide a torque exceeding this value in order to reduce the turbine

speed. The amount of extra torque required would depend upon the rate at which the system is required to slow down and reach its new operating point.

The turbine would operate on the constant torque line with its speed decreasing with increasing wind speed for wind speeds from 12.5 m/s to 15 m/s, and then after reaching the stall point at 15 m/s (point z), it would require to speed up for an increase in wind speed, eventually reaching its speed limit again at 26 m/s (point x). For further increase in wind speed the generator could be made to mimic a low slip induction generator, corresponding to a vertical line from x down to v . For all wind speeds during the speed reduction phase the generator is producing less than rated power.

2.3.5.2 Speed reduction at constant power (CPSR)

This scheme would operate in a similar way to the system above, except it would reduce speed along a torque line as shown in Fig.2.7c, which corresponds to operation at rated power.

This scheme would, in steady state energy capture terms, produce the same energy capture as a variable speed variable pitch system. However it would require a higher continuous torque rating at z' .

2.3.5.3 Control of speed reduction systems

A disadvantage with the speed reduction systems would be both the complexity of the control scheme (requiring knowledge of wind speed) and the dynamic problems associated with attempting to control the turbine under gusting and rapid ramping of wind speed conditions. These can be outlined for two "worst cases":

(i) Positive gusting at rated power, average wind speed 12.5 m/s.

In this case, corresponding to a gust occurring during operation at point x on Fig.2.8, the gust will produce an increase in the torque

produced by the blades and so provide a net accelerating torque, e.g. to point g_1 . The generator, however, must attempt to reduce the rotational speed. Initially, the control scheme may assume that the rise in wind speed is only a temporary gust and the system could allow the speed to increase, similar to the operation of a low slip induction generator. This can be achieved by using a steep torque-speed characteristic. If, after a certain time period, the wind speed has not subsided, then the control can begin to attempt to reduce the speed by applying a torque greater than the shaft torque produced by the wind.

This problem can then be controlled as outlined using a suitable, though complex, control system.

(ii) Positive gusting at rated power, at average wind speeds exceeding 16 m/s (during the speed reduction phase).

If we consider operation in the constant power speed reduction mode, at a point where the wind speed is greater than 16 m/s , for example 20 m/s (point y on Fig.2.8) at this point, a positive wind speed gust produces a negative torque excursion from the blades, and so a decelerating torque, to point g_2 for instance. In this condition, the control system requires the turbine to speed up, and to achieve this the generator must shed load such that the torque is less than the torque produced by the blades. This is difficult to achieve, as the torque produced by the blades in this condition could be very low, and may require the generator to drive the shaft around. This is due to the extremely steep torque-speed characteristic of the blades past their stalling point.

A similar procedure to that used in (i) above could be used, i.e. a steep torque-speed line would initially allow some speed drop to react to gusting, but the drop in speed would have to be small to prevent even more reduction in the torque produced by the wind, as this would cause the torque produced by the wind to fall away. A torque-speed line must be used which is steeper than the torque-speed characteristic of the turbine

in order to overcome this problem. This would be so steep as to imply that effectively the generator is suddenly applying and removing very large torques during wind fluctuations, which could cause control and stability problems.

The problem of reducing the speed of rotation of a turbine during increasing wind speed conditions is intuitively obvious. The control strategy for the speed reduction systems will be necessarily complex, requiring accurate knowledge of wind speed in order to determine the required operating point. Large loading torques must be applied or removed in order to make the turbine move to a new operating point. During operation in fluctuating wind conditions it may be necessary to rapidly remove and apply these torques, which will produce a dynamic problem and also large fluctuations in the power supplied to the grid.

It would seem that the only way to completely overcome these problems would be not to allow the turbine to operate over the problem area, either by shutting it down when the wind speed exceeds 16 m/s or by operation as a pseudo-fixed speed machine for wind speeds greater than this (corresponding to a rotational speed held as at point z on Fig.2.7). In these cases the energy capture figures would drop drastically.

2.3.5.4 Torque rating for speed reduction systems

For the non-speed reduction systems the torque produced by wind gusts at rated power at the generator can be suppressed by allowing an increase in speed. However, in the speed reduction systems the speed increase must not be too great as the "gust" may resolve into a ramp increase, in which case the turbine will have to slow down again. The largest loading torques will occur during a rapid ramp increase in wind speed, when the generator must load the blades with a greater torque than the blades provide in order to slow the turbine down. The worst case has been chosen as a 2 m/s increase in wind speed in 2 s , as used in a MOD2 test analysis, ref (13), though it must be noted that in the event of

increases >2 m/s the torque rating must be increased accordingly. The braking torque has been chosen so as to be able to reduce the speed to its new operating point in 10 seconds from the time of its application. For the constant power system this extra braking torque above that produced by the wind is 750 kNm , and for the constant torque system is 1200 kNm . This duty will be reflected in the cost of the speed control equipment though it may not incur any penalties for the generator or drive train.

2.4 Torque Rating/Energy Capture Results

The energy capture figures have been calculated for Cp curves derived from the Nibe system at two different fixed pitch angles (this refers to the state of the blades before pitch control limitation of power occurs). This was done to change the shape of the Cp curve and assess the effects of this change upon the results (the Cp curves were shown in Fig.2.5). NIBE1 refers to operation at a pitch angle of -1 degree , NIBE4 at -4 degrees . The results are shown in Table 2.1 below where the percentage energy figure is based on the fixed speed variable pitch case. The torque rating figures are shown in Table 2.2 for the NIBE1 system only.

Table 2.1

	NIBE1			NIBE4		
	w max	E	E(%)	w max	E	E(%)
F.Speed F.Pitch	1.45	8119	91	1.51	7735	86
F.Speed V.Pitch	1.8	8932	100	1.8	8303	93
	2.15	8672	97	2.0	8017	89
V.Speed V.Pitch	1.8	9226	103	1.8	8868	99
	2.15	9231	104	2.0	8880	99
V.Speed Const.T Speed Red.	1.8	8095	91	1.8	8102	91
	2.15	7258	81	2.0	7537	84
V.Speed Const P. Speed Red.	1.8	9226	103	1.8	8868	99
	2.15	9231	104	2.0	8880	99
V.Speed Max Cp	2.15	9231	104	2.0	8880	99

Table 2.2

Operation	Maximum Continuous Torque	Intermittent Values				
		Worst Case	Torque peak LS	Torque peak HS	Speed peak LS	Speed peak HS
			(kNm)		(rad/s)	(rpm)
F.S.F.P.	1811	-	1811	16.7	1.45	1500
F.S.V.P.						
(i) S.M.	1463	2 s gust	2632	30.16	1.8	1500
(ii) 2% I.M.	1463	2 s gust	2520	28.8	1.815	1512
(iii) 5% I.M.	1463	2 s gust	2276	26.1	1.827	1522
V.S.V.P.	1463	2 s gust	1463	13.9	1.865	1865
Speed Reduction						
Constant Torque	1463	2 s ramp	3243	30.97	1.81	1810
Constant Power	1811	2 s ramp	2793	26.67	1.81	1810
Max Cp	1330	10 s gust	1717	19.57	2.387	1998

A power against wind speed profile for the various systems operating on NIBE1 data is given in Fig.2.9. Also energy capture per annum vs. wind speed is plotted in Fig.2.10 for each system. These graphs show how the different control strategies are more or less effective at different wind speeds. Note in particular the very considerable energy loss of the VSCT system due to the speed reduction needed to keep the torque constant. The figures are calculated for 1 m/s increments in wind speed, but are plotted as a continuous line for clarity.

Only the VSCP system achieves the same energy as the VSVP without incurring higher speed operation and this is only achieved with a possible 20% increase in torque rating, with additional control difficulties.

VS MaxCp achieves higher energy but at the expense of 17% higher operating speed which may result in a significant increase in the cost of the complete WTG installation.

2.5 Effect of Inertia

2.5.1 Dynamic energy capture

The theoretical energy capture results for variable speed wind turbines have been based upon the assumption that the turbine has negligible inertia and therefore instantly achieves its steady state operating point for each windspeed. In practice the system inertia will prevent this and so the dynamic results will differ from the theoretically derived figures.

The dynamic results have been obtained by running a real time computer simulation of a wind turbine. This was written in cooperation with D. Donegani for a BBC B microcomputer, (see Appendix 1 for further details). Two-second wind data was input to the simulator and the Watt-hours of energy generated were calculated. The computer programme allowed the simultaneous comparison of performance for the following three operating situations.

(i) Fixed speed variable pitch.

This is used as the datum for the comparison. The rotational speed is held constant at $1.8\,\text{rad/s}$. If the generated power is calculated to be greater than $2.5\,\text{MW}$ then it is recorded as $2.5\,\text{MW}$ on the assumption that it would have been so limited by the pitch mechanism.

(ii) Variable speed variable pitch - zero inertia.

For all wind speeds for which this system could run at a rotational speed giving Cp_{max} then the Cp was set instantly at Cp_{max}. The steep torque curve preventing a speed increase above $1.8\,\text{rad/s}$ was assumed to be a vertical line, i.e. giving the same generated power as in case (i) above. It should be noted that this corresponds to the way in which the steady state theoretical energy figures were calculated.

(iii) Variable speed variable pitch - including inertia.

This time the turbine takes time to accelerate or decelerate towards its new steady state operating point. The pitch controls limit power by limiting the speed, i.e. the pitch control was not assumed to operate until maximum rotational speed is reached. During acceleration below the speed limit, the blade torque may exceed the torques corresponding to 2.5 MW generation at rated speed.

Comparative results have been obtained for three different sets of wind data each containing 16 minutes of data at 2-second intervals with linear interpolation every 0.4 s . Results for three different wind regimes are shown in Table 2.3.

Table 2.3

Wind Sample	Fixed Speed	Control Strategy	Inertia (kg m^2 x 10^6)		
			0	10	50
1	155.01	VSVP	179.21	177.47	177.72
		MaxCp	179.21	177.46	177.47
2	343.11	VSVP	352.35	349.36	348.49
		MaxCp	353.89	352.88	350.08
3	573.4	VSVP	573.92	572.81	582.4
		MaxCp	580.5	590.13	610.81

All figures are in kW hrs

It should be noted that for the wind samples the velocities are:

1. 5 to 10 m/s - operation is mainly on the Cp_{max} curve.
2. 6 to 15 m/s - operation is partly along the Cp_{max} curve with operation along the steep torque limit curve (VSVP) and power limiting region.
3. 8 to 15 m/s - operation mostly in the power limiting region.

To ensure that the net transfer of energy into the inertia is zero each computer run was arranged to begin and end at the same wind speed and steady state operating point.

Comparison of the actual and theoretical energy available shows that for windspeeds predominantly below rating, a system obtains less than its theoretical energy capture. This is due to the time taken for the turbine speed to reach its new operating point, during which it is not operating at maximum Cp . However, when the wind speeds are fluctuating about the rated speed, the effect of an inertia is to hold the system at its rated point, and not allow the turbine to slow down during short term drops in wind speed.

2.5.2 Torque pulsations

Although the inertia does not significantly affect the energy captures, its effect upon the torque fluctuations seen at the generator is marked.

Figure 2.11 shows the blade and variable speed generator torques for a 10 minute wind sample. If the generators used were restricted to a fixed speed operation, then it would have to accept the complete fluctuations in blade torque, with corresponding power fluctuations back into the grid. From the figure it can be seen that allowing a speed change reduces the torque fluctuations seen by the generator quite considerably and so also reduces the power fluctuations back into the grid. Note that in the VSVP case shaft torques greater than 0.75 MNm correspond to operation on the steep torque region, and so have a greater fluctuation. This steep torque characteristic is not present in the VS MaxCp case.

2.6 Discussion

Various studies, refs.(15,16,18) have considered that the advantages of variable speed wind energy recovery are:

(i) Increased energy capture.

(ii) Reduction in intermittent torque levels on the generator,

and hence reduction of power fluctuations into the grid.

(iii) Reduction in stressing of the structure.

(iv) Flexibility of operation for differing site conditions.

(v) Motoring from start up/assisted braking during shut down.

(vi) Operation at demanded Cp , e.g. operation with constant power output.

This work has concentrated on points (i) and (ii) for assessing different operating strategies applied to an existing wind turbine. However, some implications for the other points have been obtained.

(i) The extra energy captured by the variable speed facility calculated for a Rayleigh distribution wind regime is 3 to 4% per annum (see Table 2.1). Over a range of wind speeds at which Cp_{max} operation is possible, the extra energy captured can be approximately 15% (Table 2.3, wind sample 1).

(ii) Reduction of intermittent torque levels depends on the ability to absorb blade input torque into the inertia as an increase in speed, (see Fig.2.11). This will depend on the proposed operating strategy and its associated speed limit. Continuous and peak intermittent torque levels are shown in Table 2.2.

(iii) Reduction of stressing on the turbine structure will depend on the torque and rotational speeds the system will have to accept. The assessment of these effects is beyond the scope of this thesis.

(iv) Whereas fixed speed machines obtain Cp_{max} at only one wind speed, and are thus optimised for one particular site, variable speed schemes obtain Cp_{max} over a range of wind speeds and so can be used to advantage over a range of site conditions.

(v) The slip recovery scheme outlined in this thesis will allow motoring from start up. Electrical braking may be used to supplement other braking techniques. This would require the generator torque, as controlled by the slip energy recovery equipment to be greater than the accelerating torque from the blades. This may be possible during low wind speed conditions. However, shut down in this way during high wind speeds will require the generator to provide very large torques and the slip recovery devices will have to be rated to accept the resulting high currents.

(vi) Operation at any desired λ (or Cp) may be achieved by means of an appropriate torque-speed characteristic. Control of speed to produce constant power output is equivalent to the speed reduction with constant power scheme of Section 2.3.5.2, which may be difficult to implement.

2.7 Conclusion

Despite the relatively low improvement in energy capture (3-4%), variable speed operation may have sufficient advantages to merit consideration for the next generation of wind turbines. This study has shown the importance of including all operating features in a realistic assessment. Designs which allow increases in speed or torque or power to increase energy capture are liable to incur added costs which may not be justified by the extra energy gained. The reduction in severe torque fluctuations may prove to be the main advantage of variable speed operation. Of the five systems considered the technique giving operation at max Cp to the power rating has the best overall potential. The turbine must be capable of about 20% overspeed but this will give the best energy capture, greatest smoothing of torque fluctuations and can be implemented by a relatively unsophisticated control system.

Specifically for the work involved in this thesis a torque speed characteristic of the VSVP type was used. This was to be able to assess the operation of the power electronic system both over a "max Cp" type characteristic and also over a steep torque characteristic.

CHAPTER 3

3.0 Slip Energy Recovery Using a Cycloconverter

3.1 Slip Energy Recovery

Slip energy recovery is a technique of enabling a slip ring induction machine, connected to the grid, to operate over a variable speed range by control of the power flow into and out of the secondary windings, (ref.7). A block diagram of such a system is shown in Fig.3.1. Note that in this scheme the rotor winding was used as the primary. Figure 3.2 shows the required power flow directions for operation at sub- and super-synchronous speed. Note that the direction of power flow to the secondary windings changes at synchronous speed. If this system is to operate both sub- and super-synchronously then the slip energy recovery equipment must then be able to control power flow in both directions (ref. 23). As the frequency of the induced voltage in the secondary windings varies so the power flow must be achieved by a frequency converter. Several different methods of achieving this have been outlined in the introduction. In this case a cycloconverter will be used to achieve this frequency conversion.

3.2 The Cycloconverter

A cycloconverter is a direct a.c. to a.c. frequency converter which can produce low frequency voltage and current waveforms from the mains supply. This conversion is achieved directly and without utilising a d.c. link. This can be used to control the direction and amplitude of current flowing between a fixed frequency a.c. voltage and a voltage of varying frequency, (ref.8). A conventional cycloconverter circuit, using 3 phases of mains supply to produce a single phase output is shown in Fig.3.3. Pulses of current are produced by firing portions of the mains supply into a normally passive resistive and inductive load, see Fig.3.4. A low

frequency current waveform is produced from the high frequency supply by using the thyristors to fire segments of the high frequency voltage into the load at varying phase angles, with the phase angles being modulated at the required output frequency, see Fig.3.5. The firing points are usually achieved at the intersection of the "control waveform", which is of the frequency of the required output, and a "firing waveform" associated with the supply across the device to be fired. An increase of the amplitude of the control waveform produces an increase in the amplitude of output current, and vice versa.

Three of these three-phase to neutral cycloconverter units are used, each with its associated control wave. In this system, for simplicity, the firing waveforms are the device line to neutral supplies. Variation of the amplitude of the control waveform produces variation in the amplitude of the current produced.

3.3 Cycloconverter for slip energy recovery

The required control of power flow in the machine windings is achieved by controlling the current produced by the cycloconverter. The figures for the flow of power in the generator for operation between $\pm$ 20% slip over the required torque speed characteristic (see Section 2.7) are in Table 3.1.

Table 3.1

Speed rpm	Slip	Torque p.u	Pm p.u	P1 p.u	P2 p.u
1200	+0.2	0.0	0.0	0.0	0.0
1300	+0.13	0.15	0.11	0.13	-0.02
1400	+0.06	0.175	0.13	0.14	-0.01
1500	0.0	0.205	0.17	0.17	0.0
1600	-0.06	0.23	0.20	0.19	+0.01
1700	-0.13	0.4	0.37	0.33	+0.04
1800	-0.2	1.0	1.0	0.83	+0.17

The 1.0 p.u. torque and 1.0 p.u. power are defined as ocurring at 20% supersynchronous speed. At this point 83% of the total power is delivered by the stator, and 17% by the rotor. As the power electronic equipment only controls the rotor power, the cycloconverter losses

are dependent on this proportion only.

The change in power flow direction required at synchronous speed can be obtained by changing the phase relationship of the cycloconverter-produced current and the secondary emf. By firing positive current into a positive secondary emf subsynchronously, and firing positive current into a negative secondary emf supersynchronously, this power flow direction change is obtained. This required phase relationship must be kept at all times for smooth operation of the system throughout its speed range.

There are certain limitations and problems associated with the use of a cycloconverter for slip energy recovery:

(i) There is an upper frequency limit to the output of a cycloconverter. This is due to the reduced number of mains supply waveforms available during a high frequency output cycle.

(ii) There is a possibility of a short circuit occurring between two phases of mains supply if a p group and n group thyristor fires simultaneously.

(iii) The load is not passive, but contains an emf source of varying amplitude. This is the secondary emf induced in the windings.

In this thesis several novel techniques are applied to counteract these problems in the operation of a cycloconverter as a slip energy recovery system.

3.4 Six Phase Supply

The frequency and amplitude of the emf induced in the secondary windings is given by

$$Fs = s.Fm \quad \text{and} \quad Vs = s.k.Vm$$

and

$$s = \frac{N-Ns}{Ns}$$

where s is the slip

Fs is the frequency induced in the secondary windings

Fm is the mains supply frequency

Vs is the peak value of the secondary induced volts

Vm is the peak value of the mains supply volts

k is the turns ratio of the machine

Ns is the generator synchronous speed

N is the actual operating speed

From this it can be seen that the frequency and amplitude of the induced emf varies with speed.

The upper frequency limit of the cycloconverter must be equal to or greater than the maximum frequency of the secondary emf. This implies a speed restriction on the slip recovery scheme as a whole.

During operation at high slip the required output frequency becomes large and so there are fewer mains supply cycles available during the output period. This leads to a deterioration in the quality of the waveform produced. The speed range of the slip recovery system is dependent upon the slip allowed before the waveform deteriorates to a large degree.

A feature of this system is that the cycloconverter uses six phases of mains supply, which provides a greater number of mains supply waves per output cycle. This will generate smoother sinusoidal current waveforms in the secondary of the induction generator, see Fig.3.6, and should also enable the speed range to be extended. The six phases are obtained by using two three phase transformers connected in opposing senses.

3.5 Divided Layer Winding

As has been mentioned, in a conventional cycloconverter system there is a problem of a possible short circuit occurring between two mains supply phases. This is normally overcome either by the use of electronic blanking, which increases considerably the complexity of the electronic control, or separate intergroup reactors. In an electronic blanking system, the p group devices are only allowed to fire during a positive

half cycle of output current, and are blanked off during the negative half cycle. Similarly the n group devices are blanked during positive half cycles. A zero current detect is necessary to decide when to blank the necessary devices off, see Fig.3.7. Discontinuous current operation introduces the need for a time delay in the current zero detection circuit to ensure that a true current zero has been achieved. Intergroup reactors may be introduced to limit the intergroup current as shown in Fig.3.8.

In this scheme the generator used had a double layer winding and the end connections for each layer were accessible. The layers were separated, one being connected to the p group thyristors, and the other to the n group. This divided layer winding arrangement was first proposed by Holmes (ref.12), see Fig.3.9. This effectively uses the machine winding as an intergroup reactor, and eliminates very simply the possibility of high short circuit currents occurring between two phases of mains supply.

It was found in this work that an additional advantage of this scheme is that it allows the cycloconverter to drive the induction machine from standstill as a motor to just below its operating range as a generator, i.e. the machine runs up as a motor to 1000 rpm, and the lowest generating speed (20% subsynchronous) is 1200 rpm, see Section 5.5.

A more detailed diagram of the complete system is shown in Fig.3.10.

3.5.1 Generator derating

A disadvantage of separating the windings is that there is a net derating of the machine. This can be seen intuitively by noting that each winding is only being used for half of the time.

Under normal conditions the generator is operated with the two layers of the secondary windings connected in parallel. For the generator used the rated current is 10 A rms, each layer carrying 5 A .

In the cycloconverter system, each layer is taken to a separate output of the cycloconverter and positive half cycles of current are sent

along one layer, negative along the other. This leads to a derating of the generator as the copper in the windings is not being used efficiently.

With the cycloconverter fitted, the current in each layer must not exceed 5 A rms . The effective derating is shown as follows:

Where I_ℓ refers to the layer current

I refers to the line current

Subscripts 1 and 2 refer to the case of operation with the layers in parallel and separated respectively.

N is the number of pairs of layers.

With the layers in parallel, and the currents as shown in Fig.3.11a:

$$I_{\ell_1} = I_1/2$$

$$\text{Total A.T.} = N.I_1$$

With the layers divided, and the currents as in Fig.3.11b:

$$I_{\ell_2} = I_2/\sqrt{2}$$

$$I_2 = \sqrt{2}.I_{\ell_2}$$

In the limit, at rating, $I_{\ell_2} = I_{\ell_1}$

$$I_2 = \sqrt{2}.I_{\ell_1}$$

$$= \sqrt{2}.I_1/2$$

$$= I_1/\sqrt{2}$$

$$\text{Total A.T.} = N.I_2$$

$$= N.I_1\sqrt{2}$$

i.e. the A.T. and so the torque rating is $1/\sqrt{2}$ down.

This shows that the split layer arrangement implies a 30% reduction in the maximum torque available for a given machine.

However, due to operation at a higher rotational speed, there is an advantage in torque rating. This can be shown in three cases, depending upon the restrictions implied in the wind turbine operation.

(i) Torque and speed limit (Fig.3.12a)

If we use a slip recovery generator to provide T_o , w_o at 1.2 Ns (synchronous rotational speed), where w_o is the normal fixed speed running speed, the gear ratio must be changed. This will mean that the generator is at synchronous speed when the turbine is at 1/1.2 i.e. 0.8333 p.u. speed.

The maximum torque at the generator will only be 1/1.2 of the torque for the fixed speed case. The maximum turbine power has been generated by the generator running at a higher speed with less torque.

The generator rating is normally specified by its torque capability at rated slip (i.e. very near synchronous speed). Thus the size of the generator can be reduced to 83% of the fixed speed generator requirement.

If, however, the divided layer winding is used the inefficient use of copper limits the operation to a current of $1/\sqrt{2}$ of normal, with the same reduction in torque. So for this mode of operation the generator size would have to be specified at its rated slip to be $P_o.\sqrt{2}/1.2$ i.e. 1.18 P_o .

If the speed range possible were $\pm$ 41% then the generator size would be $P_o.\sqrt{2}/1.41$ i.e. 1.0 P_o . Thus the divided layer winding technique could be used without increasing the generator frame size.

(ii) Torque limit only (Fig.3.12b)

Suppose α was within the capable operating range of the cyclo-converter i.e. the gear ratio was not changed from fixed speed operation. The maximum torque at the generator is unchanged and if the divided layer windings were used the generator rating would have to be increased by a factor of 1.41 . However, the output power is increased to $\alpha.P_o$.

If α is 1.2 (20% slip) then a 20% increase in power can be achieved with an increase of 41% in generator rating, (net derating to 85%). If, however, a $\pm$ 41% slip range is possible then a 41% increase

in power can be achieved with an identical rise in generator rating.

(iii) Operation along maximum Cp curve to P_o (Fig.3.12c)

Suppose again that the gear ratio is not changed from a fixed speed case, and that β in the figure is within the operating range.

The maximum torque will be T_o/β. The generator can so be derated, but must be uprated by 1.41 for divided winding operation, i.e. a generator rating change of $1.41/\beta$ is required to deliver the normal output power P_o. Again, if β happened to be 1.41 then P_o could be obtained without an increase in generator size. β is a function of the Cp curve for the turbine, and can be calculated as follows:

If we assume the Max Cp curve to be of the form $T = k\omega^2$, where k is dependent upon the turbine characteristic, then

$$P = k.\omega^3$$

so
$$\beta.\omega_o = \left(\frac{P_o}{k}\right)^{1/3}$$

also
$$\omega_o = \frac{P_o}{T_o}$$

so
$$\frac{\beta.\omega_o}{\omega_o} = \beta = \frac{T_o}{k^{1/3}.P_o^{2/3}}$$

For a given turbine design cases (i) or (ii) are the most likely. These results can be used in conjunction with the torque rating figures of Table 2.2 in Chapter 2 to provide some indication of the required torque rating of the complete wind turbine system.

The advantage of a much simplified control circuit, avoiding the need for thyristor blanking etc., and the ability to start up from standstill may outweigh the disadvantage of this derating.

3.6 Presence of Secondary emf

It has been previously stated that a firing point for the thyristors is obtained at the point of intersection of two electronically produced waveforms, one associated with the supply across the device, the "firing" waveform, and one associated with the required output frequency, the "control" waveform. Under normal circumstances, with the cycloconverter operating into a passive load, and with a normally wound machine, the "cosine crossing" technique is used, where the control waveform is a sinusoid of the required output frequency. Operation with such a system tends to produce a sinusoidal output current waveform which lags the control waveform, due to the inductance in the load, see Fig.3.13.

In this work, it was attempted to produce sinusoidal current in phase with the secondary emf induced in the windings. As the windings are now separate, it is no longer possible to simply use a sinusoidal control wave, as this would produce a current of the form as has been shown in Fig.3.13. This is due to the current having to build up from zero every cycle. Another problem in this scheme is that the load is no longer passive, but contains an induced emf whose amplitude varies with speed. Depending on the required direction of power flow the secondary emf may aid or oppose the generation of sinusoidal current. During operation as a generator this induced emf opposes the production of current subsynchronously, and aids it supersynchronously. The effect on the output current can be shown clearly if we assume that the control wave is a square wave of a fixed amplitude, and so all the firing angles are the same, as in Figs.3.14a and b. In order to produce sinusoidal current in the load, the firing angles must be modified to counteract these two problems.

For an application in which large torques are required subsynchronously this emf may be an important problem as, for instance, in a positive half cycle of output current the firing angles have to be decreased to counteract the opposing emf, and a firing angle limit may be reached. However, for the

wind turbine system only relatively low torques are required subsynchronously, and the opposing emf does not present too great a difficulty.

In order to overcome these problems, a modification to the cosine crossing technique was devised. In this, the basic technique of firing a device at the intersection of waveforms was retained, but the control waveform would now no longer be a simple sinusoid, but a waveform calculated to produce an output current which is sinusoidal and of the correct amplitude. This waveform would then incorporate the modifications required to overcome the problems outlined above.

A computer programme was developed to calculate the required firing angles, see Appendix 2 for further details. These were then used to produce a new control wave. It was decided to use a representation of the actual supply volts across the device as the firing waveform, this would then simplify the timing of the six-phase system.

As the secondary emf induced in the windings changes amplitude with speed, the firing angles must compensate for this change over the speed range. This means that the control waveforms produced by the programme effectively changed shape with speed. In order to produce sinusoidal current over the complete operating range, the speed range was divided into 64 intervals, each of which had its appropriate control waveform. The correct waveform was addressed at its required speed by the secondary emf signal generator, (see Section 4.6). Also, to further simplify the system, each waveform was calculated in order to provide the correct current (and therefore torque) to operate the scheme over the demanded torque-speed characteristic (shown in Fig.1.5). This also obviates the need for a servo control system. The given torque speed characteristic can be scaled as a whole by modification of the amplitude of the control waveforms. Some typical waveforms for sub- and super-synchronous operation are shown in Fig.3.15.

3.7 Stable Operation

Conventionally a doubly fed machine with a variable frequency source on the secondary operates in a synchronous mode. A voltage is injected into the secondary winding at a frequency corresponding to the desired speed, (ref.21). If a large change in speed is demanded, the machine is effectively out of control until it reaches the required speed. This problem is usually overcome by incrementally changing the frequency of the injected voltage until the demanded speed is reached. However, for a wind turbine operating with a fluctuating shaft torque, this operating scheme could still prove to be unstable. Also, as this type of operation is under speed demand, the wind speed would have to be known, and the optimum operating speed calculated and then demanded to the system. Such a control which depends on an inherently fluctuating input (wind speed) is likely to be rather complex.

In the operating scheme proposed here, frequencies are not forced into the rotor, but are controlled by the machine speed to be of the same frequency and phase as the secondary emf. With the current in phase with the secondary emf, the torque is directly proportional to current. Changes in speed are obtained by control of torque. The frequency and phase of the secondary emf is obtained by the use of the secondary emf signal generator (see Chapter 4). This provides an 8 bit digital word corresponding to the phase angle of the secondary emf. This word is derived electronically, without actually observing the secondary emf. The output of the signal generator is locked in phase with the secondary emf at all speeds and so can be used to enable the control wave required above to be output in phase with the secondary emf. The correct phase relationship is thus obtained for operation of the cycloconverter as described previously. This completely removes any control instability.

For other applications, the signal generator output can be used to provide control of doubly fed machines in other modes of operation, e.g. cycloconverter motoring or other static Scherbius systems.

CHAPTER 4

4.0 Control of the Cycloconverter

For correct operation of the induction generator above and below synchronous speed, the current provided by the cycloconverter must be in phase with the secondary emf. A number of methods have been used to achieve this control requirement. Ohno and Akamatsu (ref.23) used a distributor connected to the shaft of the induction machine in order to provide a signal locked in phase with the secondary emf. Smith (ref.7) developed a digital electronic system to provide similar information. The digital approach seemed most reasonable, but there were problems associated with the misreading of pulses in the electronics. This study aimed to improve the digital technique, incorporating a self-checking system for overcoming any electronic problems, and therefore providing a reliable system for a commercial environment.

The thyristors must control the current flow between the mains supply and secondary windings of the generator. For a given current the direction of power flow depends upon the sign of the secondary emf and the amount of the power flow upon the magnitude of the secondary emf. The thyristor firing angles are to be derived from control waveforms (Section 3.6). These control waveforms must be produced electronically and must remain in synchronism with the voltage induced in the secondary windings for the power flow to be controlled correctly. The phase relationship of the control waveform and the secondary emf must change by 180° through synchronous speed. The frequency and amplitude of the secondary emf varies with speed. Information about the frequency and phase of the secondary emf cannot be found by direct measurement, for several reasons;

(i) Near synchronous speed, the secondary emf approaches zero, with considerable superimposed slot noise.

(ii) The voltage measured is only equal to the secondary emf at zero current.

(iii) If a thyristor is firing between the secondary and a particular mains supply wave, then the voltage seen will be those supply volts.

By fitting a slotted disc to the shaft of the rotor, scanned by an optical device, the angular position and rotational speed of the generator can be found, and if the phase angle of the mains supply is known the slip frequency and amplitude can be derived. It is possible to electronically derive a representation of the secondary emf phase in this way, locked in synchronism with the actual emf.

The frequency of the secondary emf is given by

$$Fs = s.Fm \quad ,$$

where $s = (Ns-Nr)/Ns$

Fs = secondary emf frequency, Fm = mains frequency

s = slip

Ns = synchronous rotor speed

Nr = actual rotor speed.

If two counts are produced, one proportional to the phase angle of the mains supply, the other proportional to the rotor shaft phase of rotation, and the "rotor count" subtracted from the "mains count" electronically, a count proportional to the slip frequency phase angle is produced; the "secondary count".

The synchronous speed of the induction generator in this work is 1500 rpm, and at this speed the frequency of the secondary emf is zero, with the phase angle unchanging. If there are N counts per cycle of mains and the rotor at synchronous speed is turning at 25 revs/sec then there must be 2N counts per revolution of the shaft such that the mains and rotor counts progress at the same rate. In this case the difference count remains unchanged, corresponding to a constant secondary emf phase angle.

At other speeds the counts can be shown diagrammatically as in Fig.4.1. The figure assumes that at time zero the mains, rotor, and secondary counts are zero which can be achieved by positioning of the disc on the rotor shaft, as will be explained in Section 4.2.2. below.

Fm,Tm,Nm are supply frequency, period, count

nr,Nr are rotor speed, count

F2,N2 are secondary frequency, count

ns is synchronous speed

s is slip

N is the total count in one cycle of the mains.

At time T in Fig.4.1 the counts can be described mathematically as follows

$$Nm = N.T/Tm = N.T.Fm$$

$$Nr = 2.N.T.nr$$

$$N2 = Nm - Nr$$

$$= N.T.(Fm - 2nr)$$

$$= N.T.(Fm - 2ns(1-s))$$

Now $2ns = Fm$

$$N2 = N.T.(Fm - Fm(1-s))$$

$$= N.T.s.Fm$$

$$= N.T.F2$$

Therefore N2 is a count of N per cycle of secondary emf. This shows that when the counts are initially synchronised, if the rotor and mains counts are accurate then for any speed the secondary count is in synchronism with the secondary emf.

The maximum count N has been chosen at 256 to ensure no redundancy in an 8 bit digital counting system, and to overcome any problems with the mode of arithmetic being used (see Section 4.3).

4.1 The Mains Count

The mains count is produced by squaring up the 50 Hz mains supply and then multiplying this frequency by 256 using a phase locked loop IC and divide-by-N counters. The resultant pulses are clocked into an 8 bit counter, continually reset on positive edges of mains supply, thus maintaining synchronism in the event of any high frequency pulses being lost or misread. The output of the counter is an 8 bit digital word representing the phase angle of the mains supply. A schematic diagram of the electronics required is shown in Fig.4.2.

4.2 The Rotor Count

4.2.1 Rotor pulses

The rotor count is produced by optically scanning a slotted disc fitted to the rotor shaft. For correct operation of the secondary emf signal generator, at synchronous speed both the mains and rotor counts must be progressing at the same rate. Synchronous speed in this case is 25 revs per second (1500 rpm), and so the rotor count must be two consecutive counts of 256 per revolution, i.e. 512 counts per revolution. The disc fitted to the rotor has 128 slots per revolution and so some method of multiplying this frequency by four is required. It is possible to do this by use of a phase locked loop and a divide-by-4 counter in a similar way as for the mains count. This was tried and found to be occasionally unstable, due to the large lock-in range required, i.e. over a $\pm$ 20% slip range. The slot frequency was finally multiplied by means of monostables triggered on the positive and negative edges of the slot pulses, and also on the positive and negative edges of the resulting pulses. These pulses must be made short enough to ensure no collision at high slot pulse frequencies.

4.2.2 Synchronising and rotor reset

The secondary count must start from zero when the secondary emf passes through zero in the positive sense. As has been shown above;

Mains Count - Rotor Count = Secondary Count

so that when the mains count equals the secondary count the rotor count must be zero. If this condition is met the secondary count will be in phase with the secondary emf. This is achieved as follows:

Two extra slots are available on a second track of the disc. These are 180 degrees mechanical apart, corresponding to the two counts of 256 as mentioned above. At standstill the rotor is turned so that the mains and secondary emfs are exactly in phase. At this point the rotor count should be zero. The slotted disc is then aligned so that a reset pulse is being read, and used to set the rotor count to zero. Note that this alignment need only be done once on fitting the disc to the shaft, and is left in that position for all subsequent operation.

The system must receive 256 pulses per half revolution of the shaft. It is possible that pulses may be misread. However, the reset pulses can be used to reset the counter at the point at which 256 pulses should have been read even if this has not been achieved.

The rotor pulses are clocked into an 8 bit counter, reset by the rotor reset pulses, which produces an 8 bit digital word representing the phase angle of a half-rotation of the rotor shaft.

With the mains count being continually reset on each positive edge of the mains supply, and the rotor count reset twice per revolution, each count is maintained accurately. Under these conditions the subtraction of the two counts will give an accurate representation of the secondary emf, locked in synchronism with it.

4.3 The Output Count

The output count is obtained by electronically subtracting the two digital 8 bit words produced from the above, i.e. mains count minus rotor count. This produces an 8 bit digital count in synchronism with the secondary emf. If the rotor count is greater than the mains count (i.e. the output count is negative) then the output number is given in the form as shown below: (i.e. two's complement)

Mains Count		Rotor Count		Output Count	
MSB LSB		MSB LSB		MSB LSB	
00 00 00 01	(1)	00 00 00 00	(0)	00 00 00 01	(1)
00 00 00 01	(1)	00 00 00 01	(1)	00 00 00 00	(0)
00 00 00 01	(1)	00 00 00 10	(2)	11 11 11 11	(255)
00 00 00 01	(1)	00 00 00 11	(3)	11 11 11 10	(254)

etc.

The output count is fed into the 8 LSB addresses of the EPROM.

The information which is required in the EPROM is coded in pages of 256 x 256 bits. Each page corresponds to a control waveform,and if the whole page is used for each waveform, then an address number of 255(-1) will produce the correct output, as in effect the pages "wrap around". However, a count up to another number would produce an error, for instance if the designed maximum count were merely to 250 and the count addressed to the EPROM was -1 (i.e. 255), the EPROM would not have any data programmed in at this address. Note that subsynchronously the output count counts up, and supersynchronously it counts down, thus providing the necessary change of phase through synchronous speed.

This output count is continually addressed to an EPROM which contains the waveforms required to operate the cycloconverter.

4.4 Three Phase Multiplexing

In order to produce three phases of output signal, the output count has a count of 85 and 171 subtracted from it, corresponding to 120

and 240 degrees phase angle of the output waveform respectively, and these two counts and the original are multiplexed together into the EPROM. These three counts then correspond to the three phase secondary emfs induced in the rotor of the induction generator.

4.5 The EPROM

The EPROM is programmed with the control waveforms required to fire the thyristors according to the calculated firing angles and also operate the induction generator over the desired torque-speed characteristic from Chapter 2. This means that the required changes of amplitude of the control waveforms in order to operate on this torque-speed characteristic are contained directly in the EPROM. However, by changing the reference voltage to the output D-A converter, the complete set of control waveforms could be scaled in amplitude. As the control waveforms change shape and amplitude over the speed range, (Section 3.6), the EPROM is programmed with 64 pages of waveforms corresponding to 64 intervals of speed between 20% subsynchronous and 20% supersynchronous. The EPROM is a 27128, containing 128 k (= 64 pages of 8x8 bytes) of memory. It is continually addressed with the multiplexed three phase secondary emf count. As the operational speed capability of the EPROM is much faster than any changes likely to occur in this mode of operation, no time delay problems were observed.

4.6 EPROM Page Address

The EPROM is addressed with the secondary emf frequency and phase data from the secondary emf count as explained above. To address the EPROM pages so that the correct waveform is produced at the appropriate speed a 6 bit digital word representing speed is derived from the rotor count pulses as follows. A d.c. voltage is obtained from the rotor pulses by a frequency to voltage converter which produces a voltage proportional to

speed. This voltage is converted to an 8 bit digital word representing speed by an A-D converter. The 6 least significant bits are used to page the EPROM, the two others are used to indicate operation within the speed range of ± 20%. It must be noted that in order to obtain a smooth voltage output from the frequency to voltage converter, a large capacitative filter was used, which implied a lag in the response to rapid changes in speed. This was not considered a problem in a wind energy converter, with its large inertia, but for step changes in speed this may be an important effect (see Section 5.2.2).

The 8 bit count corresponds to the speed as below

Speed	MSB			LSB	
Below-Range	01	XX	XX	XX	
1200	10	00	00	00	X = Dont Care
1500	10	10	00	00	
1800	10	11	11	11	
Above-Range	11	XX	XX	XX	

Operation within range can be detected from the MSB's using simple logic and used to enable the output of the secondary emf signal generator. In this system a 2 second delay on enabling and disabling is introduced to add hysteresis and prevent excessive instability at the operating limits during testing.

4.7 Output Circuitry and Demultiplexing

The EPROM produces a digital output representing the multiplexed three phase control waveforms required to operate the cycloconverter in the mode required. This output is converted to analogue form using a D-A converter. This converter requires a reference voltage to determine the output amplitude of these waveforms. This amplitude will determine the amount of current produced by the cycloconverter (see Section 3.2). In the present system this was controlled manually; however, it would provide

a suitable method of controlling the amplitude of output current in a servo control system.

The demultiplexing of the three phase-displaced control waveforms is achieved after the signal has been converted to analogue form, by means of Sample-and-Hold devices. This was done in order to keep the chip count down (i.e. requiring only one instead of three D-A converters). However, a more suitable form of demultiplexing would probably be to demultiplex the digital outputs of the EPROM.

This completes the secondary emf signal generator, which has been built and tested and worked as required up to a speed of 30% super-synchronous, the limit being determined by the requirement for multiplying the rotor count frequency by four. A simplified diagram of the whole system is shown in Fig.4.4.

4.8 Firing Circuit

The computer program which calculated the firing angles for operation of the system over the required torque speed characteristic was based upon the firing points being produced at the intersection of the control signal and a representation of the supply voltage across the device to be fired.

The control signal will be produced by the secondary emf signal generator, which provides an analogue signal of 10 V amplitude. Similarly scaled representations of the six phase supplies are derived from transformers. The point of intersection of these two waveforms is obtained by a comparator.

Figure 4.5 shows how current can be controlled into one secondary phase (making reference to only one of the six supply waveforms). The comparator is shown to change state at the intersection of the supply and control waveforms. In Figure 4.5a the rotor emf is considered to be on a positive half cycle. If the 'p' group thyristors were triggered from

monostables operating on the leading edge of the comparator output then they would turn on as they are positively biased (shaded area). If the 'n' group thyristors were fired via a monostable operating on the falling edge of the comparator they would not turn on as they are reverse biased. Thus only the 'p' group devices would operate to give the correct polarity half cycle of current.

When the rotor emf is on the negative half cycle, as shown in Fig.4.5b, it can be seen by similar reasoning that only the 'n' group devices fire.

Therefore, using such a system, there is no need for any blanking of devices, as a natural effect of the control scheme is that the devices that are not required to fire will be reverse biased.

The pulses for the p and n group thyristors are obtained by firing a monostable on the positive and negative edges of the comparator output waveform. The monostable generated a fixed length 2.5 millisecond pulse.

4.9 Gate Drivers

The monostable pulses must be amplified in power level and electrically isolated before connection to the thyristors. Pulse transformers are used to provide this.

The circuit for the power amplification and isolation is shown in Fig.4.6. This is used to provide the necessary gate current to fire the thyristors, and also to isolate the electronics from the gate of the thyristors.

If the 2.5 millisecond monostable pulse were transformed directly into the gate drive pulse then a large transformer with many turns would be required. In this system these pulses are converted into high frequency pulse trains which require much smaller transformers and fewer turns.

The monostable pulses are gated with the Q and Q(bar) outputs from a 100 kHz clock as shown in the figure. The output of these gates drive the MOSFETs on alternative half cycles of the clock, switching a

square wave of voltage onto the primary of the pulse transformer. The pulses are rectified at the secondary side of the transformer to give a continuous gate pulse of 2.5 ms . A diagram of the pulse configurations in the circuit are also shown in the figure.

4.9.1 Design of the pulse transformers

The pulse transformer can only be designed when the gate operating point has been established. A load line for the gate circuit was chosen as shown on the gate characteristics in Fig.4.7. This indicates an open circuit voltage of 6 V and a peak gate current of 0.46 A will be required.

With a 2.5 ms pulse of amplitude 0.46 A occurring every 20 ms the rms current will be 0.16 A . The average power dissipation will be approximately 112 mW , well below the average gate power rating of 500 mW .

With a supply voltage available of 12 V , the specification for the transformer becomes

Secondary 12 V centre tapped. wire rating $0.16/\sqrt{2} = 0.113$ A
Primary 24 V centre tapped, wire rating 0.056 A

However, this does not account for the magnetising current which will be a function of the core and number of turns.

From Faradays Law $e = d\phi/dt$ $\phi = BA$

$$N_1/2 = V.t_1/B.A$$

where N_1 is the total primary turns
t_1 is the high frequency clock high period of 5 microsecs,

giving $N_1 = 12$
$N_2 = 6$ (secondary turns).

The magnetising current is calculated from

$$H.dl = Ni$$

so $$B.dl/\mu_o\mu_r = N_1.i/2$$

giving $$i = 0.4\ A$$

Assuming a waveform of the type shown in Fig.4.8, this gives a primary rms current of 0.11 A . The wire size was thus chosen as 34 SWG .

The diodes for rectification of the output must be fast recovery type to ensure accurate reconstitution of the 2.5 ms pulses. The devices used are BYV 96. The average forward current is 0.03 A , compared with rated 0.8 A .

4.10 The Cycloconverter

The cycloconverter in this scheme has six effective phases of mains supply, feeding into 3 "positive current" windings and 3 "negative current" windings, and as a result there are 36 thyristors required, in 6 groups of 6.

The devices used were Westinghouse type CS21, which were available beforehand. These are rated at 16 A mean forward current.

To calculate the power dissipation per device, the mean forward current and conduction angle of each device supply is required. Certain simplifying assumptions may be made in order to derive this. One may assume that each thyristor group carries a rectangular waveform of current having a value equal to the average value of one half cycle of sinusoidal output current. Each device in the group can be assumed to carry this level of current over its conduction angle. One assumes that the current is continuous at this point, and so the conduction angle is 60° . The maximum current produced by the cycloconverter is 7 A rms, and using the above assumptions a mean forward current per device (over one period of mains supply) is 1.06 A . From the data sheet for the device it can be seen that the power dissipated is approximately 1 Watt (at these low currents the graph is linear with a gradient of 1 Watt/Amp) .

The temperature profile for the devices and sinks are calculated and shown on the schematic diagram, Fig.4.9. Evidently in this case the devices and sinks were larger than necessary.

The R-C suppression circuit (Fig.4.10) component sizes were derived from ref.26.

CHAPTER 5

5.0 Results

The results were taken on the working system primarily in order to assess the novel concepts and techniques introduced in this thesis. These are

(i) Use of the secondary emf signal generator to synchronise the operation of the cycloconverter to the secondary emf induced in the machine windings.

(ii) Control of the thyristor firing angles to provide sinusoidal current in phase with the secondary emf in the machine secondary, and to control its amplitude in order to develop a required torque speed characteristic.

(iii) Use of six effective phases of mains supply, in order to improve the quality of the output waveform and so possibly extend the operating speed range.

(iv) Motoring from start-up.

The reasons for the use of this torque speed characteristic in wind energy applications was considered in Chapter 2.

The results were obtained by loading the induction generator with a DC machine connected on the same shaft, the DC machine being controlled by a regenerative thyristor controller operating either under speed or current control. A torque transducer measured the torque on the connecting shaft.

In order to assess the quality of the waveforms produced by the cycloconverter a commercial Fourier analysis program was used on a BBC B microcomputer, and the waveforms taken from a current probe and digital storage oscilloscope, of which more details are in Appendix 1.

No assessment was made of the total efficiency of the system, due to the low power rating and the large lossy transformers and components which had to be used. Financial restraints prevented the design and selection of optimally rated components. Also the machine was a relatively inefficient universal teaching machine, for which efficiency figures would be meaningless in terms of a practical commercial version of the system as a whole.

Operation could be obtained in several modes:

(i) Using 6 phase or 3 phase supplies.

(ii) With the secondary emf signal generator changing the output EPROM pages with speed, or holding the same output page over the complete speed range.

(iii) With varying supply voltages to the cycloconverter thyristors.

5.1 Secondary emf Signal Generator

With the secondary windings open circuited the actual secondary emf was compared with the electronically produced signal from the secondary emf signal generator. The electronic signal remained in synchronism throughout the operating range, and the two waveforms are shown (with the signal generator producing an unchanging output wave shape) in Fig.5.1 for speeds just below and above synchronous speed. There is an inherent lag between the two pens on the plotter. Note that the phase relationship of the two waveforms has changed by 180° through synchronous speed, corresponding to the required change of power flow direction. With the cycloconverter operating, the current in the secondary compared with the signal generator output is shown in Fig.5.2. The plotter has smoothed out the high frequency components of the current waveform. It can be seen that the current remains in phase with the signal generator output but the latter has changed phase with respect to the actual secondary emf. The power flow, therefore,

has changed direction in a controlled manner.

During the cycloconverter operation, the output waveform from the signal generator operated the thyristors correctly in phase with the secondary emf. When other equipment generating harmonics were operated on the low capacity supply in the laboratory mal-operation would occasionally occur. Large currents were observed at this time, indicating that thyristors were being gated at the wrong time. Further work would be required to isolate the problem area. However, the separated split layer winding prevented a disastrous short circuit. This mal-operation is probably due to distortion of the firing waveforms derived from the supply. In order to combat this it would probably be advisable in future to derive these firing waveforms from a completely independent source in such conditions.

5.2 Operating With Page Changing System

5.2.1 Steady state results

With the system operating in its designed mode, i.e. changing secondary emf pages with speed, the torque and secondary current were measured over the range of operating speeds, and these are shown in Figure 5.3, compared with the required operating scheme from the considerations of Chapter 2. Examples of the control waveform shape and secondary current for four speeds operating on this characteristic are shown in Fig.5.4. This torque was produced without any adjustment of the amplitude of the secondary emf output waveform, i.e. the changes in amplitude required to develop the torque speed characteristic had been programmed into the EPROM from the computer program.

Considering that there are no closed loop torque or current servos in the control system, the operation corresponds quite closely to the required torque speed characteristic. The main deviation is that the steep part of the characteristic is not fully achieved. By adjusting the amplitude reference signal to the signal generator output, this torque charact-

eristic could be scaled up or down, and if a current or torque servo were incorporated to modify this signal, the results could be made much more accurate but with a corresponding increase in control complexity.

Typical current waveforms with their Fourier analyses are shown in Fig.5.5 for operation on the torque-speed characteristic at speeds of 1275 and 1725 rpm (+ and - 15% slip). From the waveform shapes it is evident that the machine has a relatively low inductive component, leading to very "peaky" current pulses from the cycloconverter. These results can be compared with computer predictions of the current at these speeds, Fig.5.6. Both waveforms are quite free of any major low frequency harmonics; the higher frequency harmonics (≃ 40th harmonic) correspond to the 300 Hz six phase supply frequency. It is evident that these will be noticeably greater in the more discontinuous output at 1275 rpm, as the torque and so current at this speed is low.

5.2.2 Dynamic results

The speed of the generator was changed manually by means of the demand speed signal of the variable speed d.c. thyristor drive.

The torque and speed over the speed range are shown in Fig.5.7.

It can be seen that during operation over the steep part of the torque characteristic, i.e. speeds greater than 1650 rpm, the machine speed and torque tend to fluctuate slightly. This is due to the large steps in torque between two pages of secondary emf output. This problem was not caused by any incorrect page changing in the electronics but by the inability of the loading d.c. drive and controller to maintain constant speed accurately. In a wind energy system, containing a large inertia, such fluctuation in speed should not occur.

A problem may occur, however, due to this large step increase in torque for a small increase in rotational speed, i.e. a small increase in

speed produces a large increase in load torque, which causes a reduction in speed, which removes the load torque, which produces an increase in speed again, etc. . Even in such a situation, the turbine inertia would reduce the rate of fluctuation, and this effect would probably be slight compared with the effect of gusting input wind speeds on a fixed speed turbine.

The dynamic effects of step changes in rotational speed are obtained by demanding the step increase to the d.c. drive controller. The results were obtained for operation in the page changing and constant page modes. The resulting torques are shown in Fig.5.8. It must be noted that, due to certain requirements of the electronics, there is a time lag between a change in speed and the resulting change in page address, see Section 4.6.

Fig.5.8a shows the result of a speed change with the control waveform shape and amplitude held constant. The initial torque peak on the rising edge is due to the torque produced in accelerating the generator by the d.c. drive. The change in torque levels between the two speeds show the natural effect of the secondary emf. At 1250 rpm there is a large emf opposing the production of current in the windings. This opposing emf is reduced at 1450 rpm , leading to an increase in current, and therefore torque.
Fig.5.8b shows the same speed change but with the page changing system. As this speed change occurs over the shallow part of the torque-speed characteristic, the results are quite similar to Fig.5.8a, i.e. the change of amplitude and shape of the control waveform is small, and therefore has little effect.

Fig.5.8c shows the effect of a speed change between 1550 and 1750 rpm. The strange effect occurring at the leading edge is due to a combination of the time lag in paging mentioned above, and the abrupt change in torque-speed characteristic at approx, 1675 rpm. Initially there is an accelerating torque peak as above, falling back to a torque level corresponding to operation still on the shallow part of the torque-speed curve,

where page changing has little effect. Some time later a page corresponding to operation on the steep part of the torque-speed curve is addressed and this results in a large increase in torque. If results are taken more completely on the steep part of the operating characteristic, this unusual effect is reduced, and it is eliminated when operation is wholly on the steep part of the curve (Figs.5.8d,e).

It must be noted that the lag was only present in the paging of the output waveform shape, but not in the data for the slip frequency and phase, which responded instantaneously to changes in speed, i.e. the shape of the output waveform was momentarily incorrect but the frequency and phase were correct.

The above effects are all given for a step change in speed. Such a change will never occur during wind turbine operation, due to the large blade inertia present. The control system was designed for use with a large inertia, i.e. a wind turbine, and under these circumstances would work correctly.

5.3 Constant Page Operation

The above results show operation with the complete page changing system. Results were also taken for operation with the page address held constant, with only one waveform shape used over the whole speed range. If this mode of operation could be found to have any useful characteristics, it would provide a very simple control system. Such operation was assessed using three of the waveforms present in the ROM, corresponding to the pages normally used at 1350 , 1500, and 1650 rpm. Note that the 1500 rpm page was equivalent to a square wave output waveform.

With the waveform amplitude held constant each page produced a torque speed characteristic as shown (Fig.5.9). The amplitude of each waveform was set to produce the same torque at 1750 rpm, and then held at this value as the speed was changed. In this case the change in amplitude of the current

is determined simply by the change in secondary emf with speed. The emf opposes the production of current subsynchronously and aids it supersynchronously. As the secondary emf changes linearly with speed, in theory the current should increase linearly with speed. However, the quality of the current waveform will also change with speed. The torque versus speed is plotted in Fig.5.9. The gradient in both cases is linear subsynchronously, but increases more rapidly supersynchronously. This may be due to the general improvement in waveform quality supersynchronously, due to the aiding sinusoidal secondary emf and also the more continuous nature of the current.

As the quality of current produced by such operation was better than expected over the operating range, a more detailed assessment of this mode of operation (with respect to the actual page changing system) was carried out. Each waveform was assessed in terms of its torque per amp capability over the complete speed range, and compared with the page changing technique. The amplitude of the control waveform was adjusted to give the required current and so torque at each speed. At synchronous speed the page changing system uses a square wave output signal to fire the thyristors. This ensures that wherever the count stops (as it must at synchronous speed), the firing angle remains constant. Steady operation is also achieved at synchronous speed using a constant sinusoidal page. Each phase of the winding may receive differing amounts of current, but the net effect produces a torque as shown in the figure, which shows a smooth transition in torque between sub- and super-synchronous speed.

The torque per amp figures for operation on the required torque-speed characteristic are shown in Fig.5.10. It can be seen that the page changing system has the best figures for all speeds, but the actual values vary considerably. The advantage of using the calculated waveforms is rather small, except at the low subsynchronous speed (1250 rpm where the advantage over the nearest rival is 14%). This is to be expected, as the secondary

emf at this speed will be a large voltage opposing current production, and this is the case where the greatest modification of a conventional cosine crossing technique is required. The square wave produces the worst results over the complete speed range.

However, it is more useful to assess the waveforms for a constant torque level over the speed range, which has been done for two levels of torque in Figs.5.11a and b. Similarly to the above results, the page changing system here gives the best torque per amp figures. The advantage in terms of torque per amp for paging is small compared with the next best figure, i.e. only 2 or 3%. These results are also reflected in the Fourier analyses of the waveforms, shown in Figs.5.12a-h, where the page changing system has the best current waveform output, with least harmonics. As with the torque per amp figures, page changing gives the best results, but the advantages are not particularly great.

An interesting point is that using these waveforms at fixed amplitude produces a torque speed characteristic which is essentially linear sub-synchronously, with a more steep part supersynchronously, as has been shown in Fig.5.9. As this bears some relationship to the desired torque-speed relationship evaluated in Chapter 2, it may be possible to use this charact-eristic on a wind turbine. This would then operate the turbine with virtually no control system at all, and so be extremely simple.

The general qualities of the two waveforms used in the fixed page system, and are generally true of most of the waveforms contained in the EPROM, are that they have a relatively sharp leading edge, with a sinusoidal "top". The rapid rise at the leading edge helps the quick production of current and counteracts the lagging effect of the inductance. From the computer program the control waveforms for large supersynchronous slips have been shown in Figs.5.4d and 5.6b. The dip in the middle has the effect of reducing the firing angle and so counteracts the effect of the large aiding secondary emf present. However, the experimental results do

not indicate that this type of control waveform is absolutely necessary, as a good sinusoidal current is obtained with waveforms not possessing this dip. This may mean that in the program calculation for the current in the secondary winding the resistive component was too low, i.e. the program overestimated the current being supplied for a given firing angle.

5.4 Three Phase Operation

Six phases of mains supply were obtained by using two three-phase transformers with their secondaries connected in opposing senses, as shown in Fig.5.13. This provides a greater number of current pulses per given output cycle and so improves the quality of the waveform. The results presented above were obtained in six phase operation. However, as the cost of the transformers could be great, performance was assessed using only three phases of mains supply. The torque per amp results under the same conditions as the six phase results are shown with the previous results in Fig.5.11b. Results could not be obtained for three-phase operation at maximum torque as the required current levels could not be achieved before the maximum firing angle was reached. These results were taken at a torque of half maximum. At these torques the average decrease in torque per amp due to three phase operation is approximately 20%. Note however that the control waveforms have been calculated assuming a six phase supply, and so are not optimising three phase performance. The current waveforms and their associated Fourier analyses are shown in Fig.5.14 for three speeds with three phase operation, and a six phase current waveform shown for the 1750 rpm speed for comparison. This 1750 rpm case shows the worst case for the three phase system, where the harmonics produced by the discontinuous waveform are most prominent. The analyses show that in the three phase case the fundamental contributes a lower percentage of the total rms supplied to the winding, which explains the decrease in torque per amp obtained.

5.5 Motoring from Start-Up

Although a normal cycloconverter can only operate between its frequency limits, implying a maximum and minimum rotational speed for a slip energy recovery system, it was found that the system presented here would start the induction machine from standstill and drive it to approximately 1000 rpm. This was achieved by effectively making the secondary emf control waveform equal to a zero voltage; the devices are then receiving firing pulses as shown in Fig.5.15. A typical secondary emf is also shown. In this situation the p group devices fire when the secondary emf is negative, and the n group when the secondary emf is positive. This produces a current as shown in Fig.5.16, which is in phase with the secondary emf and produces a motoring torque. In a six phase system both a p and n group device fire at the same point, and although the supply voltage between the two is such as to progressively reverse bias the devices, there is a momentary short circuit. However, with the divided winding scheme, this is avoided. The torque and current during start-up are given in Fig.5.17. Extra torque would be obtained if the secondary emf were larger with respect to the mains supply. The ability to start-up in this way is also possible with three phase operation. However, as there are fewer firing points available, the current waveform produced will be different, so affecting the starting torque. Start-up without a neutral is also possible.

5.6 Neutral Connection

In order to provide a stable zero voltage point for the firing of the thyristors a neutral is required. The effects of removing the neutral are shown in Fig.5.18, which shows the thyristors being fired at a constant angle, at nearly synchronous speed (i.e. virtually no secondary emf). It can be seen that removing the neutral and using a constant firing angle, by paging a square wave, the output current is a quasi square wave. For

three phase supplies a neutral is not likely to be available, and this method of operation may be suitable. The waveform will deteriorate rapidly, however, at low subsynchronous speeds when generating, due to the effect of the secondary emf, see Fig.5.19. Without the neutral the cyclo-converter still allows starting up from standstill, as described in Section 5.5 above.

5.7 Effect of Transformer Voltage

For any commercial system it should be possible to optimise the relationship between the peak voltage supplying the thyristors (provided by a transformer), and the peak secondary emf voltage. In general, the firing angle required for a particular current depends upon the ratio of secondary emf volts : thyristor supply volts. In subsynchronous generation, for instance, an increase of this ratio will require a decrease of the firing angle over a positive half cycle for a particular output current,as shown in Fig.5.20. In both cases an increase of the ratio will produce a more continuous and smoother output waveform. However, there must be enough supply voltage to provide the necessary current required over the operating speed range. The amplitude of the secondary emf varies with speed and its natural effect on the current has been shown in Section 5.3 of this chapter, where torque and current were plotted against speed for a fixed amplitude of control wave (and therefore a fixed net firing angle). Essentially it can be seen that the major problem occurs at low speeds (i.e. high subsynchronous slips), where it is most difficult to produce current in the generating mode. This is due to the net reduction of firing voltage due to the opposing secondary emf at subsynchronous speeds. Fortunately over these speeds the wind energy system requires less torque and so the problem is less severe.

In order to assess the effect of this ratio with speed, the system was operated with a varying amount of thyristor supply volts. These

results are shown in Fig.5.21 for values of torque up to the rating. Note that the control waveforms were not changed in amplitude throughout the test, and that the firing angle remained constant and at its maximum, but the net voltage available was being modified by variation of the supply volts to the thyristors. Also, due to the simplification of the firing waveforms the maximum firing angle is restricted to 90°. The figure can give some idea of the optimum supply voltage for the machine used. As has been mentioned the most preferable supply voltage will be the least possible, as long as the required torque-speed characteristic can be achieved.

To give some idea of the relative improvement of output waveform using reduced volts, the torque per amp figures were obtained for operation at a given speed and torque, for varying supply volts. These results are shown in Fig.5.22 and show an increase in torque per amp of 40 to 50% for a reduction of 50% in supply volts. The effect is also shown in the waveform quality and associated Fourier analyses in Fig.5.23. Note that the system has been designed for the full volts, and so some distortion of the current shape will be inherent in modification of these volts, but the essential point is the reduction of the high frequency harmonics. These correspond to the 300 Hz six phase supply components.

5.8 Summary

These results have been taken as an assessment of the output current quality for the novel control system contained in this system. The method of operation which was described in previous sections of this thesis, i.e. changing the shape of the control waveform with speed, was the most successful, but its advantage may be found to be small in comparison with other methods of operation which are available. This assessment has been done for operation with and without a six phase supply facility, and the effects of a neutral connection are considered. A very useful capability

of motoring up from standstill was discovered, which may be very useful in wind turbine applications. The effects of variation in supply volts have been provisionally considered, though more analytical work is required in this area. These results should be of considerable importance to the designer of a slip energy recovery system for use in wind turbine applications.

It must be noted that all these results were made easily available due to the use of the secondary emf signal generator, and that the use of such a technique is very strongly recommended.

CHAPTER 6

6.0 Conclusions and Further Work

Variable speed operation of wind turbines does not seem to produce significantly greater energy capture than a fixed speed wind turbine. For an operating scheme of the type outlined in this thesis, i.e. a $\pm$ 20% speed variation about synchronous speed, with operation mainly on the maximum Cp characteristic, the extra energy obtained by a steady state calculation is of the order of 5% . Dynamically, however, by allowing the blades to vary in speed, a much softer system is produced. This leads to reduction of the gusting torque fluctuations seen by the generator and so power variations into the grid supply are reduced. This may prove to be the most significant advantage of variable speed wind energy capture, (ref.27). Results taken from a wind turbine simulator and given in Section 2.5.2, show the significant reduction in torque fluctuations as a result of variable speed operation. At present very little data is available about the operational characteristics of wind turbines operating in a variable speed mode. Obviously more information needs to be obtained about the dynamic and structural effects of variable speed operation, especially in terms of the wind turbine structure resonant frequencies. These will have great bearing on the operating speed range of a variable speed wind turbine system, and will indicate if certain speeds must be avoided in order to prevent structural problems. Recently there has been increasing interest in the application of variable speed generating techniques to wind energy turbines, and variable speed operation is regarded as a worthwhile area for investigation. Therefore the particular system investigated in this study should be a useful contribution to knowledge in this area. Considerable interest has been shown in outline papers based on this study (ref.28).

The cycloconverter slip energy recovery system investigated has both

advantages and disadvantages compared to alternative schemes, which have been described in Section 1.2. The cycloconverter has a simple power configuration with no d.c. link (which is subject to commutation failure during transient mains outages) and only active power semiconductors (i.e. no chokes, capacitors etc.). The restricted speed range does not appear to be a major disadvantage, particularly as a motoring capability is available to initially run up the turbine. There are well known stability and control problems associated with doubly fed machines and cycloconverters. This study has concentrated on the elimination of these problems to provide a basis for an economic and reliable system. The problems that have been overcome are:

(i) The stability problem of a doubly fed machine has been resolved by allowing the machine to operate asynchronously in conjunction with a novel secondary emf signal generator.

(ii) The problem of producing a suitable output current waveform has been overcome by an electronic technique which controls the firing angles of the cycloconverter in accordance with previously calculated values derived from a computer program. These values are designed to produce sinusoidal current in phase with the secondary emf in the rotor windings.

(iii) The possibility of a short circuit occurring between two phases of the mains supply due to overlap in the cycloconverter has been removed by the use of a divided winding arrangement.

(iv) The deterioration of the current waveform for high output frequencies has been reduced by using six phases of mains supply.

(v) The control strategy and prediction of performance for a variable speed wind turbine have been obtained by the use of a computer simulation program.

6.1 Asynchronous Operation of Slip Ring Induction Machines

Other slip energy recovery systems are controlled to operate in a synchronous manner over their speed range. This is achieved by forcing voltages into the machine windings at a particular frequency. This slip frequency corresponds to a rotational speed, and the machine acts as if this were its new synchronous speed. However, if a large speed change is required, the machine is temporarily out of control, and this tends to produce control instability. This would be very difficult to remove in a wind turbine system, especially as the incident wind speed is fluctuating greatly, and so accelerating and decelerating torques are being applied rapidly to the shaft of the generator.

To remove this problem, the machine is allowed to operate asynchronously, by means of a secondary emf signal generator. This signal generator produces information about the frequency and phase angle of the secondary emf induced in the machine windings, by means of a slotted disc fitted to the shaft of the rotor. This allows the cycloconverter to operate in synchronism with the secondary emf, which effectively runs the machine in an asynchronous mode, and smooth control is provided over the complete speed range. The principle of the secondary emf signal generator was correct and the operation was effective, though minor changes in design could simplify and improve further models. These have been noted in Chapter 4.

6.2 Output Waveform Control

A conventional cycloconverter operates into a completely passive resistive and inductive load, in which the firing angles are produced by means of the "cosine crossing" technique. In this technique a sinusoidal "control wave" is used to control the firing of the thyristors, producing a sinusoidal output current waveform, which is usually lagging the control wave for an inductive load. In a slip energy recovery system, however,

a variable amplitude emf source is contained in the load, and the conventional cosine crossing technique would produce a distorted output waveform. This study proposed to calculate, using a computer, the required firing angles to produce sinusoidal output current in phase with the secondary emf, and to modify the cosine crossing control method to ensure that the cycloconverter actually operated with these firing angles. This was achieved by deriving waveform shapes from the calculated firing angles and using these waveforms as the control wave instead of the conventional sinusoid. The speed range was divided into 64 parts and each increment of speed had its associated waveform, each waveform consisting of a page contained in an EPROM. This principle of producing a control waveform from calculated firing angles, and using separate pages of waveform shapes at different speeds worked well. However, though these techniques produce an essentially simple piece of equipment, it may not possess sufficient advantages over what could be an even simpler system, i.e. using fewer pages of control waveforms, or even one control waveform over the whole speed range. An intermediate solution may be helpful, with a three page system, using one control waveform for low subsynchronous speeds, one for high supersynchronous speeds, and a virtually square wave for speeds near synchronous (it may be noted from Fig.5.4 that the waveforms programmed nearer synchronous speed are nearly square in shape). In conjunction with this, a current or torque servo could be used to control the amplitude of the waveform so that the current and therefore torque required at any speed would be achieved.

It may be noted that the computer program to calculate the required firing angles for a sinusoidal output ran for 30 mins. CPU time on a Cyber mainframe for each waveshape, which gives an idea of the difficulty of any on-line solution for firing angle calculation. Some knowledge of the machine parameters is necessary, however, for such an analysis. A one-page or a three-page system as proposed above may have to sacrifice such an exact analysis for a more general approach to obtaining a suitable control wave, if a commercial system is desired.

As indicated, the problem of a suitable method for output current control is not yet completely resolved. The general principle of the above method seems useful, however, and there are possibilities for use of a micro in a similar system (see below).

6.3 Divided Winding

Use of the divided winding arrangement incurs a derating of the machine. The net derating of the system, however, may be improved as operation at full rated torque at greater than rated speed is possible using the slip energy recovery technique. Despite this derating, the removal of the short circuit problem provides great advantages in terms of simplifying the control equipment. It seems that this arrangement also means that if at standstill the firing angles are held at 180°, and the cycloconverter is allowed to generate current by firing into the secondary emf, the machine will run up from standstill as a motor to 1000 rpm.

This ability to motor up from standstill is particularly advantageous in wind energy applications, especially as vertical axis machines will not self-start and the trend for horizontal axis machines is toward low solidity blades (ref.1), which also will not self-start. A suitable operating strategy for this system would be to allow the machine to run up to 1000 rpm, and if the wind took the speed beyond 1200 rpm (i.e. 20% sub-synchronous slip), the cycloconverter would begin to generate. This would be extremely easy to implement.

6.4 Six Phase Supply

The advantage of a six phase supply has been clearly shown in the added continuity and smoothness of the output current waveform. Its advantage in terms of torque per amp is shown to be 20% over the three phase system at the torques which the three phase supply can attain. However, the maximum torque obtained by a three phase system is only

approximately 50% of the maximum torque obtained by using six phases, for the particular supply voltage used. This advantage will have to be weighed against the added cost of the transformers needed to provide the six phases. Six phase operation may also have benefits for operation without a neutral (see below).

6.5 Further Work

For the designer of a slip energy recovery system, the specification of the thyristor supply volts and the open circuit secondary emf volts of the machine have great bearing on the performance of the slip recovery system, and it should be possible to optimise them for a given control regime. This has not been done in this work. An analytical approach is probably necessary to optimise the ratio of open circuit secondary emf volts to thyristor supply volts. Some idea has been given of the advantage of reduction of supply volts, i.e. a 50% increase in torque per amp for a 50% decrease in supply volts for a given torque. The amplitude of the secondary emf will also have consequences for the starting and running up torque in the self-start mode, as a greater secondary emf will assist the production of current and torque during start up.

Operation without a neutral is possible but for the accurate prediction of firing angles for current production a steady zero voltage provided by a constant neutral is necessary. Removal of the neutral produces distortion of the output waveform. If one attempted to do the firing angle calculations for a non-neutral scheme, taking into account the effect of thyristors firing on other phases of the winding, the calculations are likely to be even more difficult. Also, operation without a neutral in a three phase system may provide some difficulty in terms of providing a current path, as the three phase system will tend to produce a more discontinuous current. This will mean that there is not necessarily an n group device firing in one phase when a p group device fires in another phase. A more complex ring firing system would be required to ensure

that two devices were always firing at any one time. It is unlikely that a neutral will be provided for many sites, and so some resolution of these problems will be required.

With the advent of cheap microprocessors, these may have their use in a cycloconverter control scheme. If a processor could act as a control waveform generator, and assess the quality of the output current waveform produced, then this could be an effective solution. Calculating the firing angle every time is virtually impossible, and merely using the micro as a digital cosine crossing technique seems a waste of resource, although possibly increasing accuracy. If the micro could begin with an initial waveform shape, and modify it as it seems necessary, outputting this waveform into a cosine crossing circuit as used in this thesis, then, though an increase in memory is required, the need for continuous calculation of firing angle is avoided. This would in effect be an on-line adaptive control method.

Some assessment will be required of the harmonics produced by the complete system into the grid supply (i.e. the sum of the stator and rotor powers). This was not possible in this work as the stator and rotor were supplied from separate transformers.

6.6 Summary

In total the work presented here is a considerable advance upon previous work done at Leicester University, (ref.29). A more detailed assessment of a variable speed wind turbine system has been obtained, and various operating strategies compared. A scheme which allows the turbine to operate on the maximum efficiency characteristic for much of the speed range, and then automatically limit excessive speed increase, was chosen for this study. This was implemented using a slip energy recovery scheme with a cycloconverter. This system was built and tested and successfully achieved its operating demands. With the advantage of a new secondary

emf signal generator, no major difficulties were encountered in the design and running of the equipment. As a second generation design, the system was probably a little over-complex, with too many novel components, i.e. six phase supply, divided winding, modified control waveform generation, etc. This does give a good idea, however, of the relative advantages of each, and will be useful to a designer of further variable speed systems. Work is proceeding at Leicester University to obtain actual operating experience with wind turbines with a system (implemented by a d.c. link inverter) based on the computer wind turbine studies of this thesis.

CHAPTER 7

7.0 Acknowledgements

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CHAPTER 8

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APPENDIX 1

TEST FACILITIES

A1.1 Wind Turbine Simulator

The consideration of the energy capture of a variable speed wind turbine must take into account the inertial response of the wind turbine to changes in wind speed. The actual energy gained by the turbine will differ from the theoretical (steady state) value by an amount depending upon this response. During any steep torque-speed characteristic this difference can be neglected, as the system is operating in an almost fixed speed manner. However, operation on the shallow torque speed curve corresponding to Max Cp region may affect the energy capture to a greater extent.

Mathematically, a variable speed wind turbine system can be described as follows:

If we assume operation predominantly near the peak of the C_p curve, it should be a good approximation to assume that over this range the C_p curve is simply an inverted square wave, i.e.

$$C_p = C_{pm} - K_c (\lambda_m - \lambda)^2$$

where C_{pm} = maximum C_p

λ_m = tip speed ratio at max C_p

and K_c = peak shape parameter.

Now

$$P = K_\omega C_p V^3 \qquad \text{where } K_\omega = \frac{1}{2}\rho A$$

$$= K_\omega V^3 [C_{pm} - K_c(\lambda_m - \lambda)^2]$$

$$= K_\omega V^3 \left[C_{pm} - K_c\left(\lambda_m - \frac{\omega R}{V}\right)^2\right]$$

$$= K_\omega V^3 (C_{pm} - K_c \lambda_m^2) + \frac{K_\omega K_c V^3 2\omega\lambda_m R}{V} - \frac{K_\omega K_c V^3 \omega^2 R^2}{V^2}$$

$$= AV^3 + BV^2\omega - CV\omega^2$$

Dynamically speaking, the rate of change of rotational speed is given by

$$\frac{d\omega}{dt} = \frac{1}{J}\left(\frac{P}{\omega} - T_L\right)$$

where T_L is the load torque $= K_\ell \omega^2$

$$\frac{d\omega}{dt} = \frac{1}{J}\left(\frac{AV^3 + BV^2\omega - CV\omega^2}{\omega} - K_\ell\omega^2\right)$$

$$= \frac{1}{J}\left(\frac{AV^3}{\omega} + BV^2 - CV\omega^2 - K_\ell\omega^2\right)$$

One may assume a step change in V and by linearising this equation, obtain a response of the form,

$$\omega = \omega_1 + (\omega_o - \omega_1)e^{-\gamma t}$$

with $P_{generated} = K_\ell \omega^3$

and $P_{available} = K_\omega C_{pm} V^3$.

It may be possible, given the assumptions taken above, to mathematically analyse the response of a wind turbine to a given wind speed characteristic, in terms of the wind spectral density and a transfer function derived from the above equations. From this one may produce an analytical expression for the actual power generated compared with the theoretical power available in the wind. However, in this thesis it was decided that to produce a real time simulation of a wind turbine on a microcomputer would be more useful. This simulation could also then be used in conjunction with the thyristor controller and a DC machine to actually drive a working slip energy recovery system under conditions similar to actual operation.

A1.1.1 Computer simulation

The computer model was developed not only as a means for assessing system performance but also to control a d.c. motor driving the shaft of an actual variable speed constant frequency generator coupled to the grid. A diagram of the system is shown in Fig.A1.1.

A1.1.2 Wind turbine characteristics

The torque developed by a wind turbine is given by

$$T = \frac{1}{2}\rho\left(\frac{C_p}{\lambda}\right) V^2 \pi R^3 \qquad \text{(i)}$$

where

V = wind speed

R = radius of blades

The swept area and Cp characteristic for any turbine will be available, and can be input to the program. Also Cp and λ figures can be used and a curve fitted to them. The wind speed can be input manually or taken at 2 second intervals from a disc of wind data.

The torque is derived:

(i) From a torque transducer on the shaft of the generator when the computer is used to control a d.c. drive coupled to the generator, or

(ii) From an internally derived value of torque when the computer is being used to model the overall system.

A1.1.3 The rotor dynamics

The program aims to model a turbine of any size. To simplify the model the inertia of the generator is transferred across the gearbox and combined with the turbine rotor inertia. The shafts are considered to be of infinite stiffness and any damping present has been ignored. As the actual test generator is of low inertia then it is reasonable to assume that the generator shaft will instantly follow the demand for speed derived from the computer. This speed demand is produced from the following equation

$$J.\, d\omega/dt = Tr - Tg \qquad \text{(ii)}$$

where J represents the sum of the turbine rotor inertia and referred generator inertia, Tr is the torque developed by the blades and Tg is the generator torque referred across the gearbox.

The two second wind data is interpolated at 0.4 s intervals to give the blade torque from equation (i). This torque is compared with the torque developed by the generator and an acceleration determined from equation (ii), and this is used to update the rotor speed at 0.4 s intervals. The rotor speed is output through a D/A converter to become the demand speed to the variable speed drive.

When the actual test generator is being used its torque is measured by a shaft transducer and is input to the computer where it is suitably scaled to represent the much higher level of torque produced by the generator being simulated.

A1.1.4 The electrical generator

When the computer is used to control the speed of the variable speed generator on test the power generated,and therefore the load torque,is controlled by the slip energy recovery equipment to lie on the required torque-speed characteristic.

However, the computer can be used to model the whole system including a synchronous generator, a limited slip induction generator or a variable speed slip ring induction generator. These are modelled simply as providing given torque-speed characteristics rather than detailed equivalent circuit models. This enables comparative investigation of the performance of these generators.

A1.1.5 Computer output

The continuous operating performance including speeds, torque, Cp , power, and kWhrs can be displayed in tabular form on the screen. Alternatively the dynamic behaviour can be shown graphically as shown in Fig.A1.2 in which x represents the load torque due to power generation and + represents the torque developed by the turbine.

The required characteristics for the memory of the computer are the Cp curve and the blade inertia. At present the program has data for the

Nibe and MOD-2 systems, in the form of Cp curve equations. It will be possible to input Cp curve figures and the program will fit a suitable curve to them.

Other information such as gearbox ratio and operating speed can either be input from actual operating conditions or modified in the program to suit the mode of control being investigated.

A printout of the program is shown in Fig.A1.3.*

A1.2 Fast Fourier Analysis

The quality of the currents produced by the cycloconverter in the rotor windings and back to the grid supply will have great bearing on the efficiency and desirability of the cycloconverter control system. A system has been developed which will download a waveform from a digital storage oscilloscope and perform a fast Fourier analysis on the waveform. The Fourier analysis is achieved using a published† program. A printout of the program is shown in Fig.A1.4.

Typical results have been given in Chapter 5 of this thesis.

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* The analytical parts of the program were written by the author, Mr.D. Donegani writing most of the graphics.

† Newland, D.E. An introduction to random vibrations and spectral analysis, Longman 1984.

APPENDIX 2

THYRISTOR CONTROL WAVE PROGRAM

A normal Cosine Crossing technique uses a sinusoidal control wave in order to produce a sinusoidal current output. If the load is inductive the current usually lags the applied control wave. For a doubly fed system as envisaged here the load also contains a secondary emf voltage which will be of the same frequency as the required current but may be either aiding or opposing this current. The cosine crossing technique could still be used in this system if the amplitude of the control wave were modified to counteract this voltage; the net firing angle of the thyristors would still be sinusoidally modulated as the control wave and secondary emf are in phase.

However, for this system it was also considered advantageous to try to produce a current in the secondary which did not lag the emf present.

Advancing the control wave with respect to the secondary emf would improve the power factor if the system was a circulating current type, but in this method the positive and negative groups are totally separate, and advancing or retarding the secondary emf generator waveform simply produces distortion in the current output.

To counteract these effects a computer program was developed to calculate the required firing angles to obtain current in phase with the secondary emf, and also that the current should be of the correct amplitude to produce a required torque-speed characteristic.

In order to predict the current produced by a particular firing angle knowledge of the generator winding parameters is necessary. The model used for the induction machine is shown in Fig.A2.1. In the program the secondary winding is assumed to be a simple R-L circuit, with an associated emf source.

The computer program was run for 20 speeds between + 20% and - 20%

slip. For each speed the time period of the current waveform required was calculated and the required rms (from the torque-speed operating characteristic required) was input. The program then calculated, by an iterative process, the firing angles required to produce a half cycle of current of that required rms. In order to assess the sinusoidality of the produced waveform, the average quantity of current fired by each thyristor over its conduction angle is compared with the average quantity of current for the same period, assuming a sinusoidal waveform output, Fig.A2.2. This required sinusoidal current waveform had a peak value which could be modified in order to obtain the correct rms of cycloconverter output. This modification is required as the ratio of peak to rms current of the cycloconverter output is not necessarily $\sqrt{2}$. This comparison between the actual and required averages indicated whether the firing angle needed to be advanced or retarded. When these comparisons were satisfied to the required accuracy, the peak amplitude of the comparison sinusoid was then modified in order to produce the correct rms output. This modification could not be done by the program as the iterative current calculations alone nearly overran the time limit for programs on the computer, and so had to be input manually and the program run again.

The iterative scheme calculated the number of firing angles available during a half cycle of required output current and ran through these waveforms from first to last, modifying each firing angle once. This was the most effective solution. If it was attempted to remain modifying one firing angle in order to obtain the required current, and an answer obtained, as soon as the next firing angle along was calculated, the averages for the previous firing angle were changed and had to be recalculated. This in turn affected the firing angle previous to that, and so on. When each was modified once and then passed over, the effect on its neighbours could be calculated at the next pass, and less time wasted.

The equation giving the current produced by an applied voltage across

a resistor-inductor combination is

$$di/dt = (V-iR)/L$$

where

i = current

t = time

V = voltage

R = resistance

L = inductance

The calculation was achieved on the computer using a Runge-Kutta method. The current was either allowed to decay to zero, negative currents being set to zero, corresponding to the thyristor switching off, or, if another thyristor fired while current was still present that current was used as an initial condition for the next firing angle.

The computer calculated and then output the firing angles for a positive half cycle of current only.

Given these firing angles for the devices, and also the firing waves being used (in this case the supplies across the devices), the positive half of the control wave could be easily derived, see Fig.A2.3. The negative half of the control wave is simply an inversion of the positive half cycle.

The control waves were derived for the 20 increments in speed between + and - 20% . To produce the control waves for the 64 pages of the EPROM, these control waves were linearly interpolated for the other speeds required.

A2.1 Programme Description

A2.1.1 Flow diagram

The numbers refer to Fig.A2.4. A printout of the program is in Fig.A2.5.

(1) A preliminary set of firing angles was used to initialise the analysis, rather than begin with fully retarded angles, which wasted time. Mmax is the total number of firing angles for the half cycle.

(2) M is an integer which numbers the firing angles from the positive edge of the required output current. N defines which of the six phase supplies the thyristor is operating on (see variable listing).

(3) The Runge-Kutta process starts with the first firing angle, and assumes that the current is zero.

(4) This loop performs the Runge-Kutta calculation to find the current, and the SUMSQ and SUM sums are updated. If the next firing angle is reached (FA(m+1)) the program calculates the actual average current and the required average current over the period between FA(m+1) and FA(m) which are held in arrays, and then resets M and N .

(5) The actual average current is calculated using the SUM variable.

(6) Tperiod/2 is the time period for a half cycle of output current.

(7) After the Runge-Kutta loop has been completed, this loop compares the actual current produced over each firing angle period with the required current and modifies the firing angle accordingly. If the two current figures agree to a determined accuracy (within 0.05 A) the IOGOOD count is incremented. If all the firing angles agree (i.e. IOGOOD reaches Mmax) then the results are output, the rms figure of the complete waveform is calculated and the program ends.

(8) The analysis outlined above is done for the number of times determined by the J-loop . This is required as often the program did not reach a satisfactory answer before the time limit for the Cyber had been reached. The maximum J is set to end the program before the time limit and output the firing angles determined so far. These could then be re-input and the program re-run.

A2.1.2 Functions used in the program

(i) Function Runge

As part of the calculation of the current at $t+\delta t$, given the current at t, the program must calculate the value of $V-iR/L$ over the increment.

Where V = net applied voltage

i = current

R = resistance

L = inductance

Now $V = V_{supply} - V_{slip}$

Where $V_{supply} = Vp.\sin(100.\pi.t) - N.\pi/3$

$V_{slip} = T_{rat}.s.98.\sin(2.\pi.f_{slip}.t)$

and so the function calculates the value

$$\text{Runge} = \frac{\{[Vp.\sin(100.\pi.t)-N.\pi/3]-[T_{rat}.s.98.\sin(2.\pi.f_{slip}.t)]\}-Y.RES}{XIND}$$

(ii) Function RQC

This function calculates the required average current over the range FA(m) to FA(m+1) given a demanded sinusoidal current of the frequency f_{slip} and peak A_{peak}. (FA(m+1) and FA(m) are abbreviated to FAM1 and FAM in the program).

$$\text{Average} = \frac{1}{FA(m+1)-FA(m)} \int_{FA(m)}^{FA(m+1)} A_{peak}.\sin(2.\pi.f_{slip}.t)dt$$

$$= \frac{1}{FA(m+1)-FA(m)} A_{peak}.\left[\frac{-1}{2.\pi.f_{slip}} \cos(2.\pi.f_{slip}.t)\right]_{FA(m)}^{FA(m+1)}$$

$$= \frac{A_{peak}.[X1-X2]}{FA(m+1)-FA(m)}$$

where $X1 = \frac{-1}{2.\pi f_{slip}} \cos(2.\pi.f_{slip}.FA(m+1))$

and $X2 = \frac{-1}{2.\pi.f_{slip}} \cos(2.\pi.f_{slip}.FA(m))$

(iii) Function Volts

This calculates the voltage of the six phase supplies.

$$Volts = Vp.\sin(100.\pi.t - N\pi/3)$$

Where Vp = Peak supply volts

N = 0 to 5

A2.1.3 Variables

TRAT	Turns Ratio of Machine
SLIP	slip
FSLIP	slip frequency
RES	secondary resistance
XIND	secondary inductance
VPEAK	peak six phase supply volts
APEAK	peak required sinusoidal current
FA( )	firing angle
SUM( )	area of current pulse
AAC( )	actual average current of current pulse
RAC( )	required average current of current pulse
DT	time increment for Runge-Kutta calculations
M,N	see Section A2.1.1
L	number of time increments corresponding to FA(1)
RCURO-4/	
A1-5	variables in Runge-Kutta calculation
XAMPS	current
SUMSQ	sum of $[i^2].dt$ (= area^2 for R.M.S. calculation)
SUM	sum of i.dt (for average i calculation)
IOGOOD	number of firing angles producing required current
FINC	firing angle increment
RMS	R.M.S. value of complete waveform

A2.2 Run Time

The program was set to run for 2000 seconds CPU time (≃ 30 mins.). For an initial set of firing angles this was not necessarily enough time to complete the calculations to the required accuracy. On average each set of firing angles required one or two runs to achieve this. Although the accuracy set in the program may be felt to be too severe, these times give an idea of the complexity of the calculation, and show the difficulty of using an on-line micro for such calculation.

The program was written for a Cyber 73 mainframe, in Fortran V.

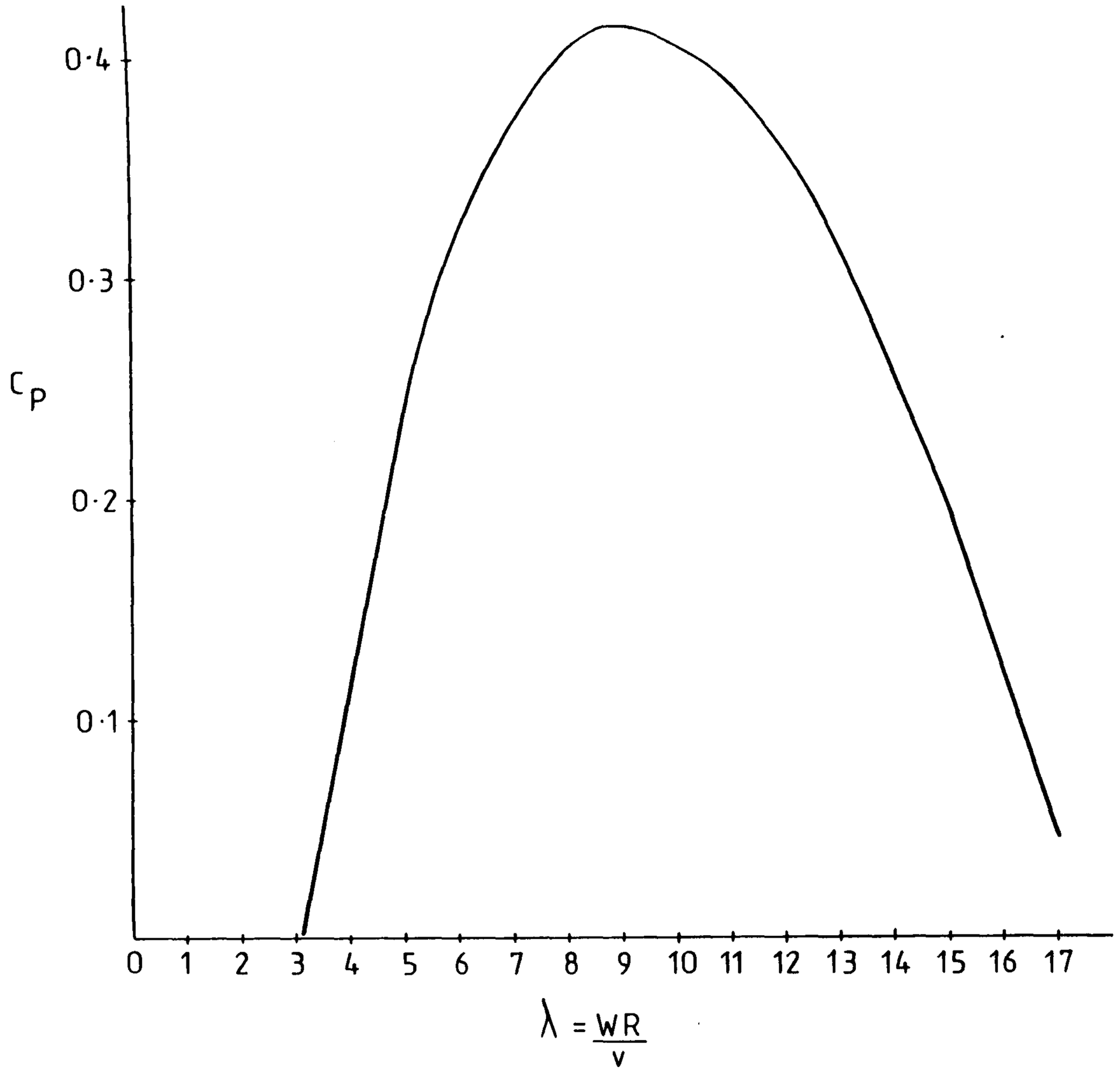


Fig 1·1 Cp curve for Boeing MOD 2

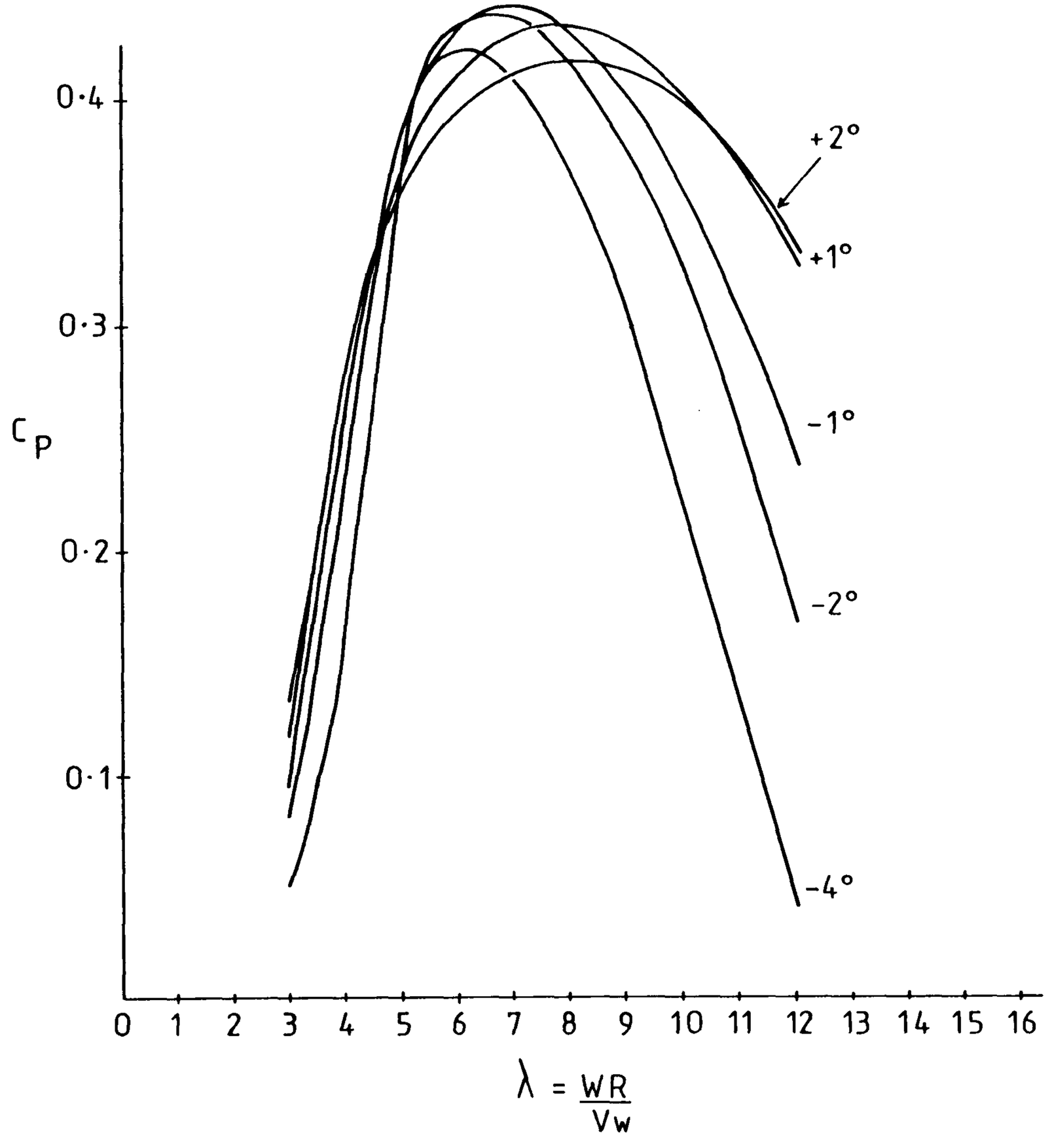


Fig 1·2 Cp curve for nibe at various pitch angles

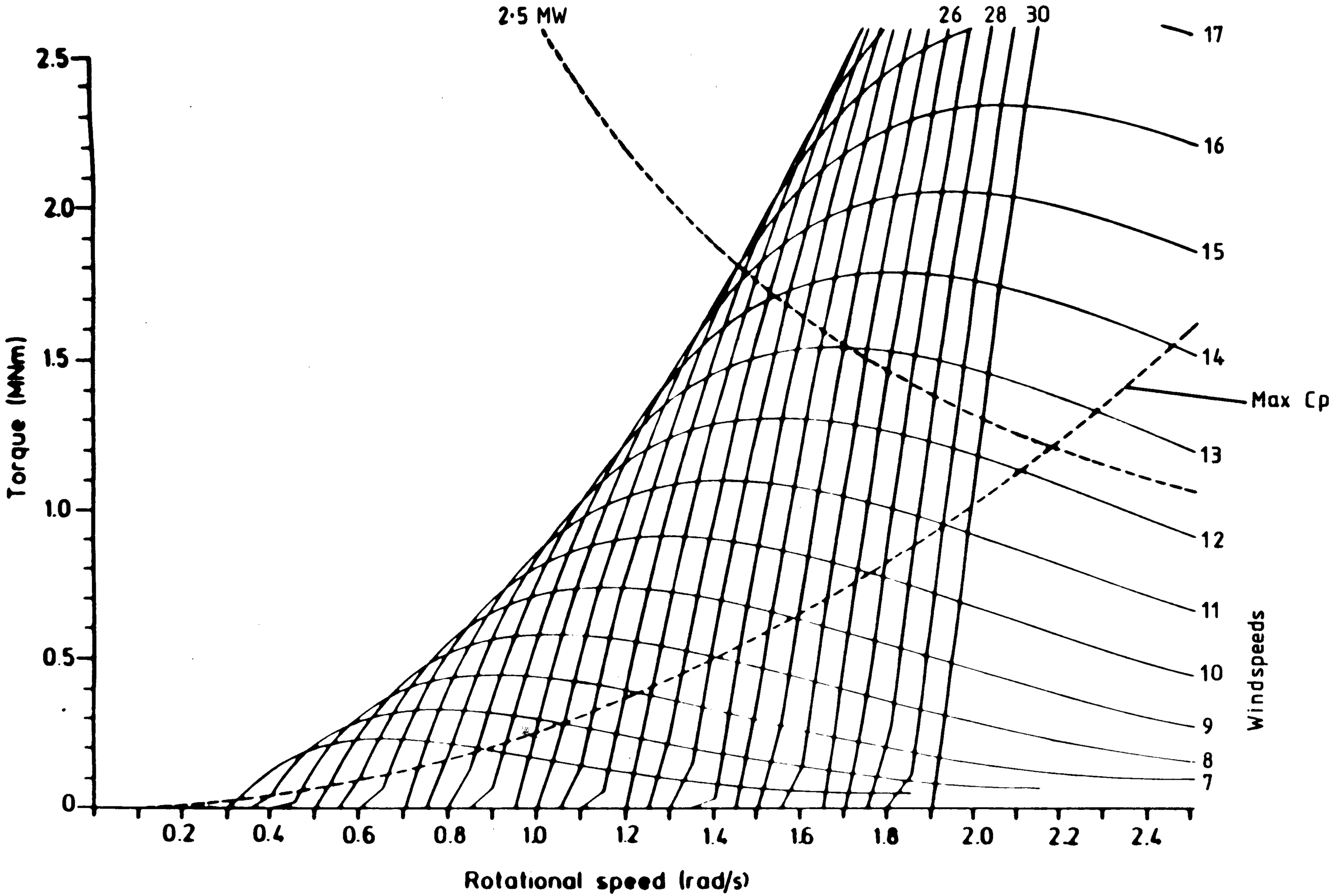

2·5 MW
26
28
30
17
16
15
14
Max Cp
13
12
11
10
9
8
7
Windspeeds
2.5
2.0
1.5
1.0
0.5
0
Torque (MNm)
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
Rotational speed (rad/s)

Fig 1·3

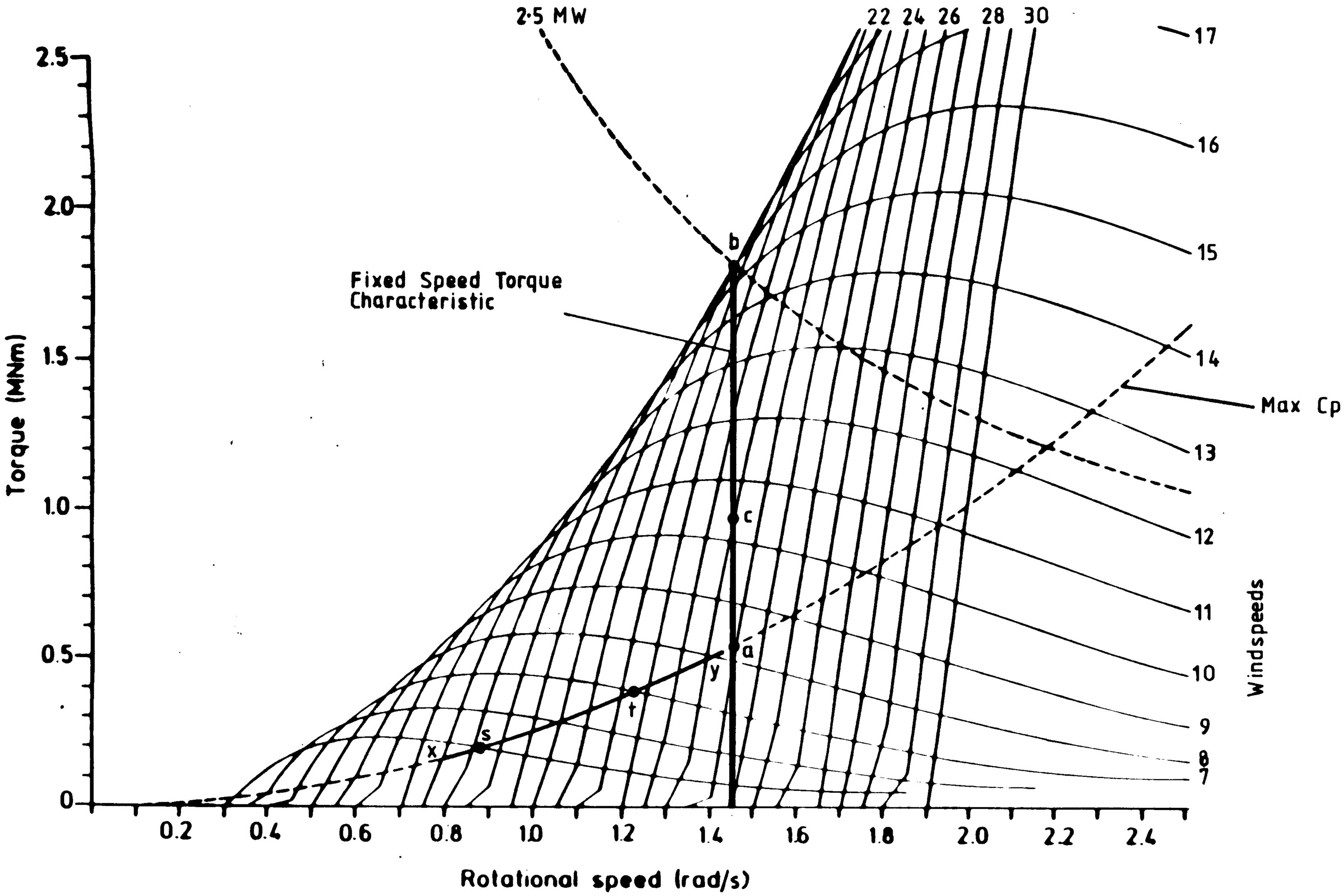

2·5 MW
22 24 26 28 30
17
16
15
14
Max Cp
13
12
11
10
9
8
7
Windspeeds
Fixed Speed Torque
Characteristic
b
c
a
y
t
s
x
2.5
2.0
1.5
1.0
0.5
0
Torque (MNm)
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
Rotational speed (rad/s)

Fig 1·4

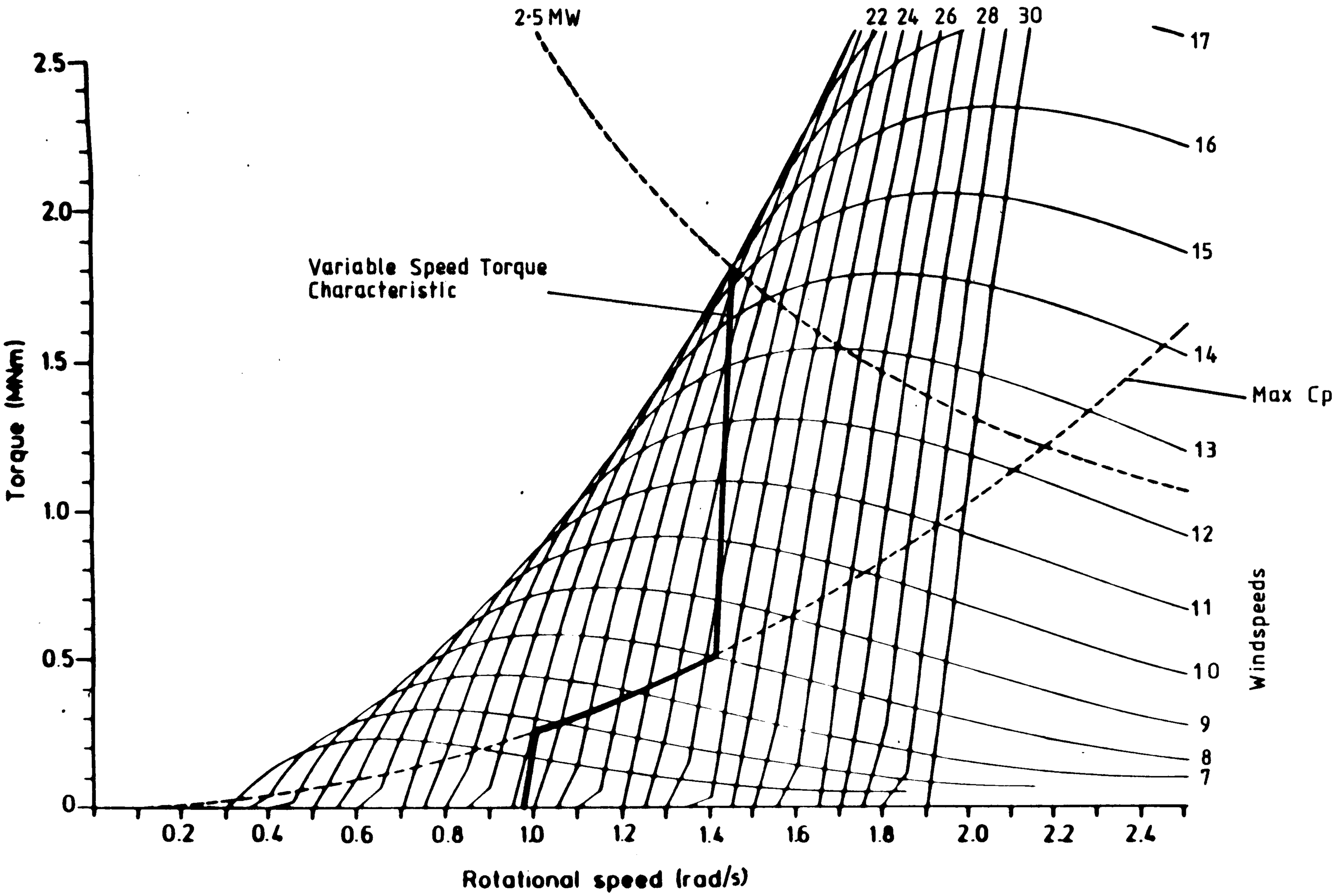

2·5 MW
22 24 26 28 30
17
16
15
14
Max Cp
13
12
11
10
9
8
7
Windspeeds
Variable Speed Torque Characteristic
Torque (MNm)
2.5
2.0
1.5
1.0
0.5
0
0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0 2.2 2.4
Rotational speed (rad/s)

Fig 1·5

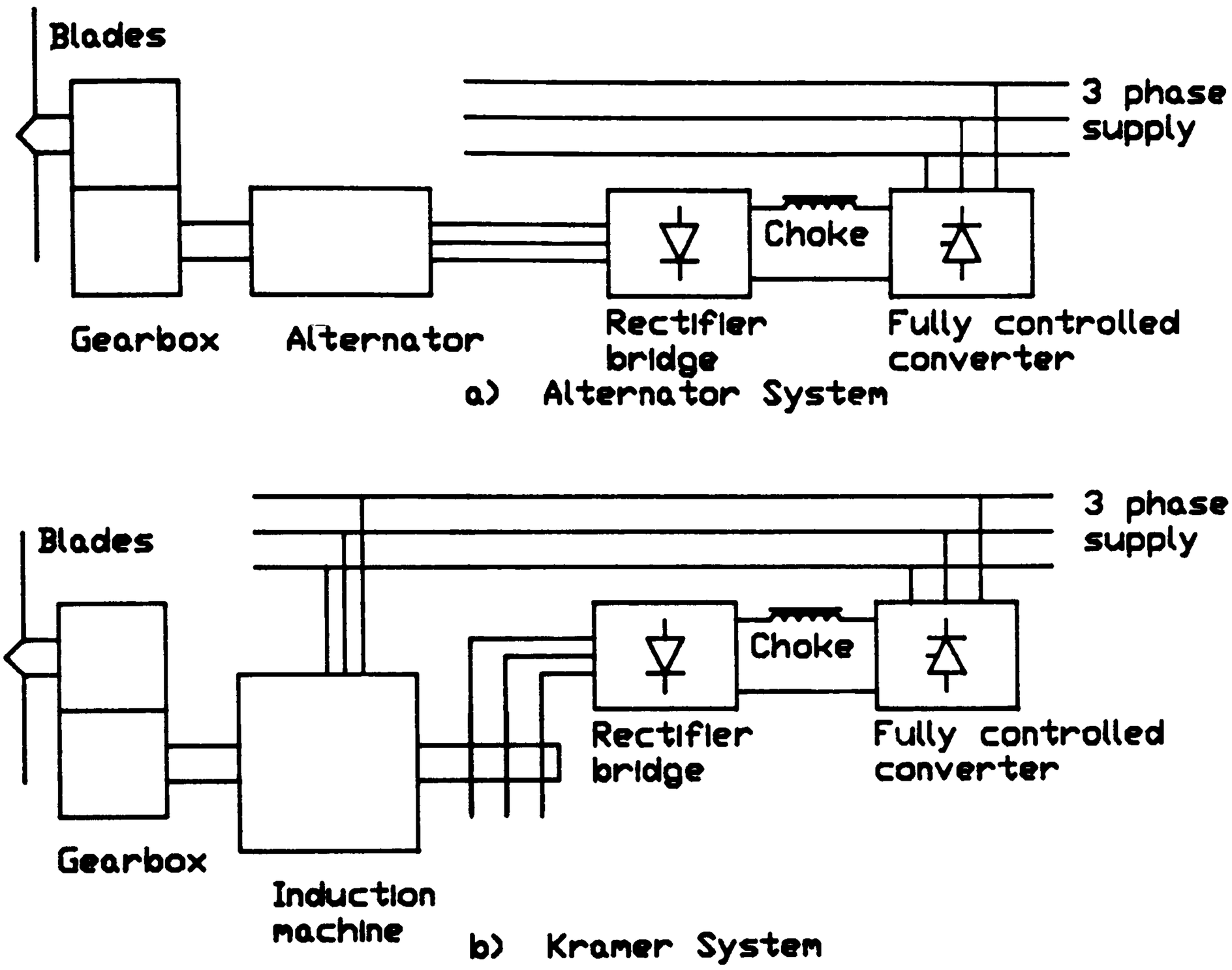

Blades
3 phase supply
Choke
Gearbox
Alternator
Rectifier bridge
Fully controlled converter
a) Alternator System
Blades
3 phase supply
Choke
Rectifier bridge
Fully controlled converter
Gearbox
Induction machine
b) Kramer System
Blades
3 phase supply
Choke
Current-fed inverter
Fully controlled converter
Gearbox
Induction machine
c) Current source inverter system
Three phase supply
Cycloconverter
Gearbox
Slip Ring Induction Machine
d) Cycloconverter system

Fig 1.6

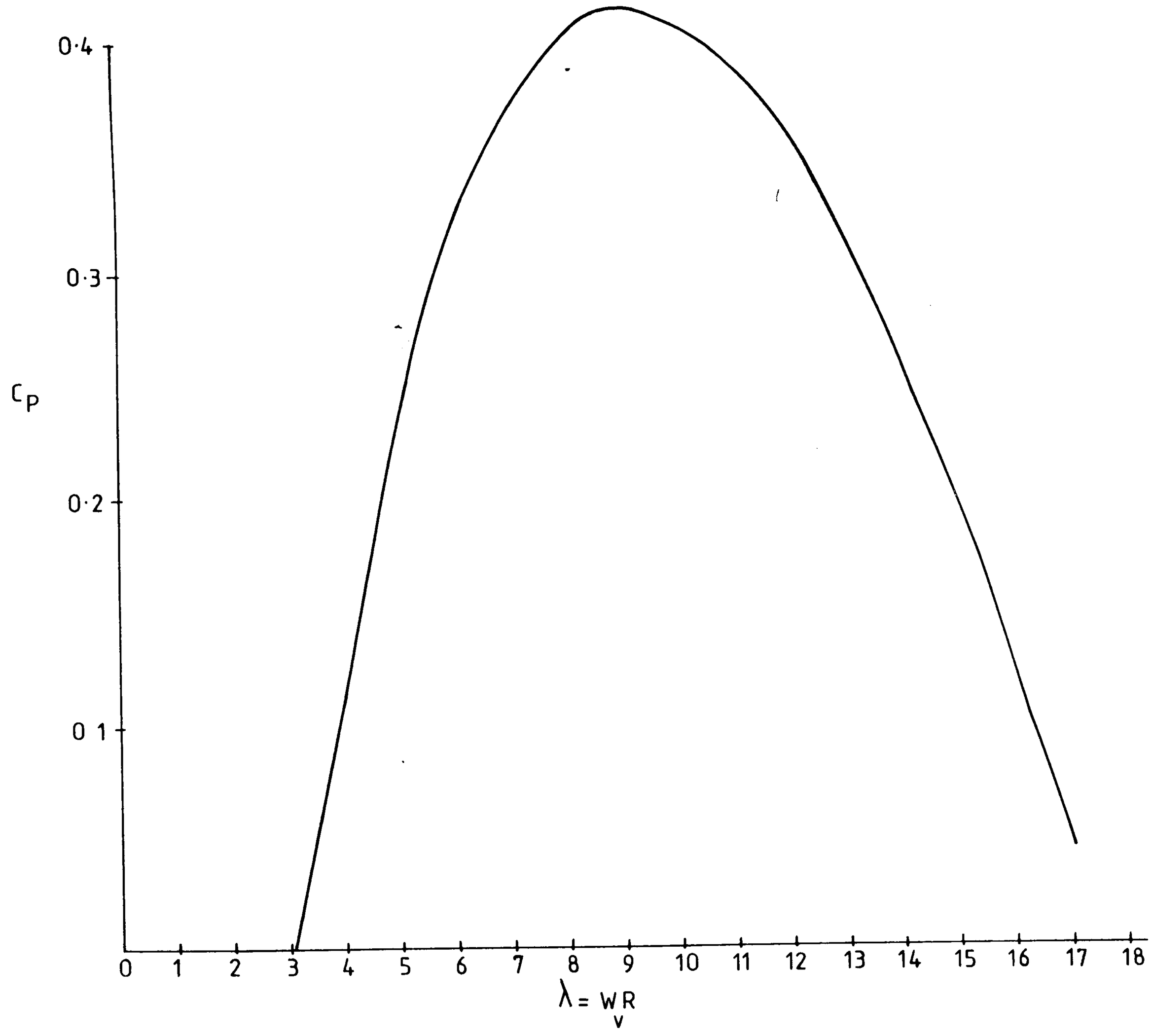


Fig 2·1 Cp curve for Boeing MOD 2

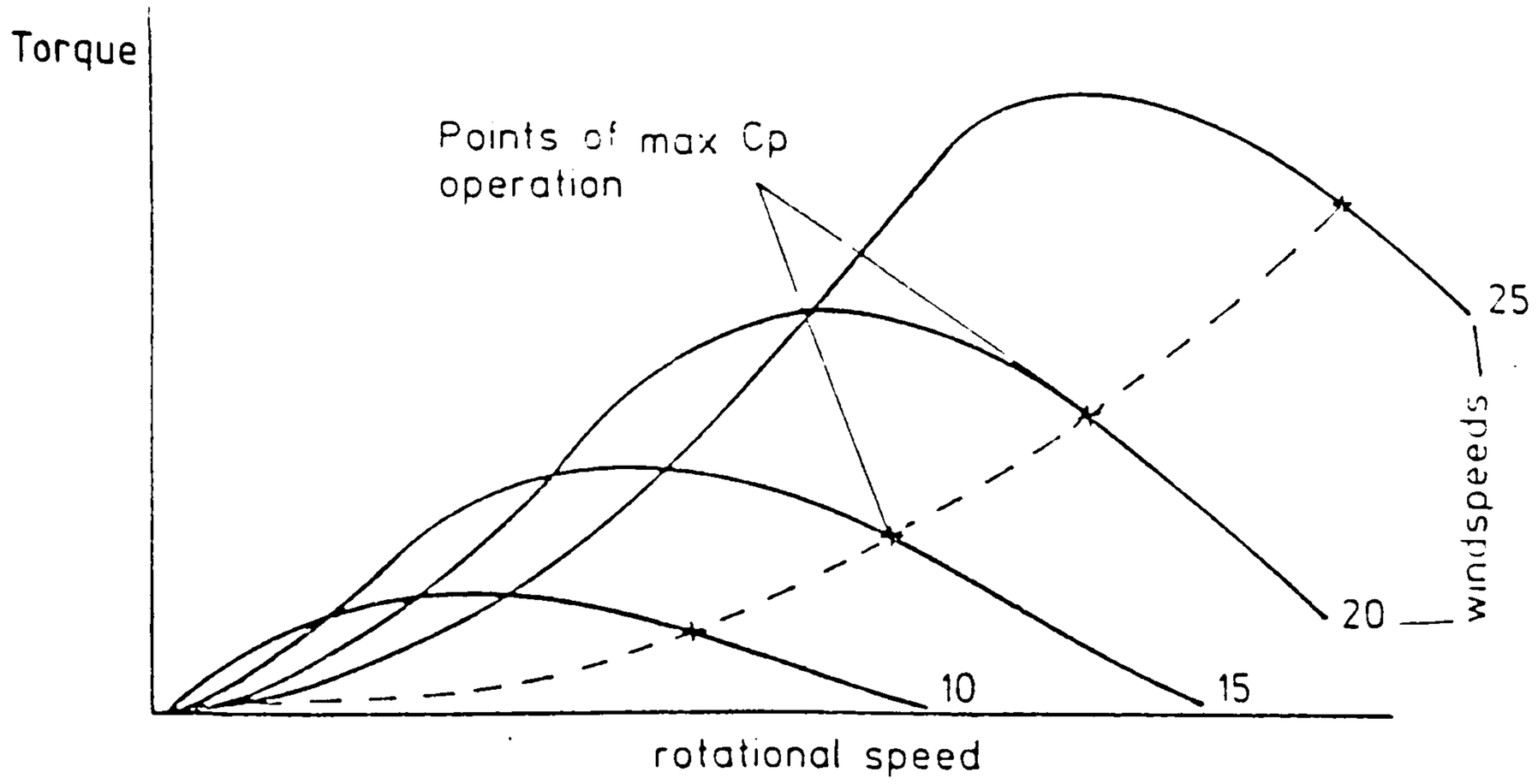


Fig 2·2

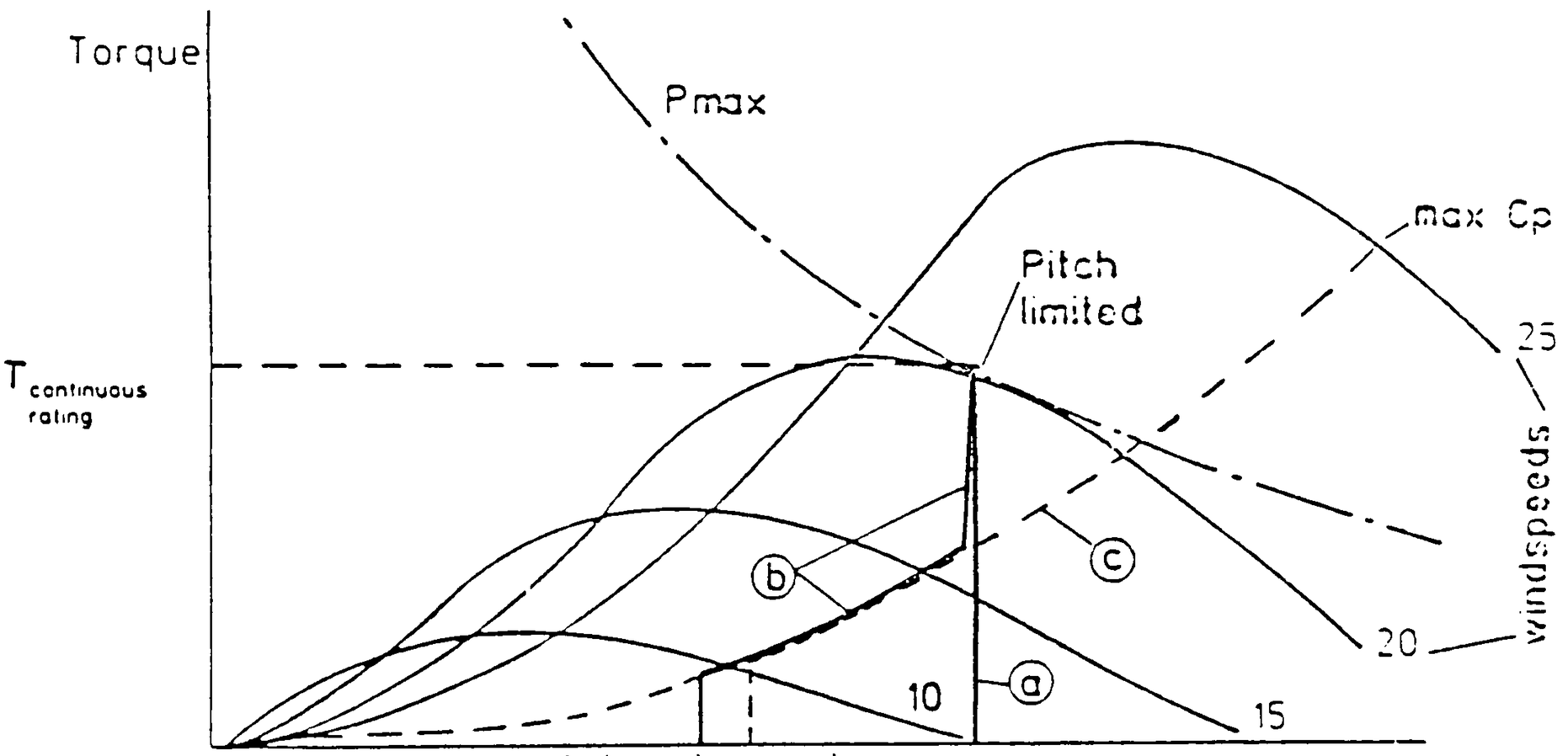


Fig 2·3

a) Fixed speed variable pitch
b) Variable speed variable pitch
c) Max Cp to power rating

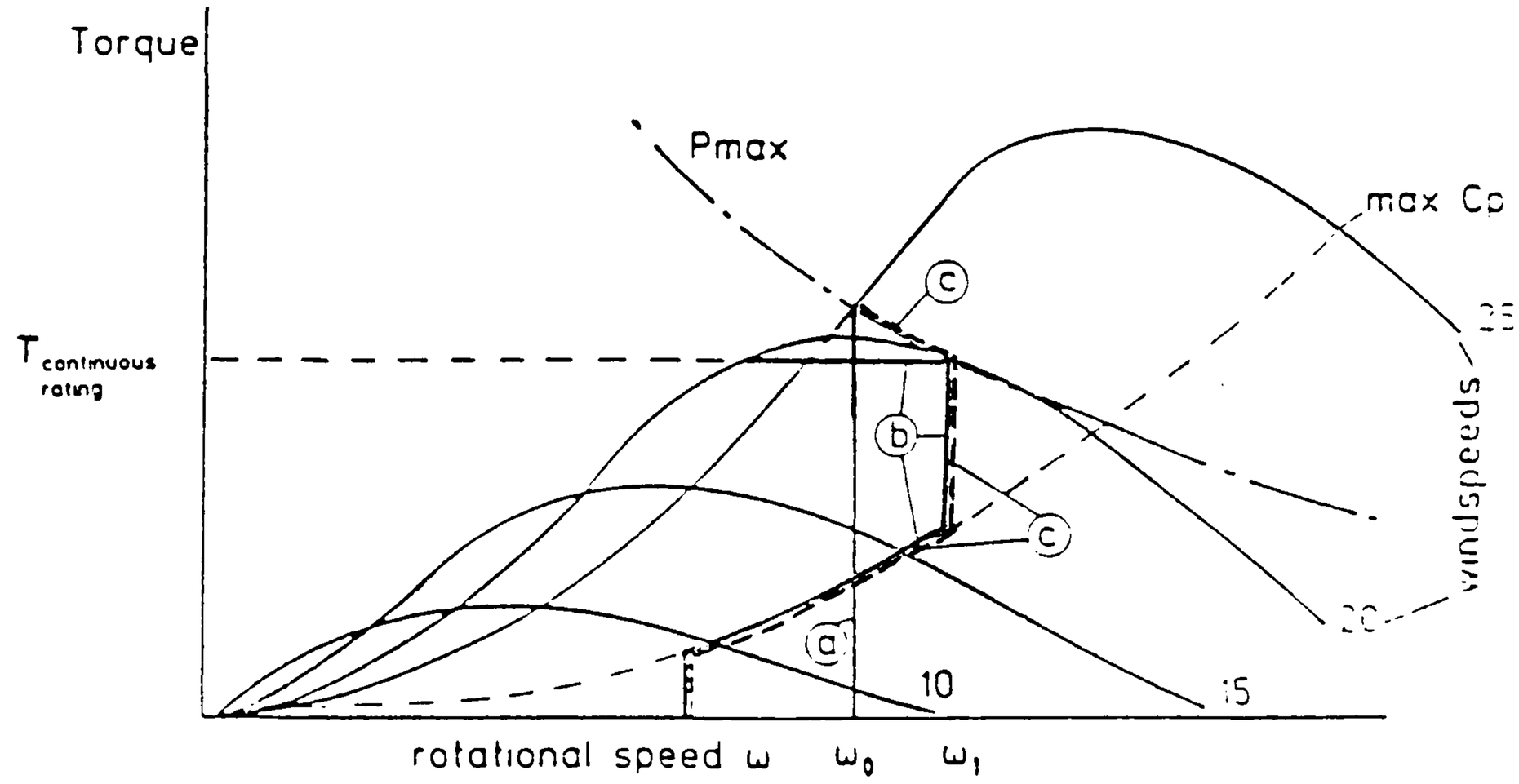


Fig 2·4

a) Fixed speed fixed pitch
b) Constant torque speed reduction
c) Constant power speed reduction

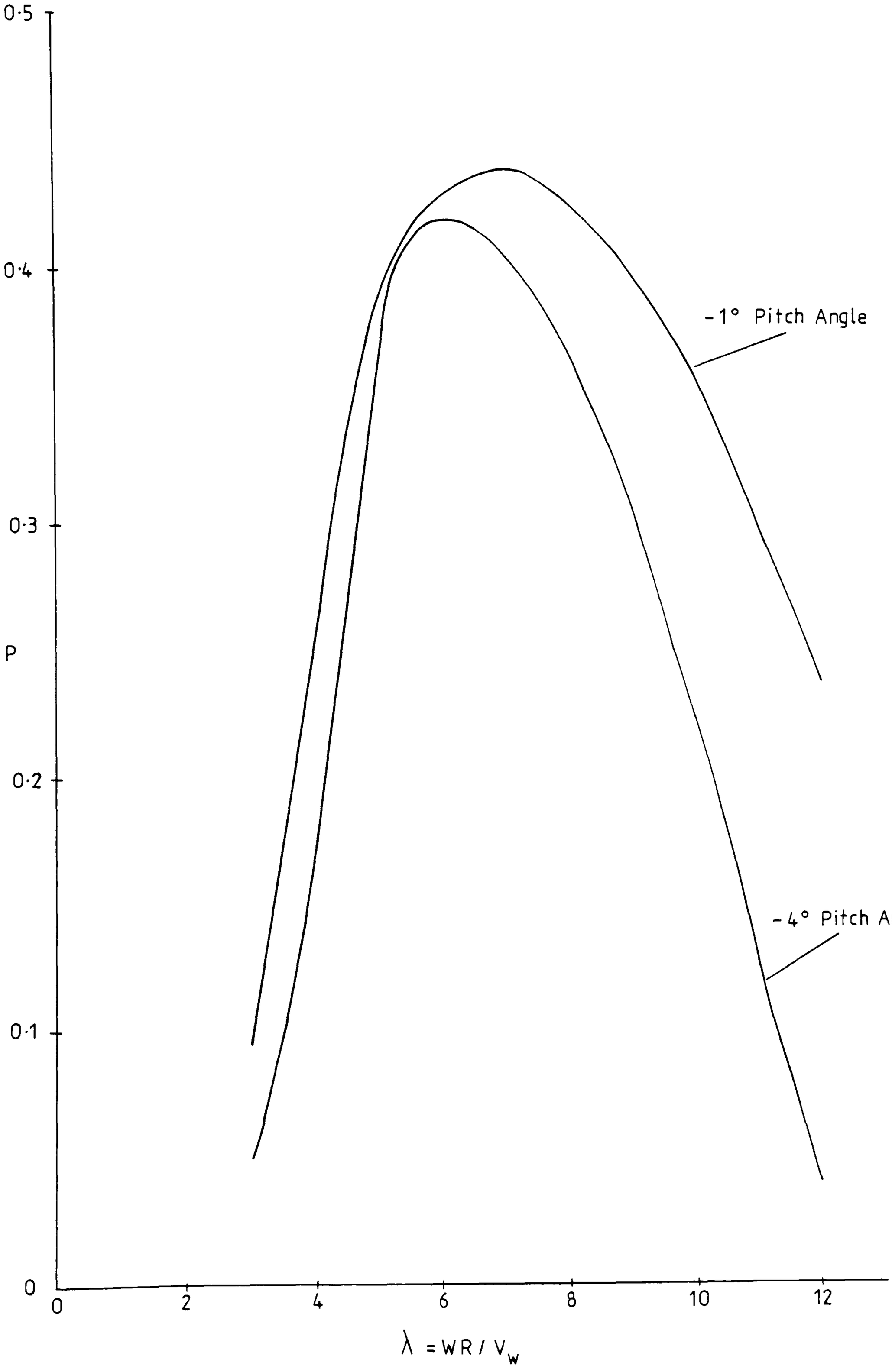


Fig 2·5 Cp curve for nibe

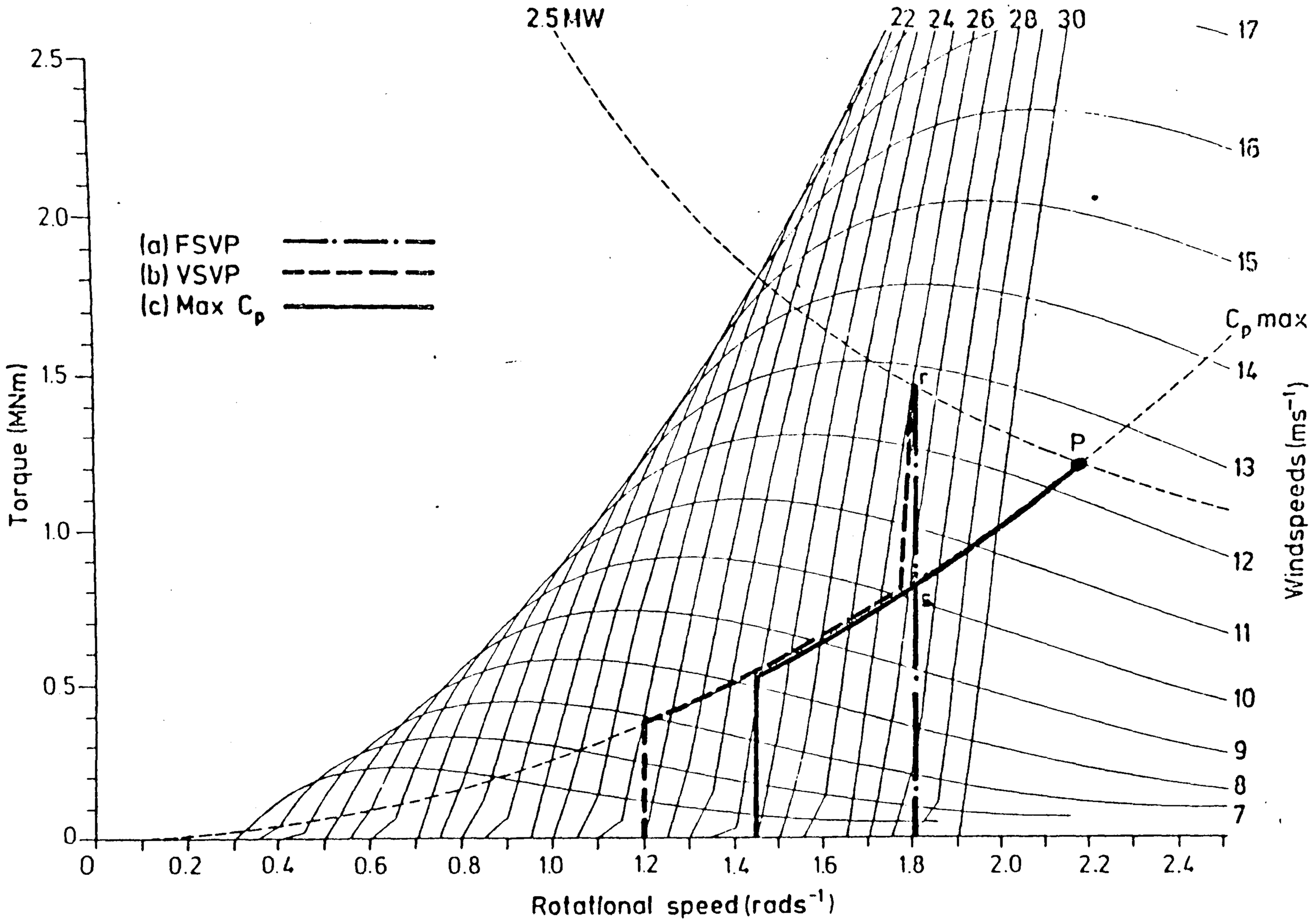

(a) FSVP
(b) VSVP
(c) Max C_p
2.5MW
22 24 26 28 30
17
16
15
14
13
12
11
10
9
8
7
C_p max
P
r
Torque (MNm)
Windspeeds (ms^{-1})
2.5
2.0
1.5
1.0
0.5
0
0 0.2 0.4 0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0 2.2 2.4
Rotational speed ($rads^{-1}$)

Fig 2·6

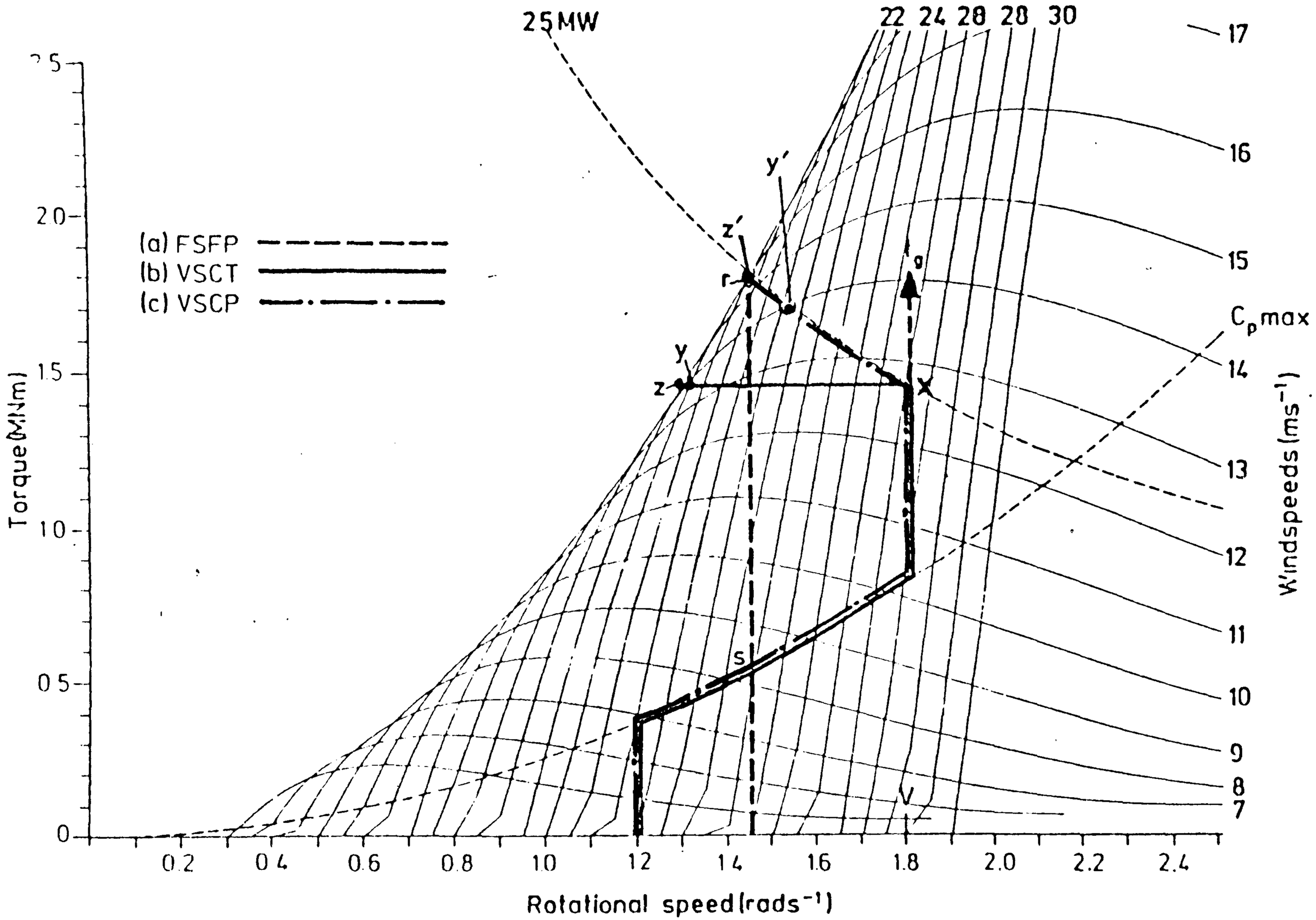

(a) FSFP
(b) VSCT
(c) VSCP
25MW
22 24 26 28 30
17
16
15
14
13
12
11
10
9
8
7
$C_p$max
Windspeeds (ms^{-1})
Torque(MNm)
Rotational speed($rads^{-1}$)
0
0.5
1.0
1.5
2.0
2.5
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
y'
z'
r
y
z
q
x
s
v

Fig 2·7

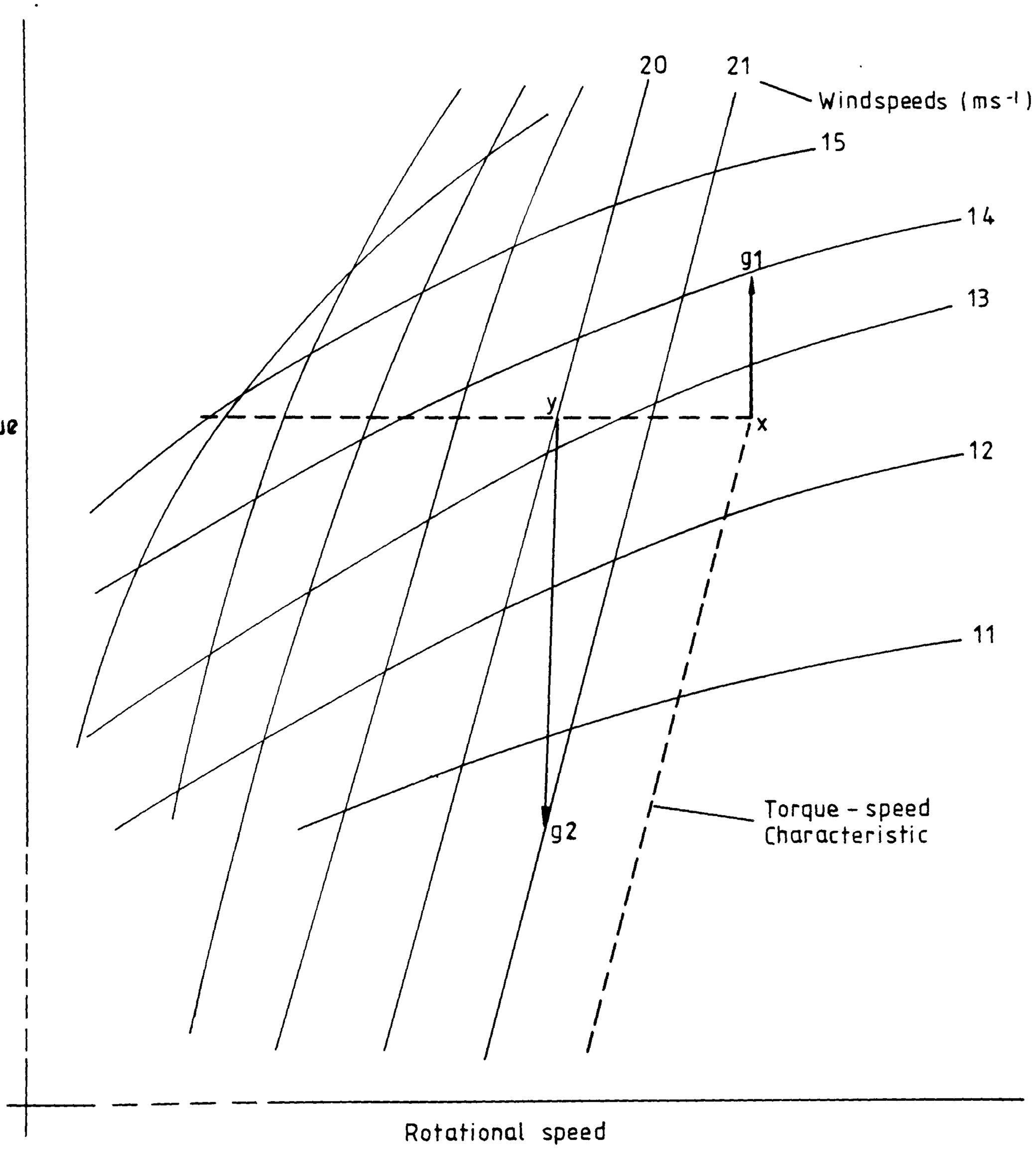

20
21
Windspeeds (ms⁻¹)
15
14
g1
13
y
x
Torque
12
11
Torque - speed
Characteristic
g2
Rotational speed

Fig 2·8

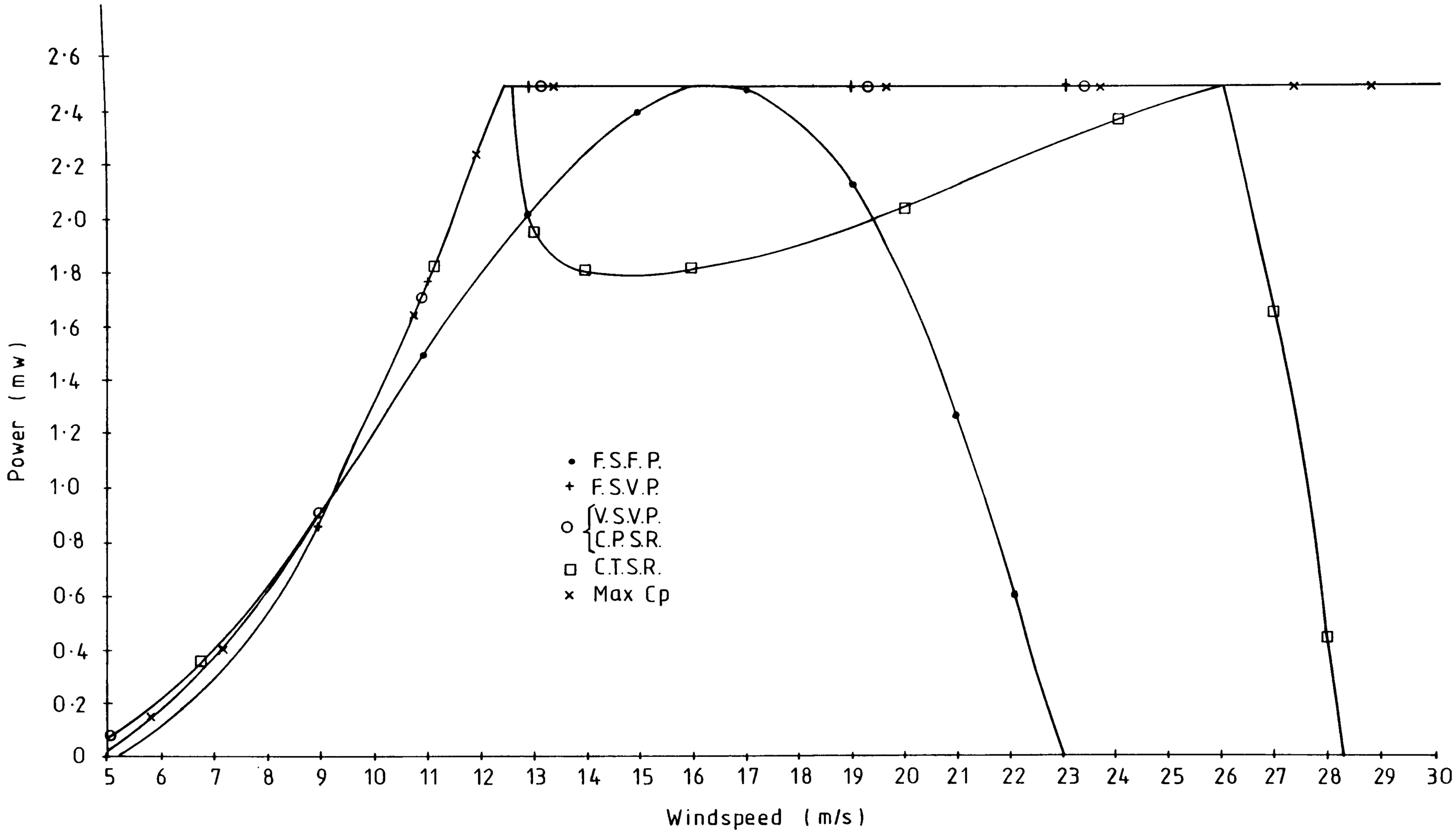

Power (MW)
2·6
2·4
2·2
2·0
1·8
1·6
1·4
1·2
1·0
0·8
0·6
0·4
0·2
0
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
Windspeed (m/s)
F.S.F.P.
F.S.V.P.
V.S.V.P.
C.P.S.R.
C.T.S.R.
Max Cp

Fig 2·9

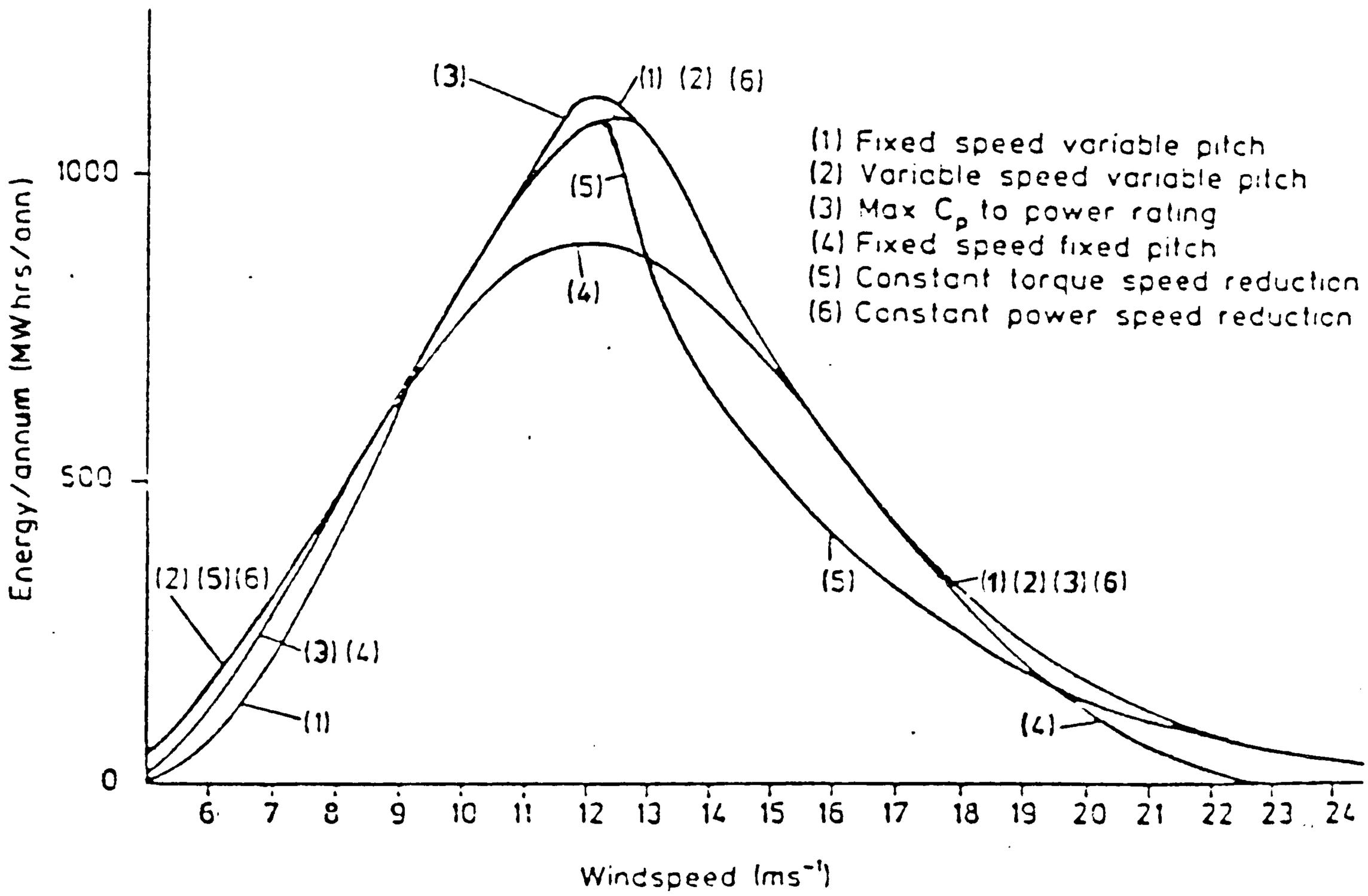

Energy/annum (MWhrs/ann)
1000
500
0
(3)
(1) (2) (6)
(5)
(4)
(1) Fixed speed variable pitch
(2) Variable speed variable pitch
(3) Max C_p to power rating
(4) Fixed speed fixed pitch
(5) Constant torque speed reduction
(6) Constant power speed reduction
(2) (5) (6)
(3) (4)
(1)
(5)
(1) (2) (3) (6)
(4)
6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Windspeed (ms^{-1})

Fig 2·10

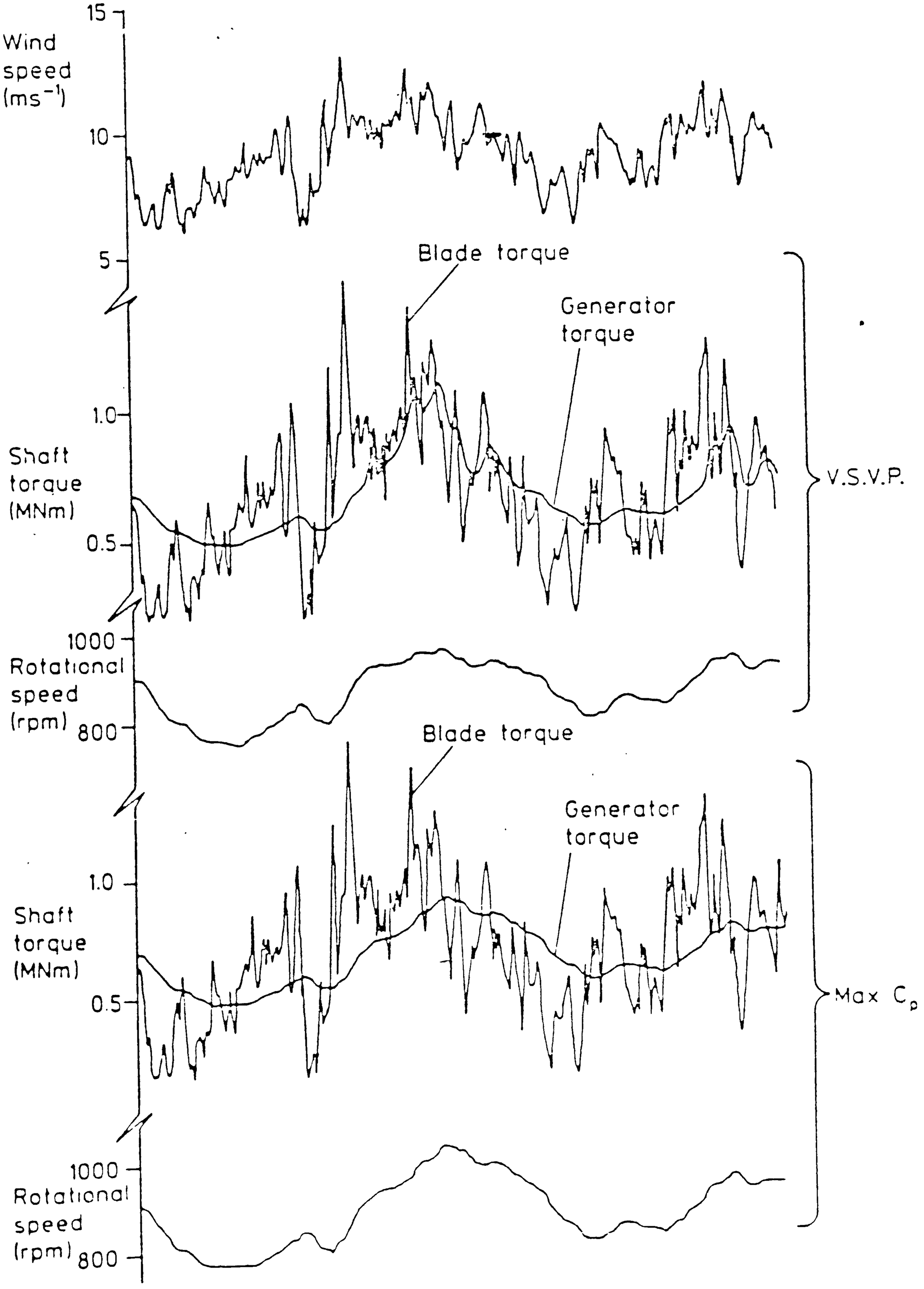

Wind speed (ms⁻¹)
15
10
5
Blade torque
Generator torque
V.S.V.P.
Shaft torque (MNm)
1.0
0.5
1000
Rotational speed (rpm)
800
Blade torque
Generator torque
Max C_p
Shaft torque (MNm)
1.0
0.5
1000
Rotational speed (rpm)
800

Fig 2·11

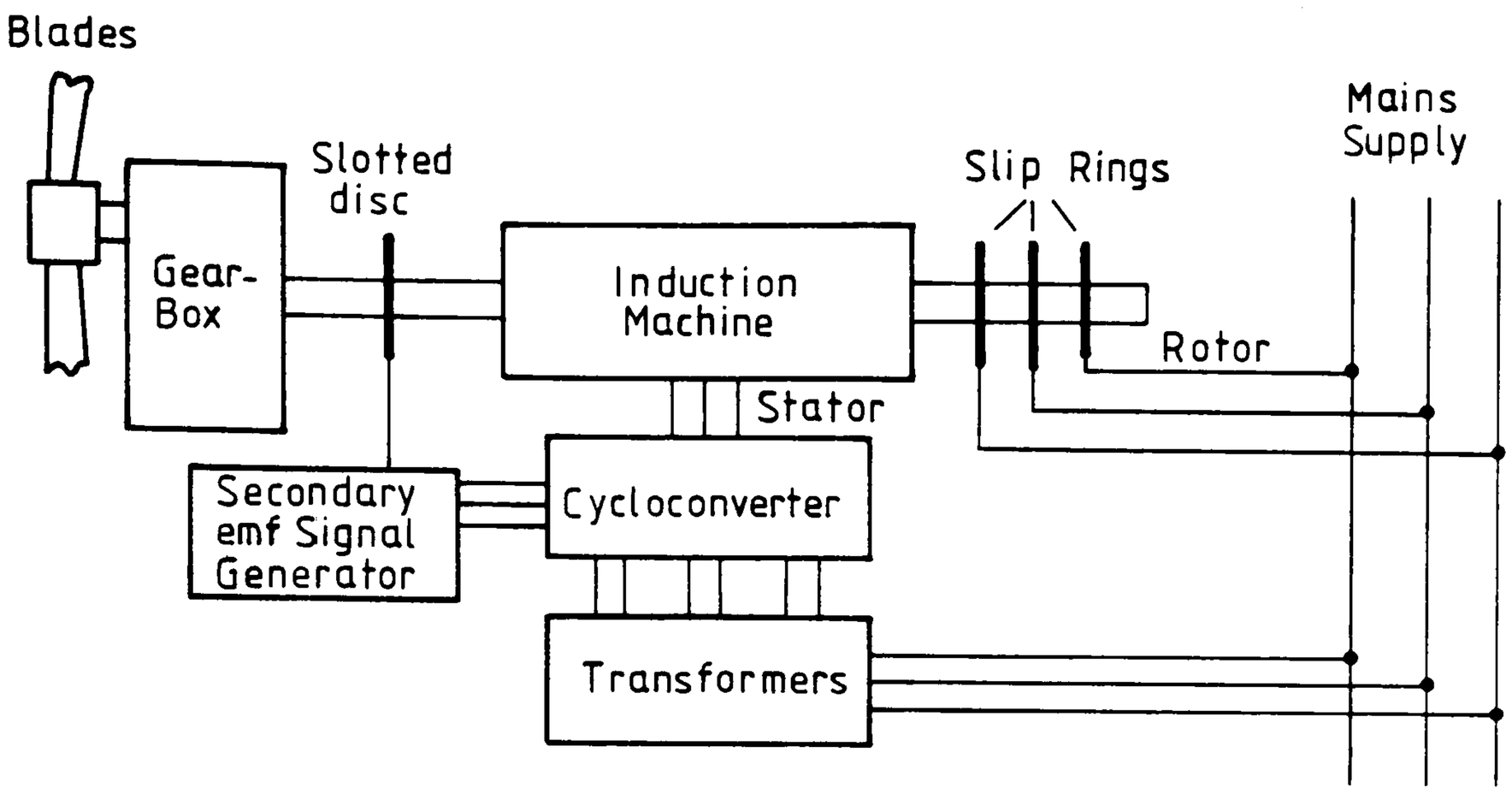
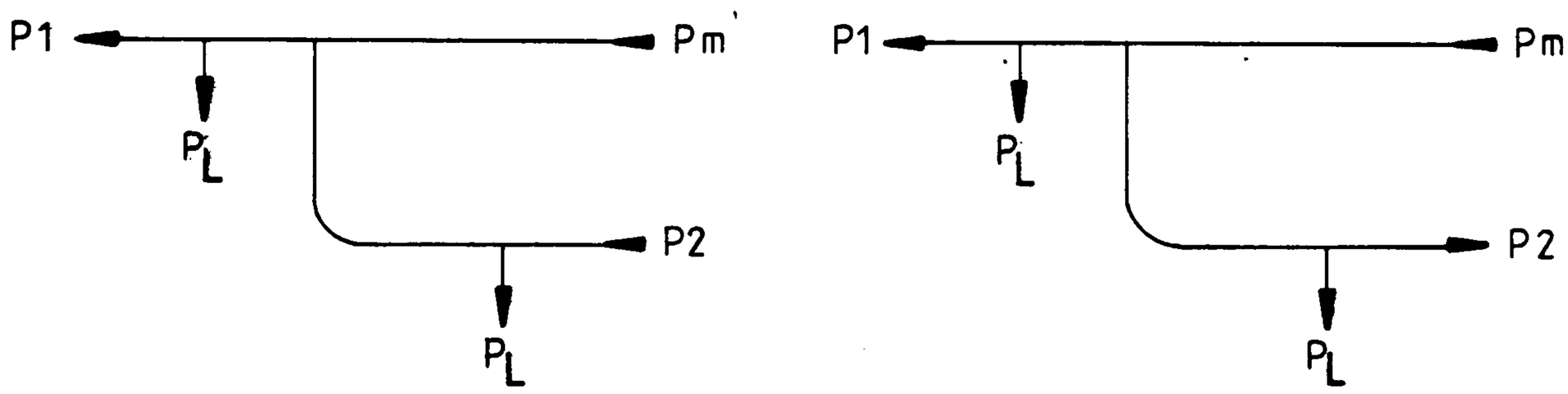


Fig 3·1



Subsynchronous Generation

Supersynchronous Generation

Pm Mechanical Input Power
P1 Primary Electrical Output Power
P2 Secondary Electrical Power
PL Iron / Copper Losses

Fig 3·2

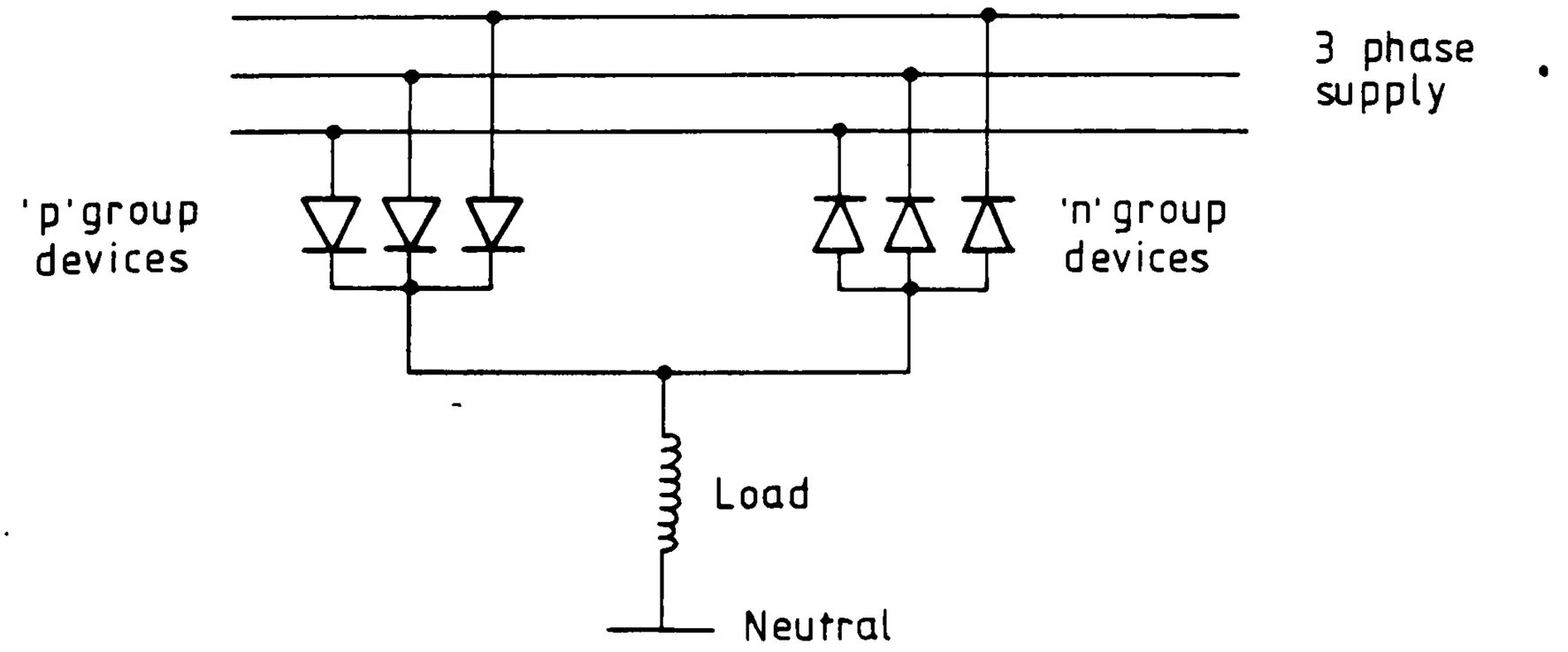


Fig 3·3

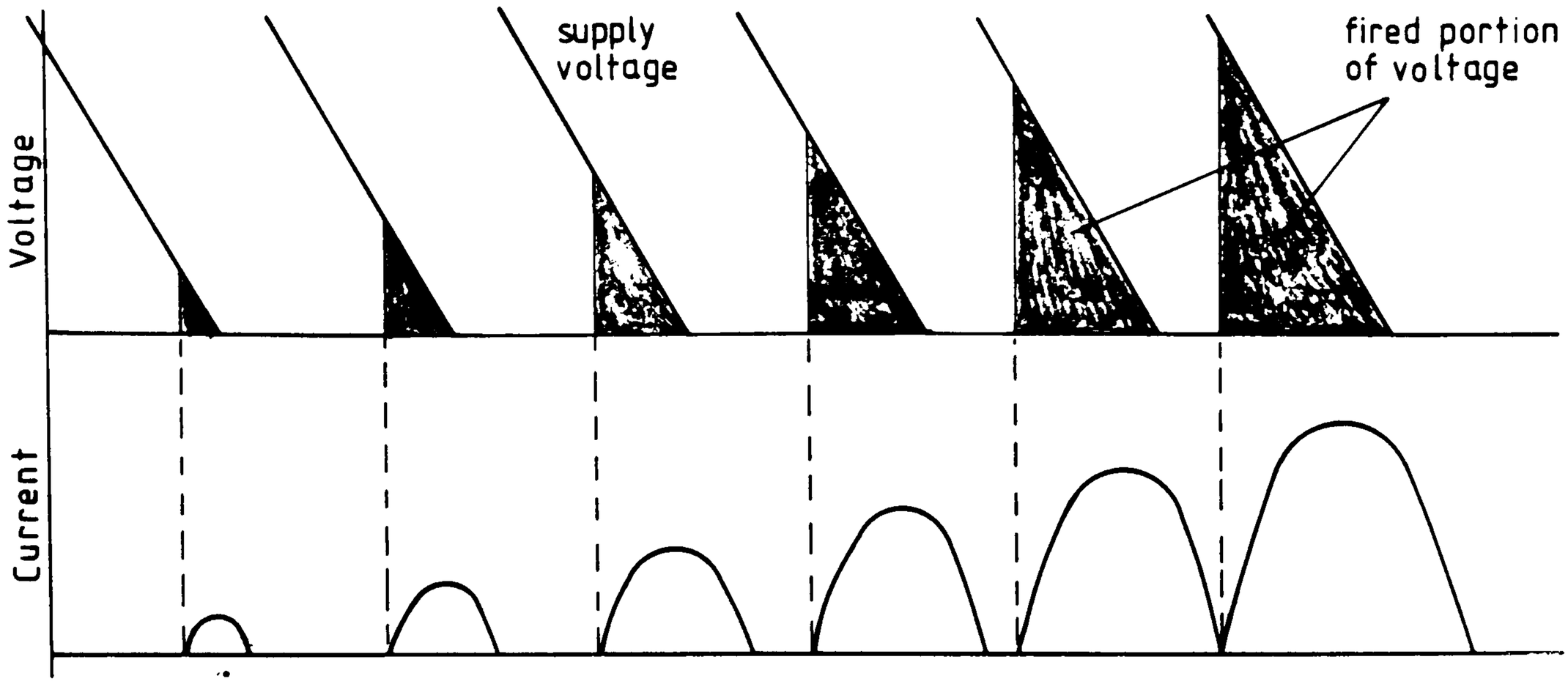


Fig 3·4

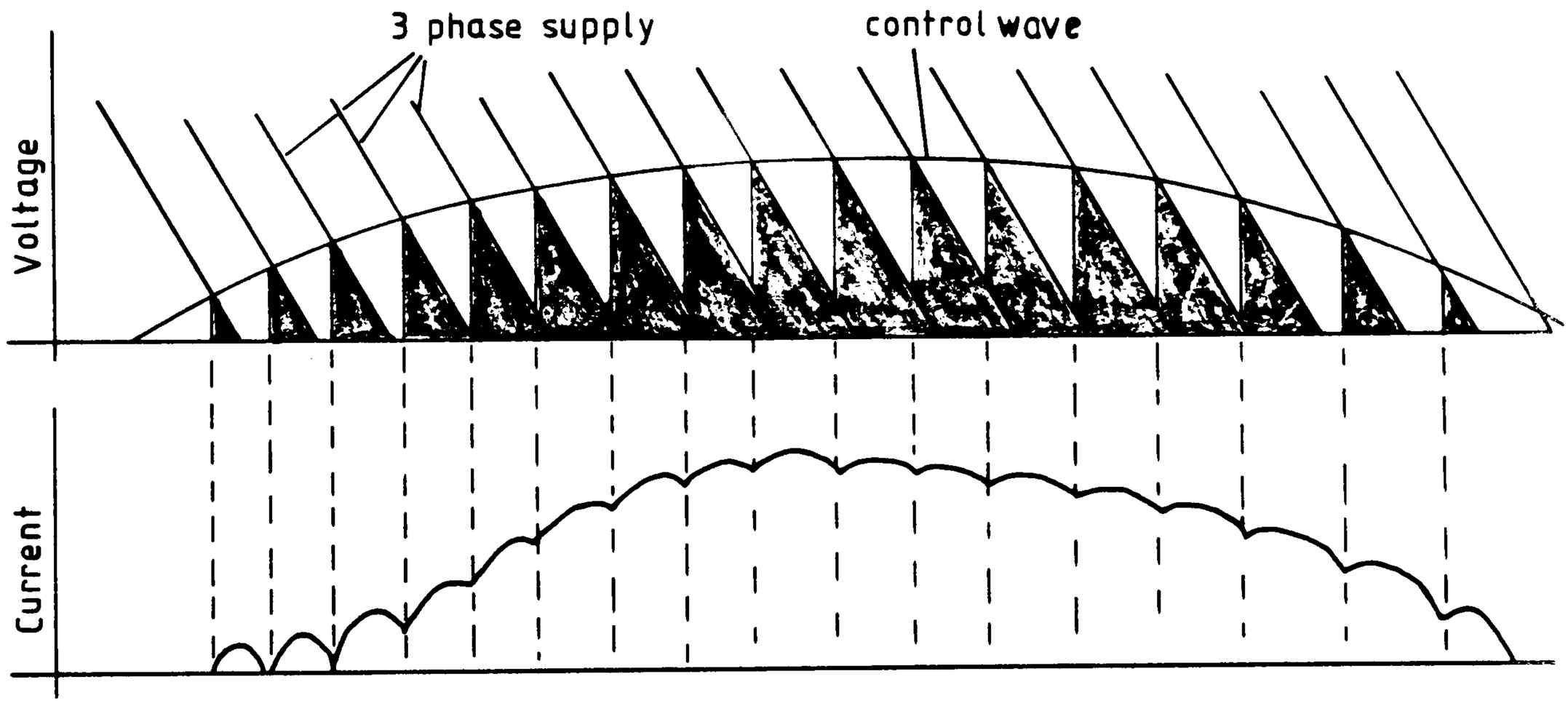


Fig 3·5

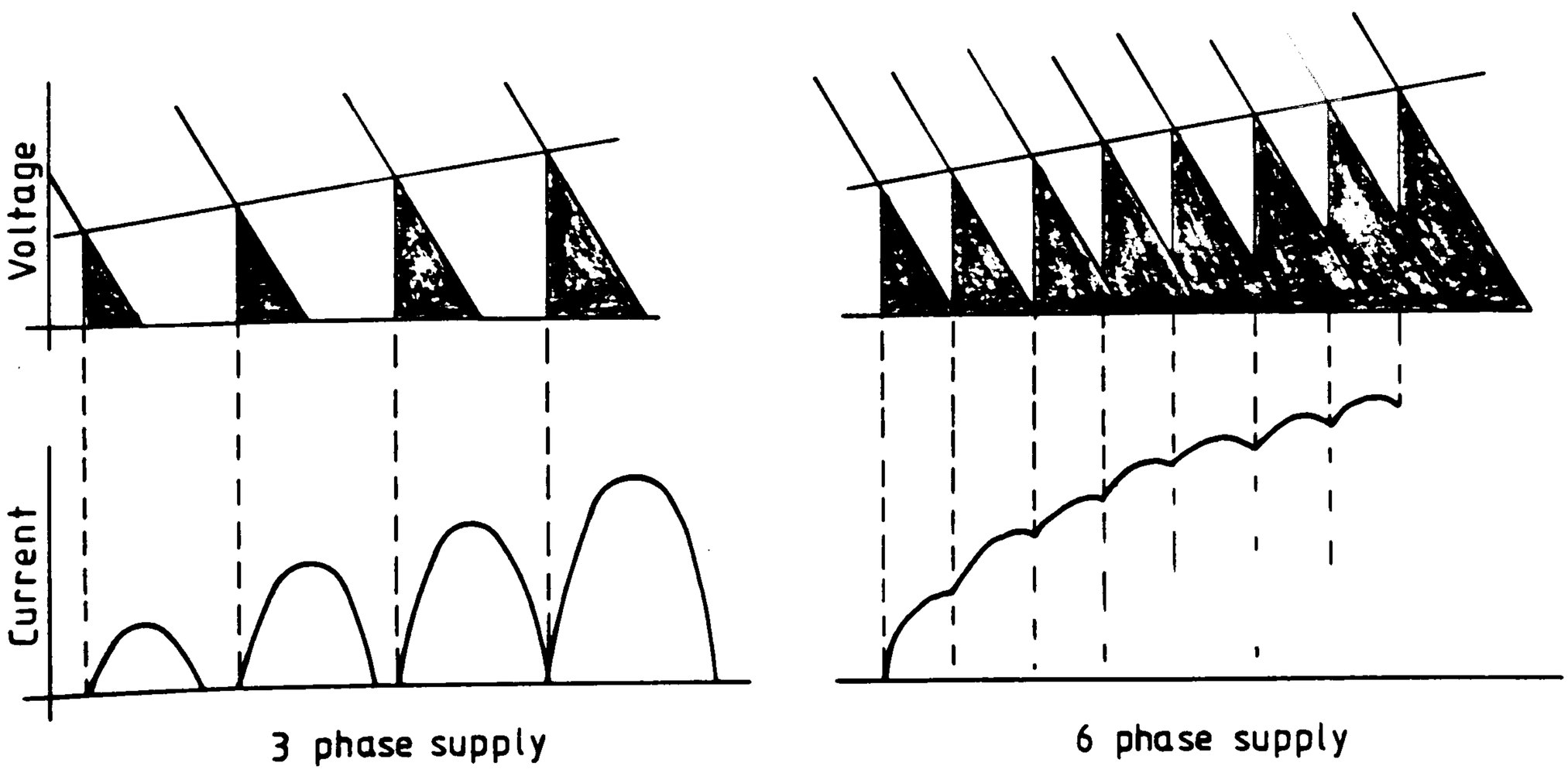


Fig 3·6

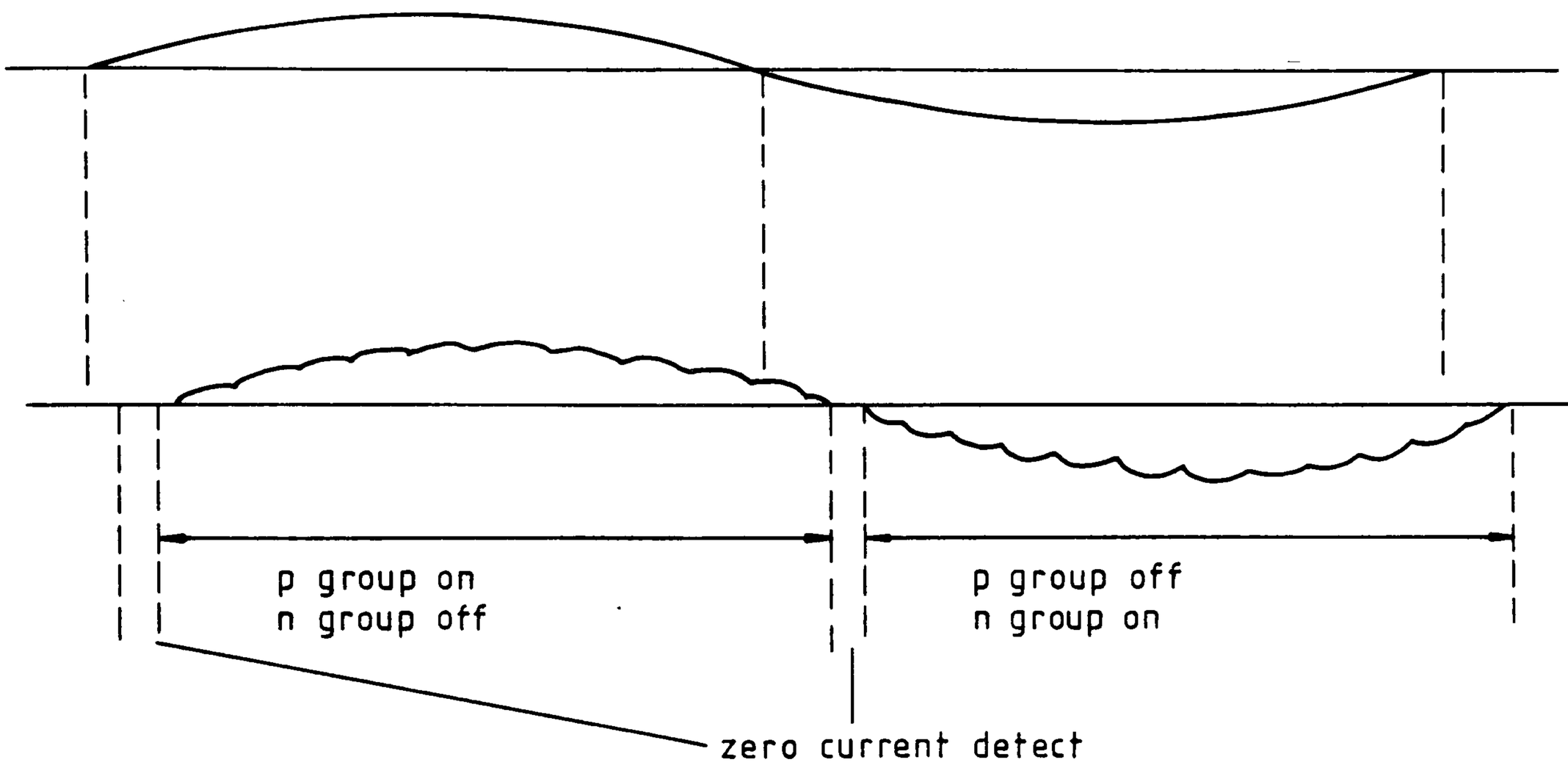


Fig 3·7

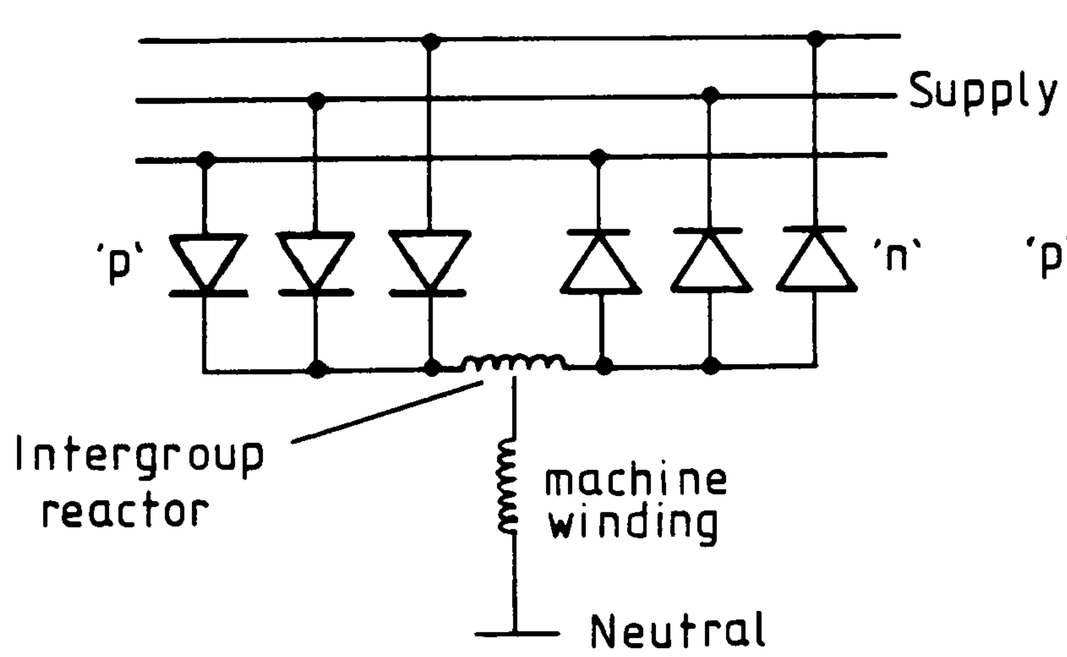


Fig 3·8

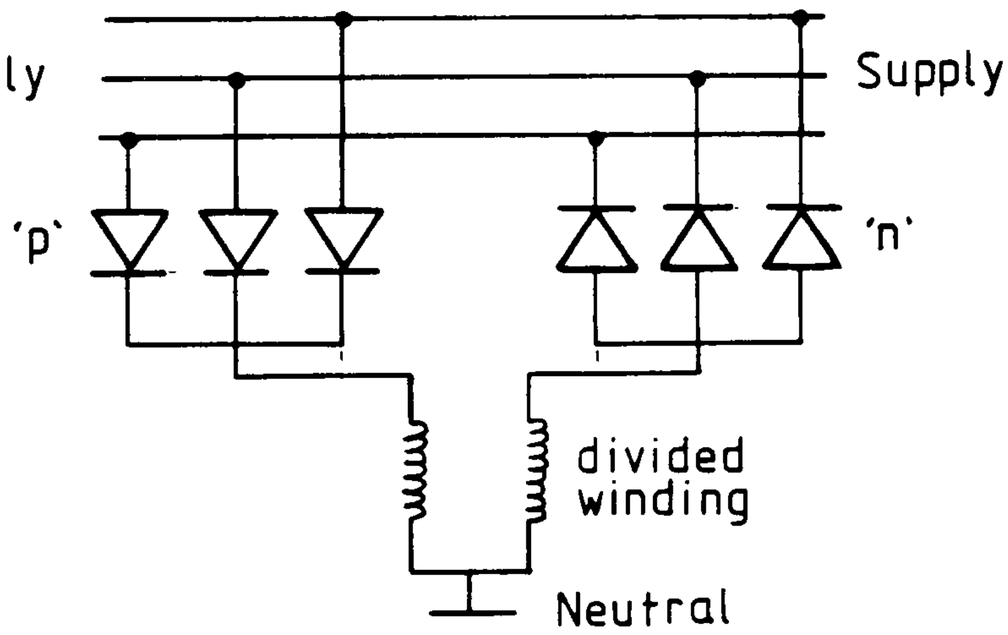


Fig 3·9

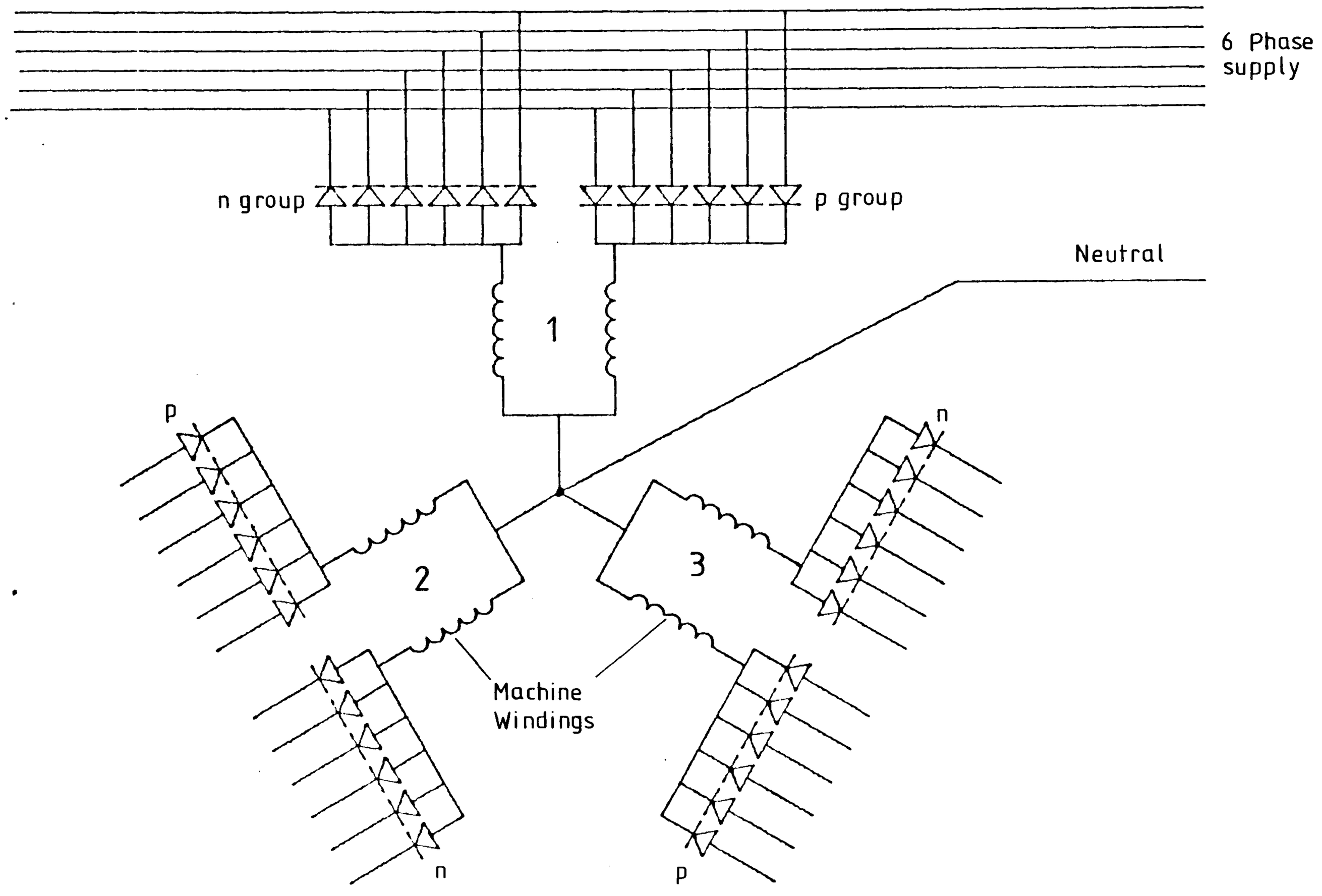

6 Phase
supply
n group
p group
Neutral
1
p
n
2
3
Machine
Windings
n
p

Fig 3·10

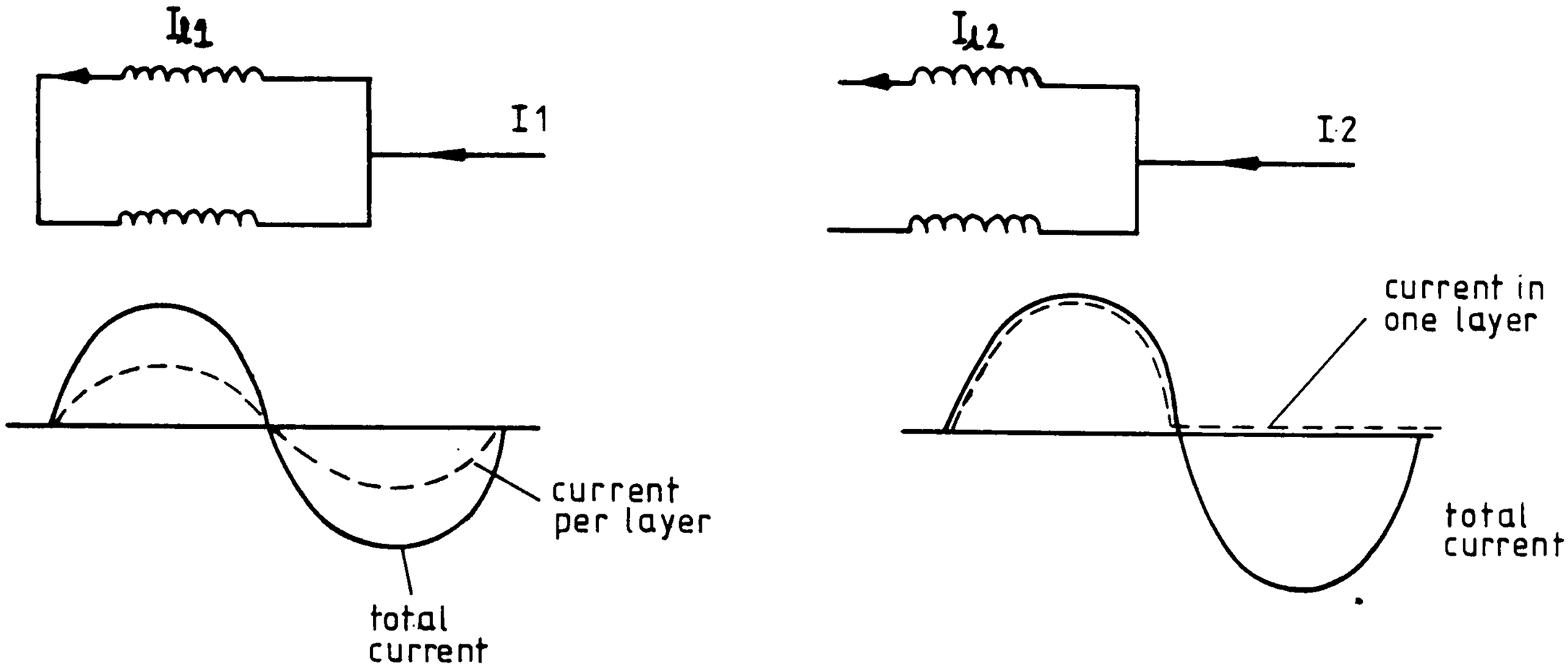


Fig 3·11a

Fig 3·11b

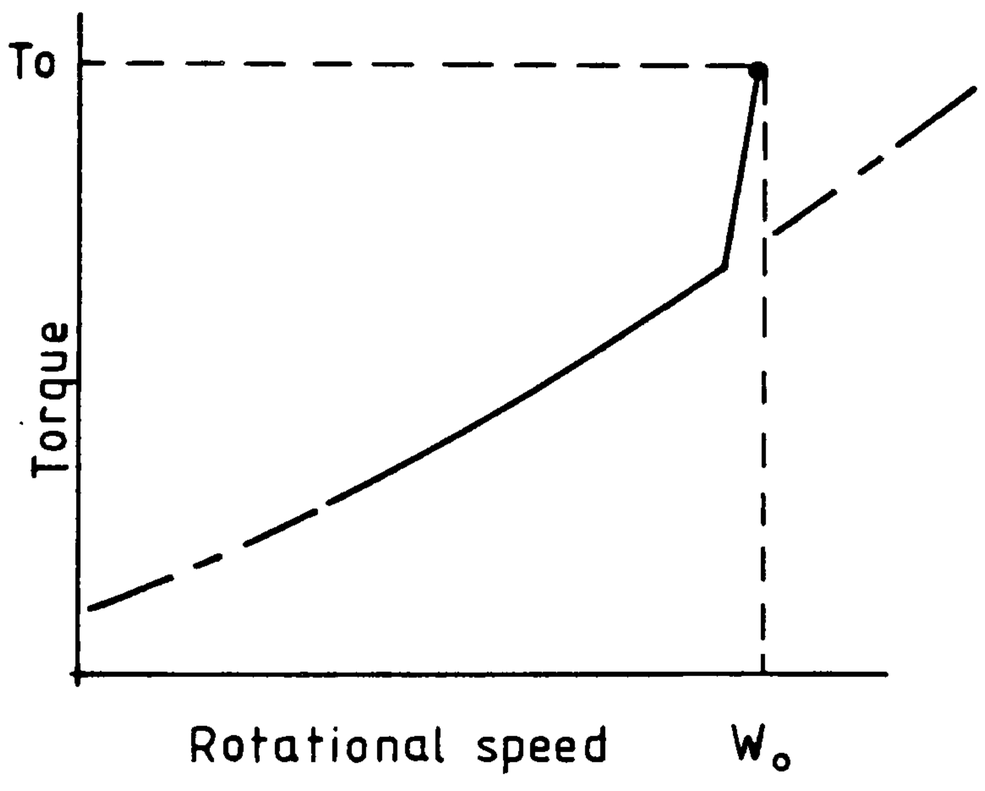


Fig 3·12a

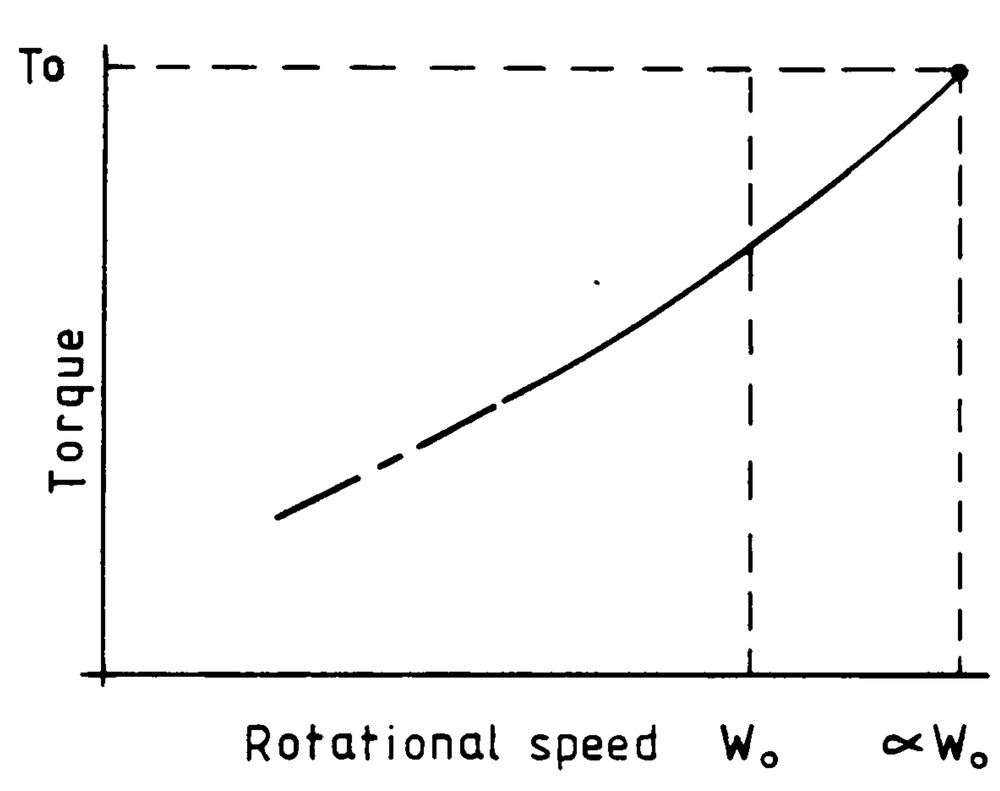


Fig 3·12b

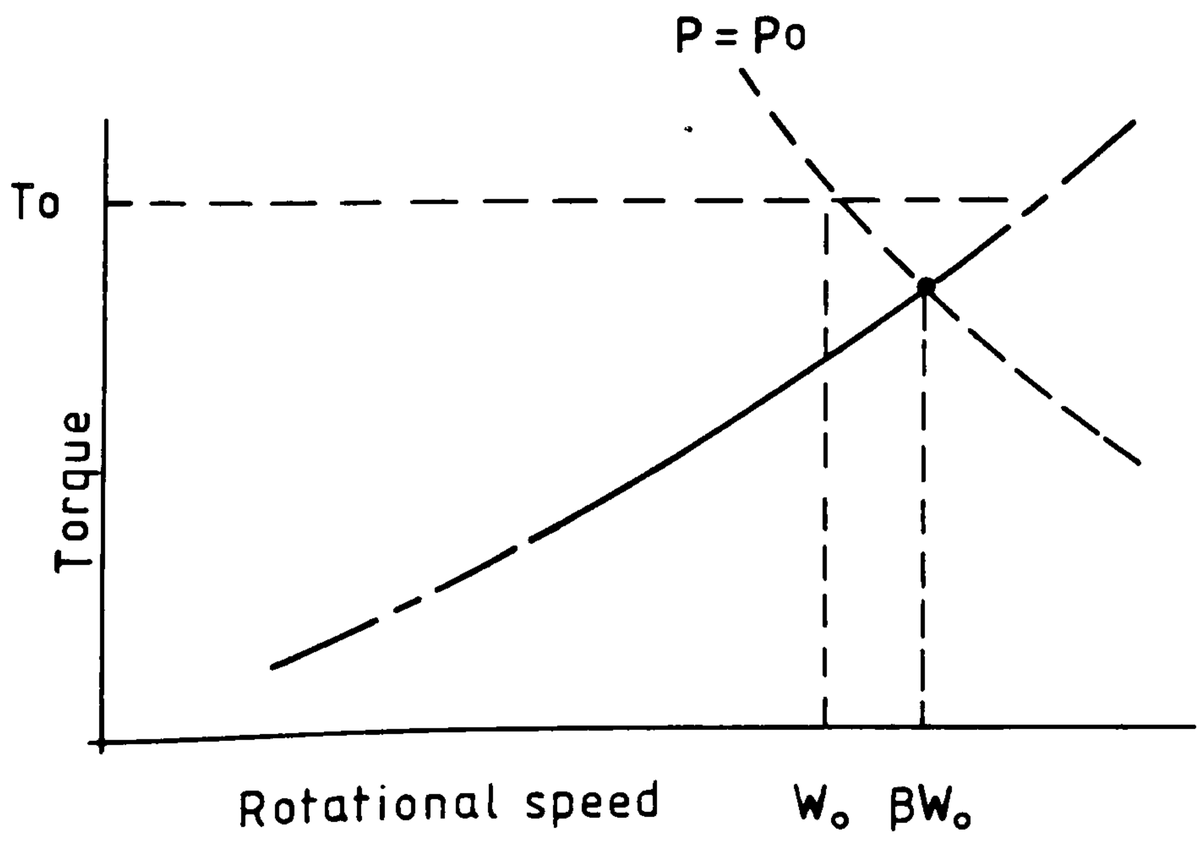


Fig 3·12c

To, Wo, Po Torque, rotational speed power rating (derived from fixed speed case)

— - — Max Cp characteristic

——— Torque - speed operating characteristic

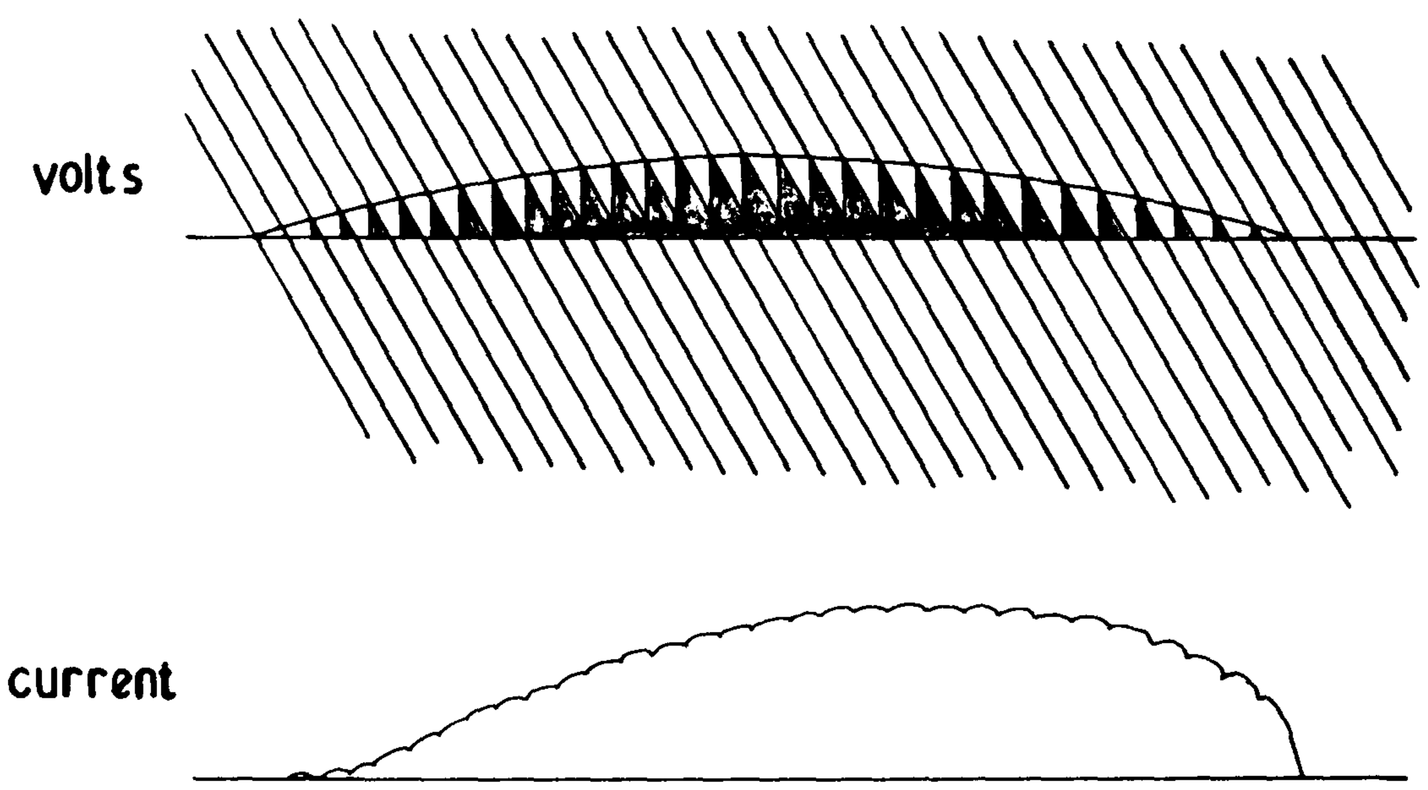


Fig 3·13

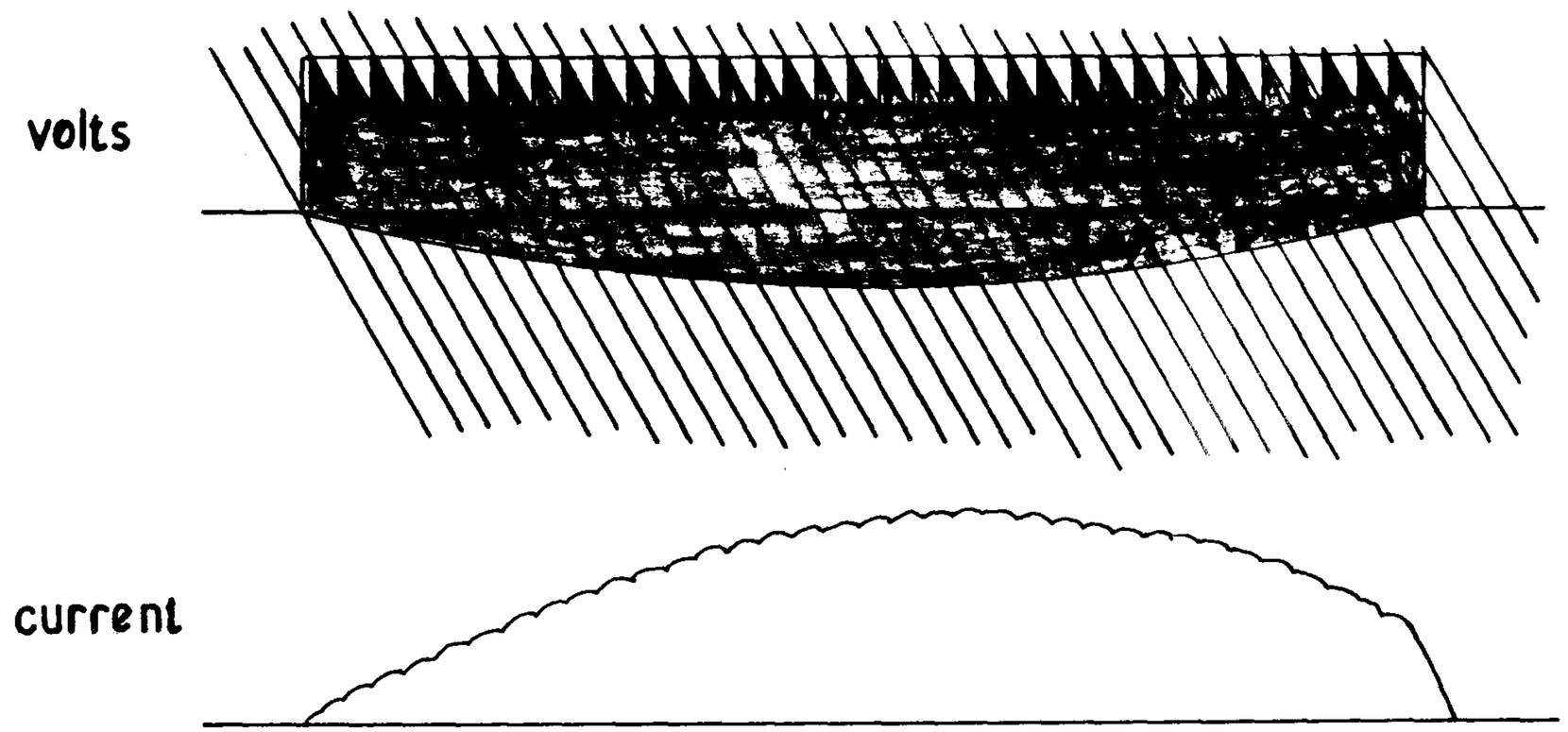


Fig 3·14 a Fixed Firing Angle:
Aiding Voltage

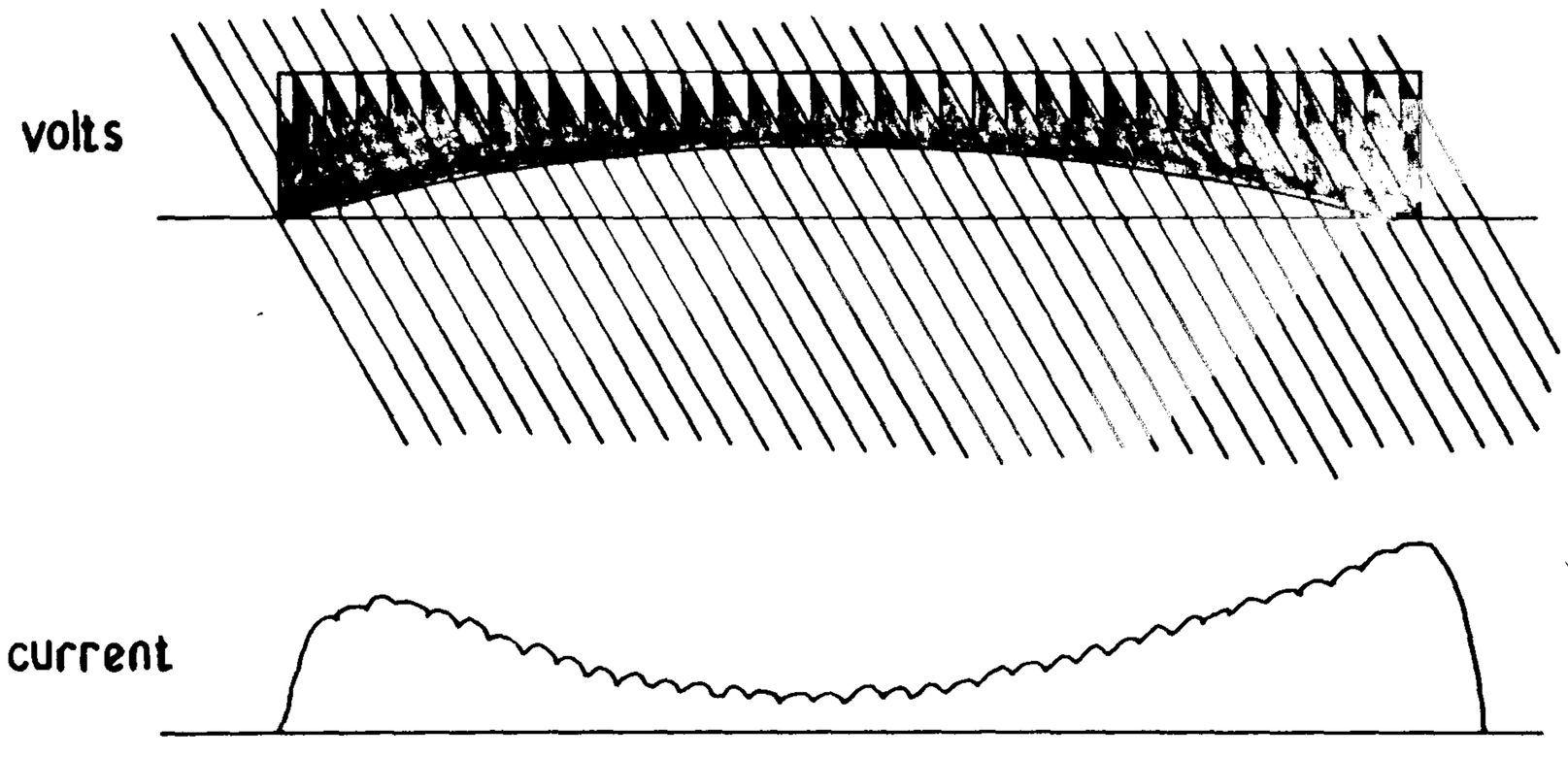
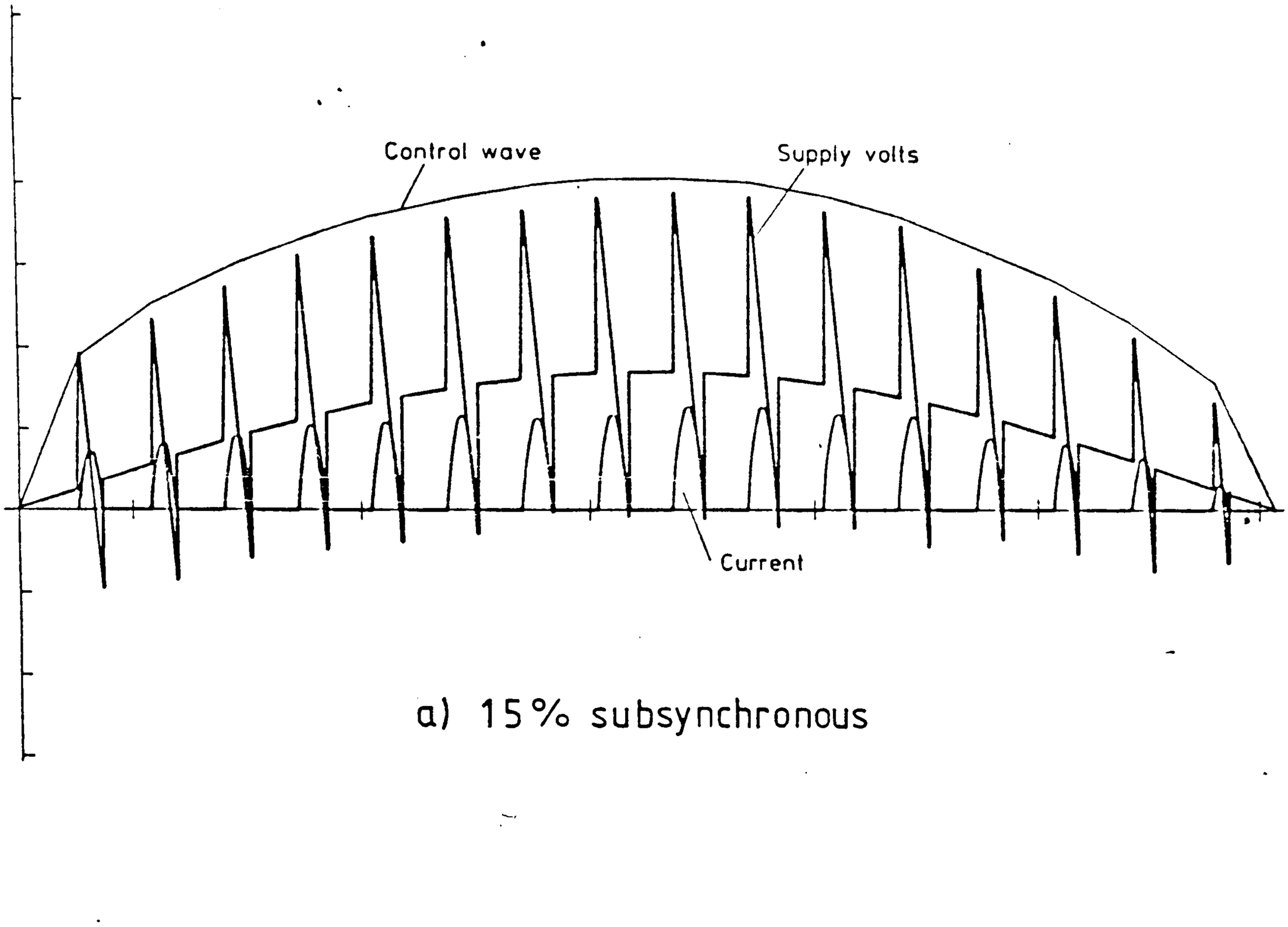
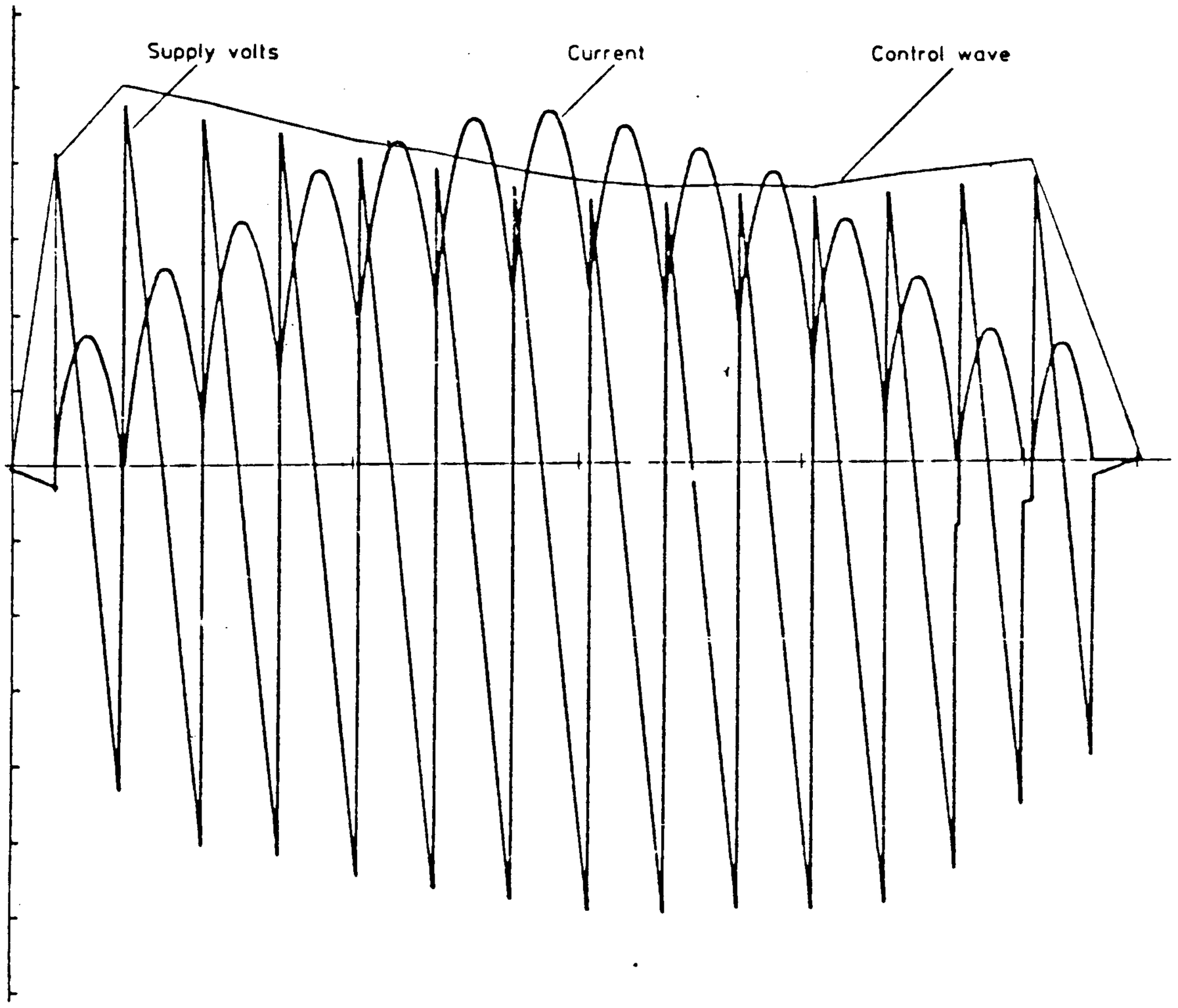


Fig 3·14b Fixed Firing Angle:
Opposing Voltage



a) 15% subsynchronous



b) 15% supersynchronous

Fig 3·15

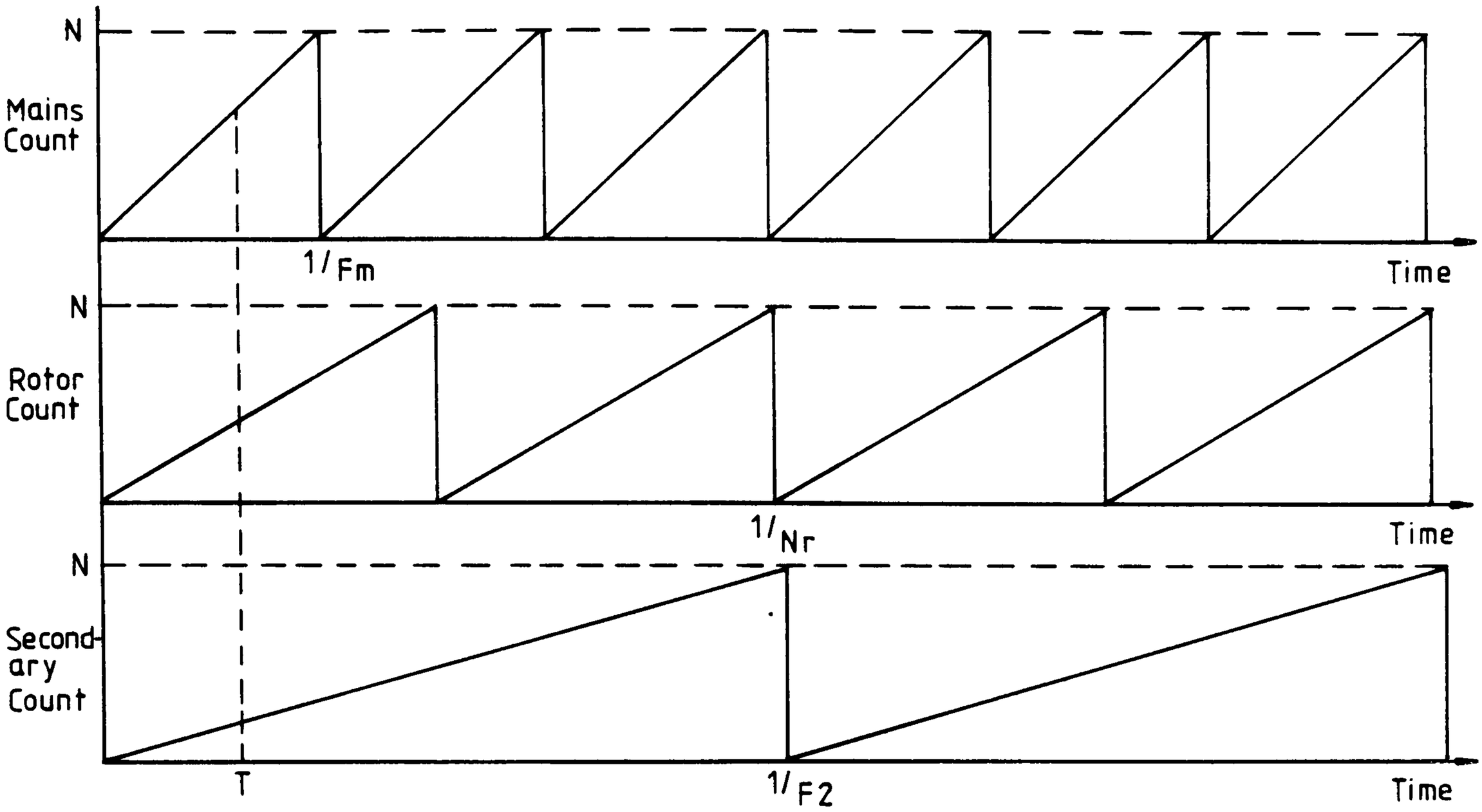
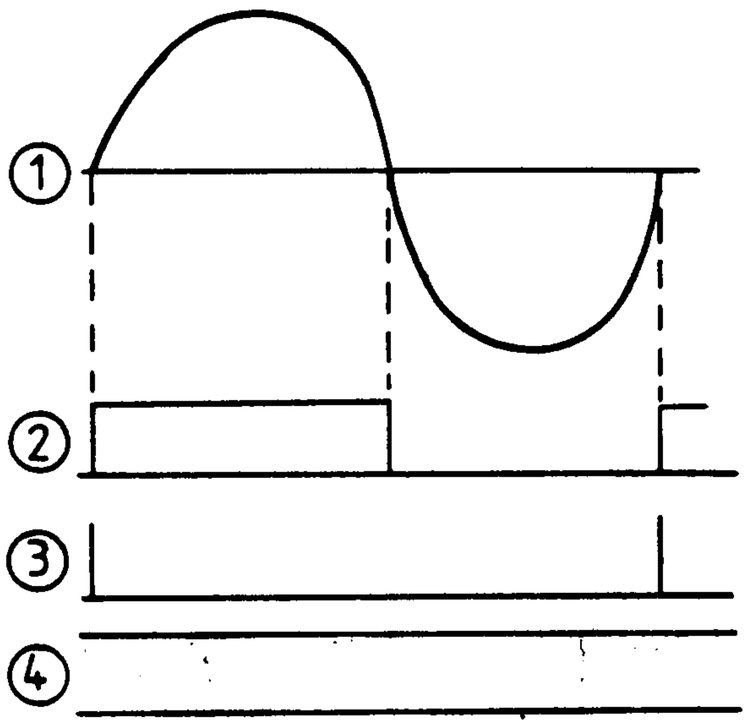


Fig 4·1



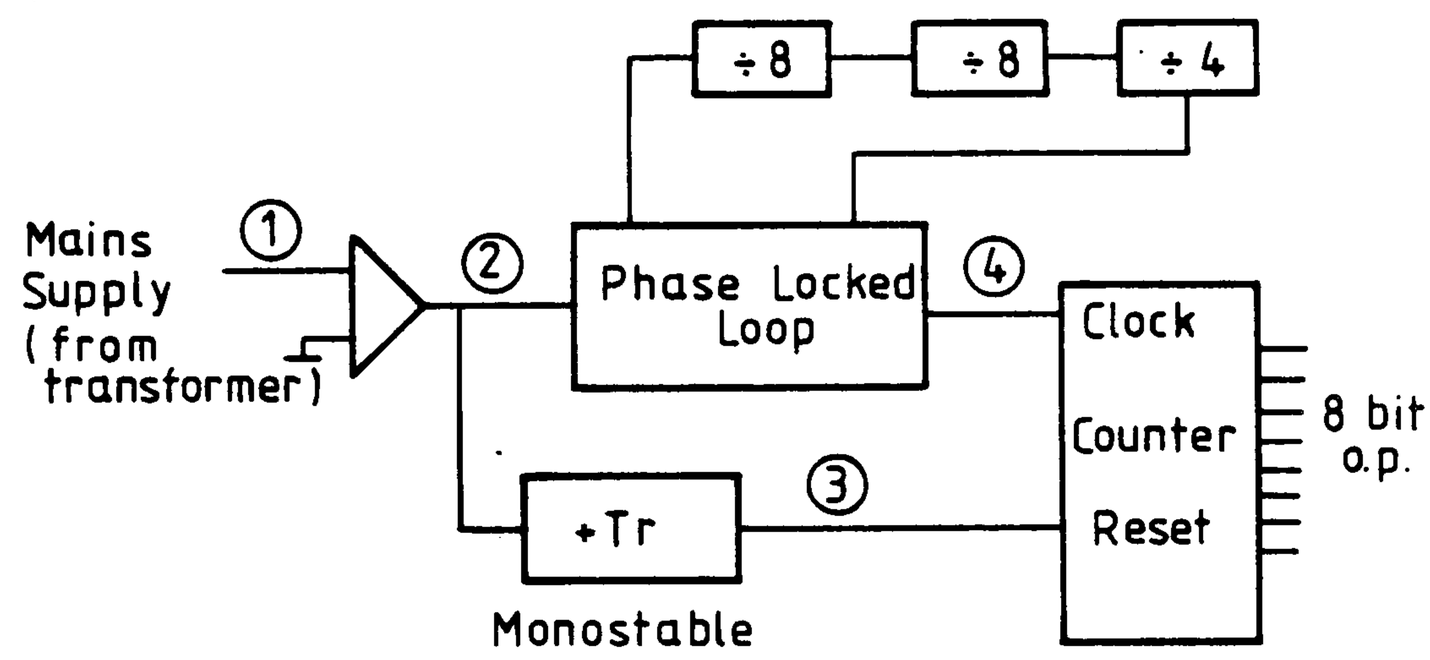
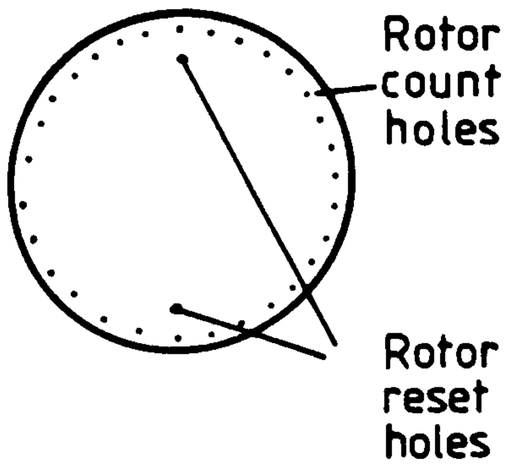


Fig 4·2 Mains Count



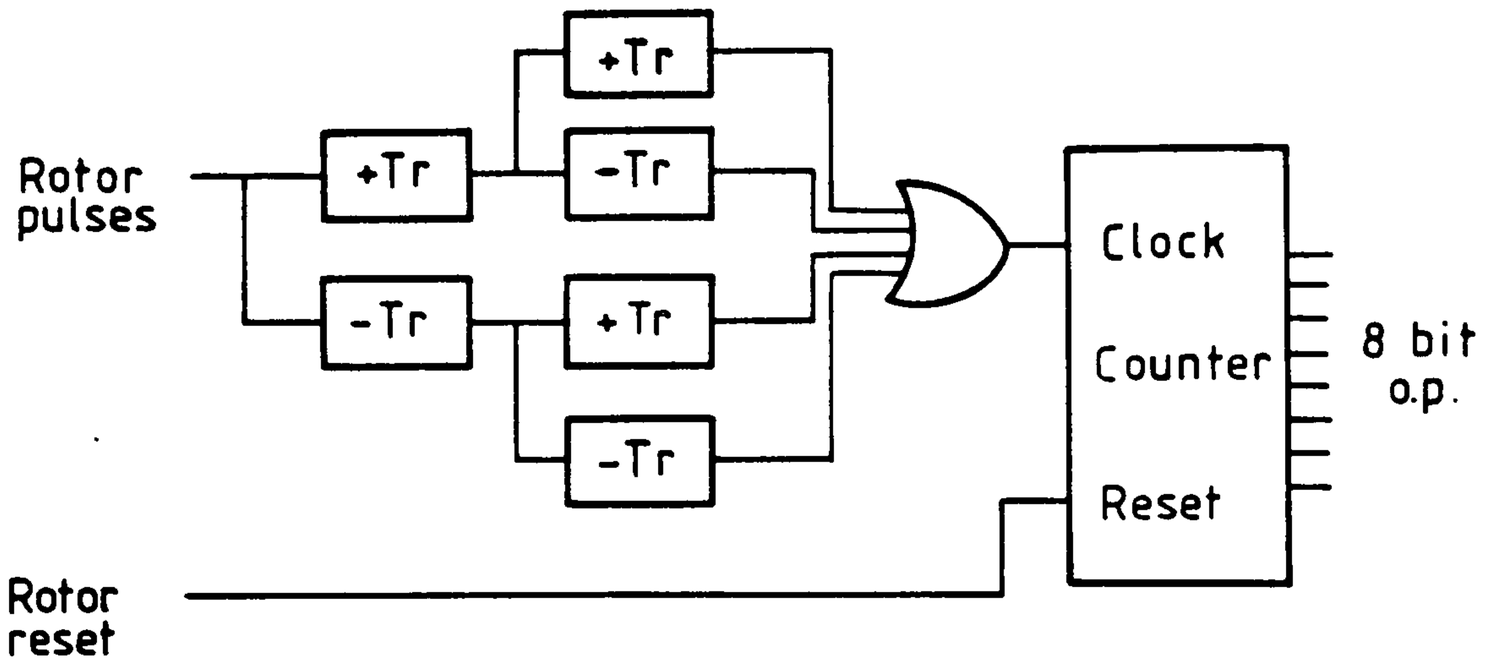


Fig 4·3 Rotor Count

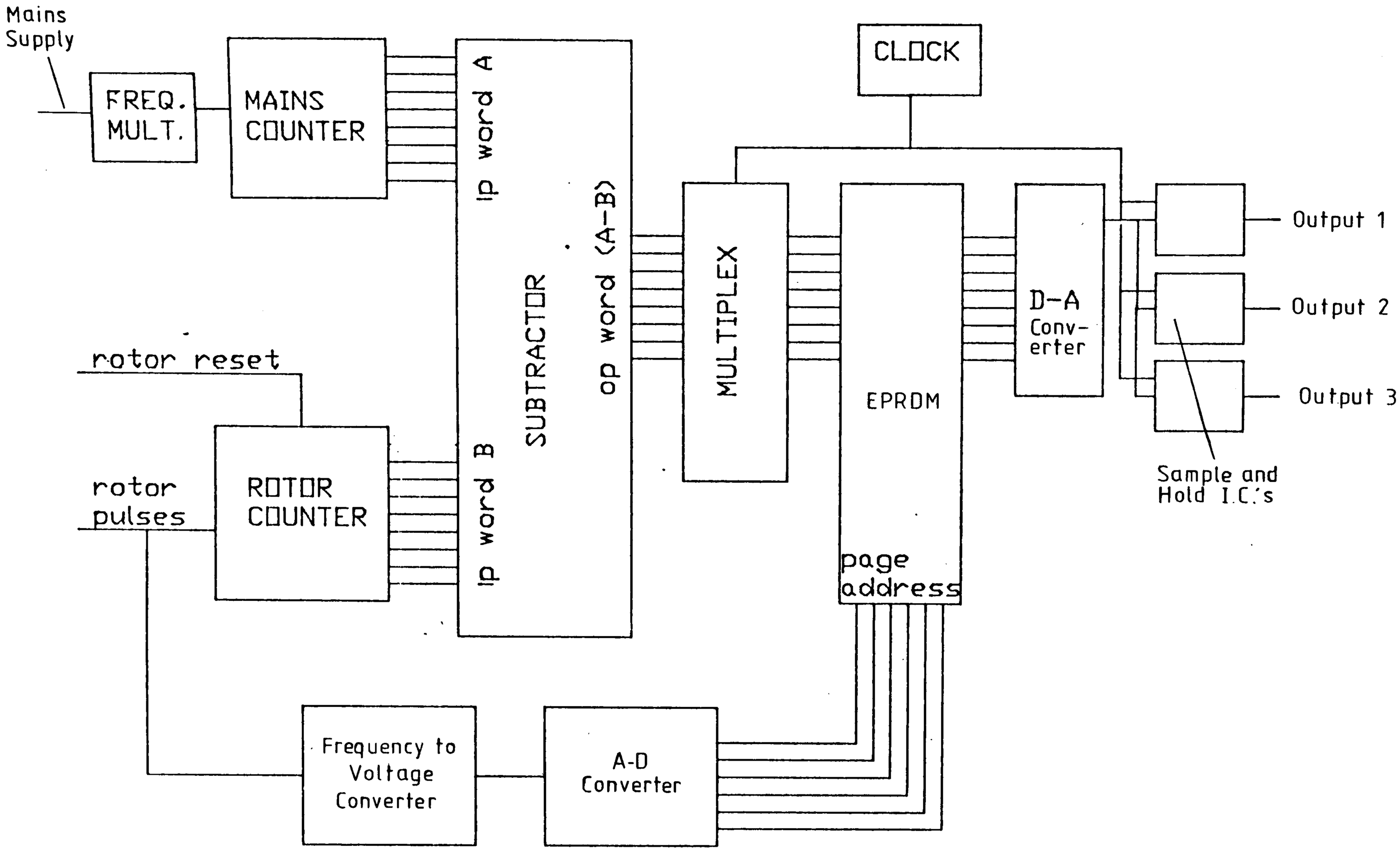
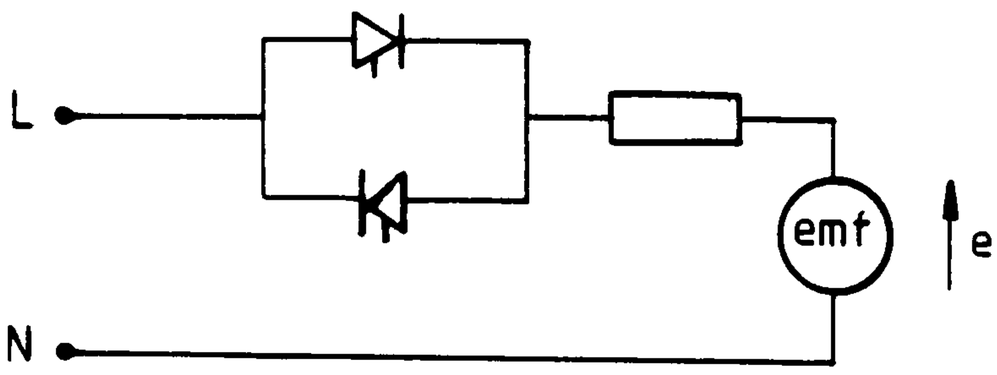

Mains Supply
FREQ. MULT.
MAINS COUNTER
CLOCK
ip word A
SUBTRACTOR
op word (A-B)
MULTIPLEX
EPROM
D-A Conv-erter
Output 1
Output 2
Output 3
Sample and Hold I.C.'s
rotor reset
rotor pulses
ROTOR COUNTER
ip word B
page address
Frequency to Voltage Converter
A-D Converter

Fig 4·4



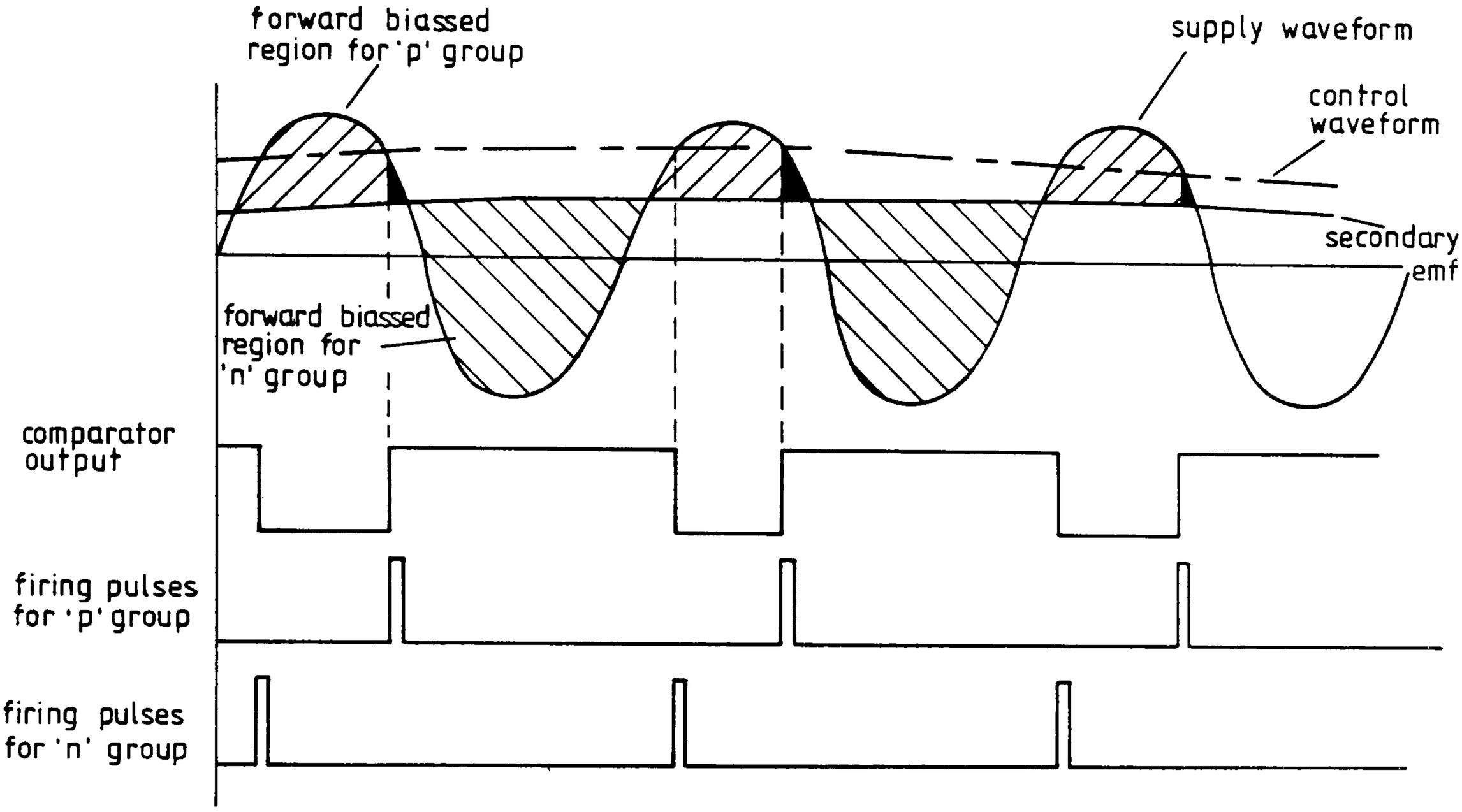


Fig 4·5 a

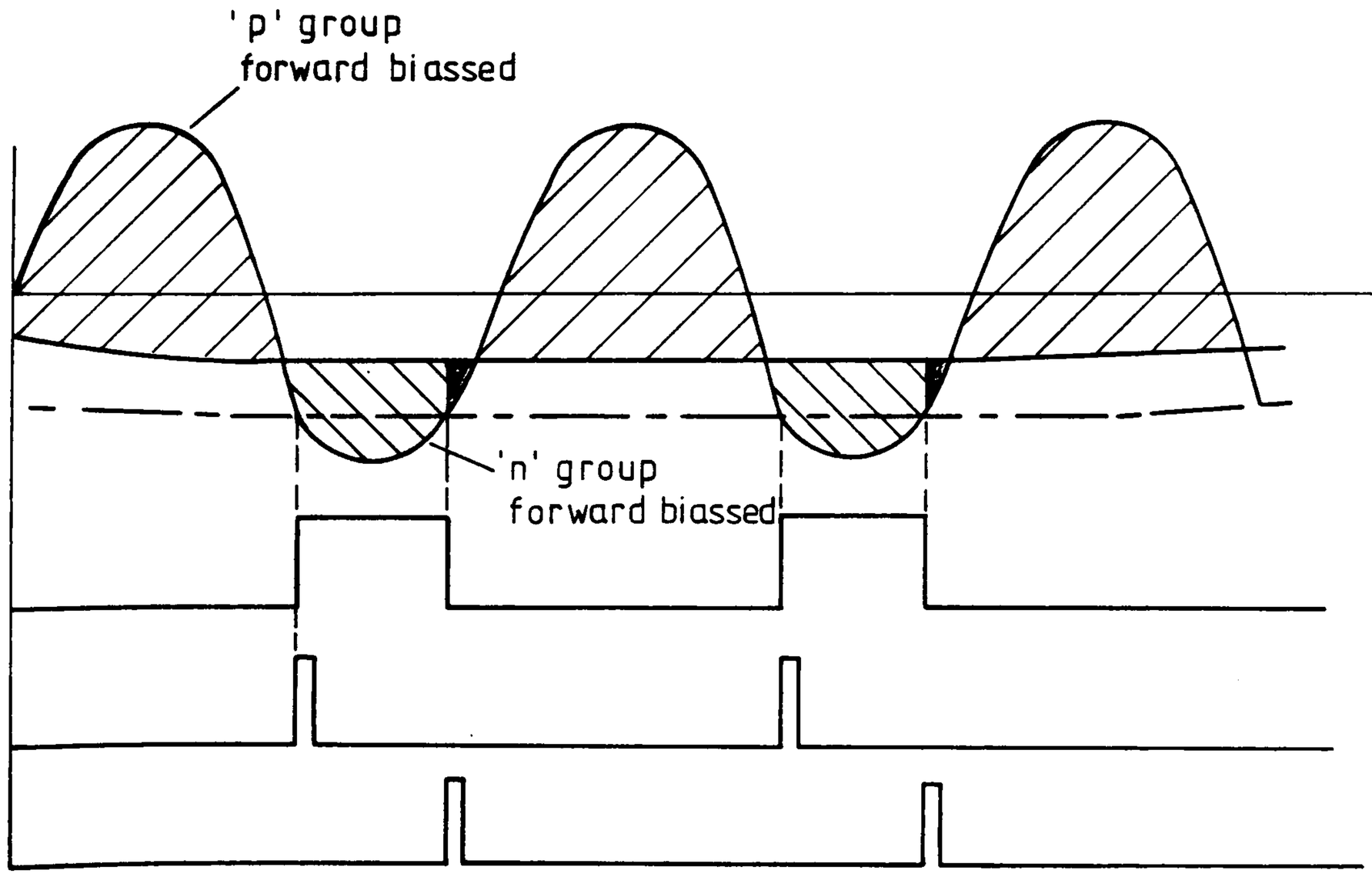
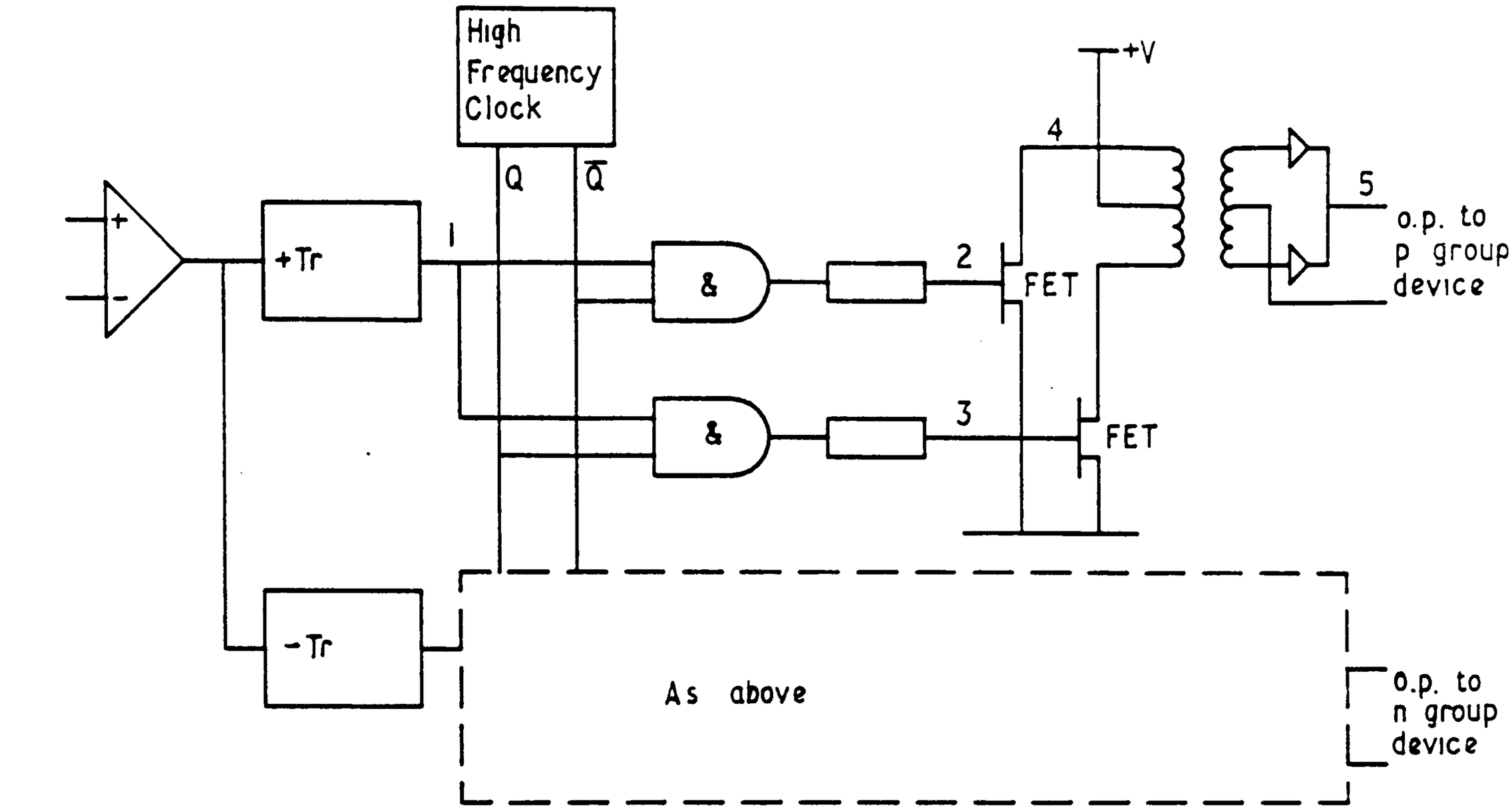


Fig 4·5 b


High Frequency Clock
Q
$\overline{Q}$
+
-
+Tr
-Tr
1
&
&
2
3
4
5
+V
FET
FET
o.p. to p group device
As above
o.p. to n group device

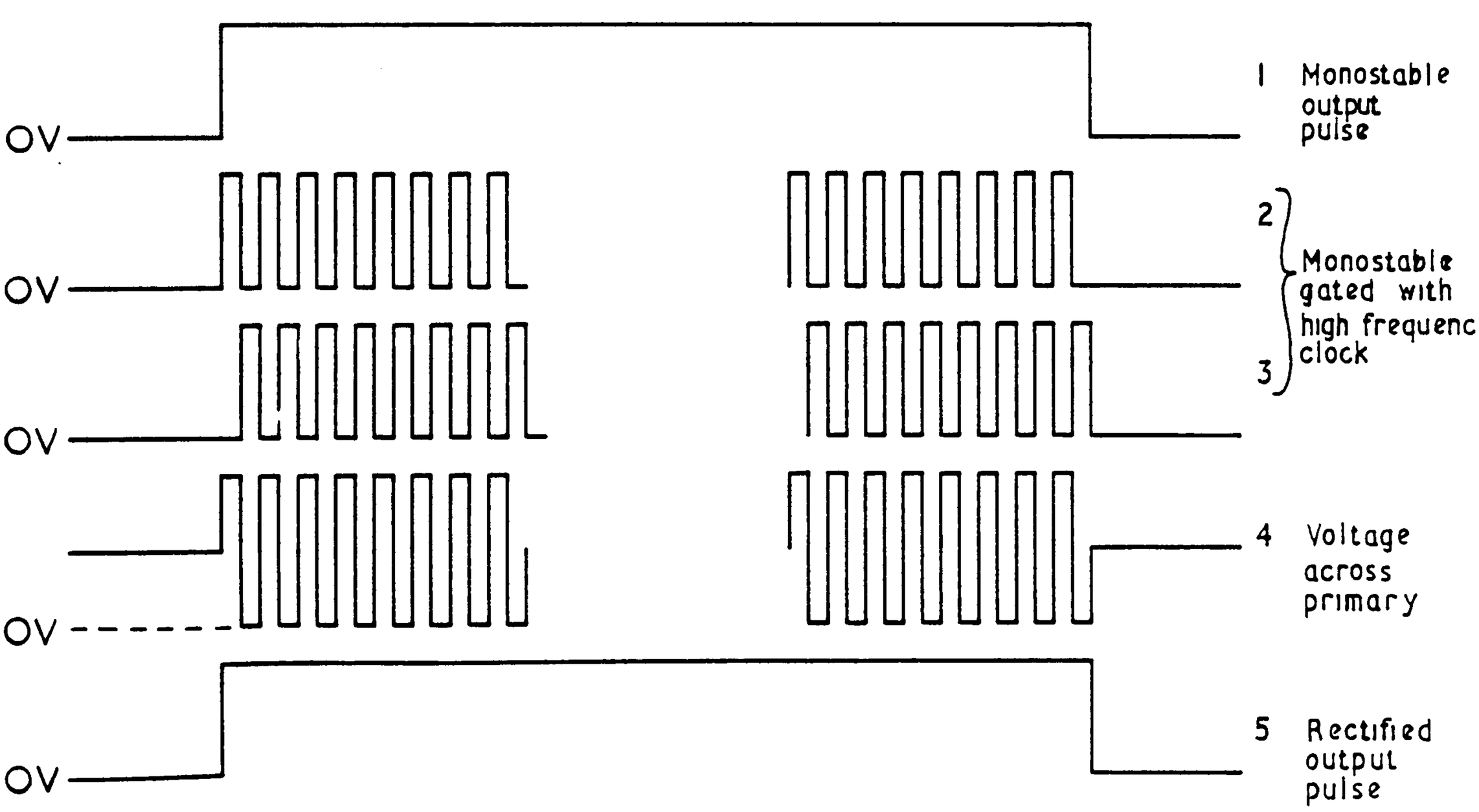

OV
OV
OV
OV
OV
1 Monostable output pulse
2
3
Monostable gated with high frequency clock
4 Voltage across primary
5 Rectified output pulse

Fig 4.6

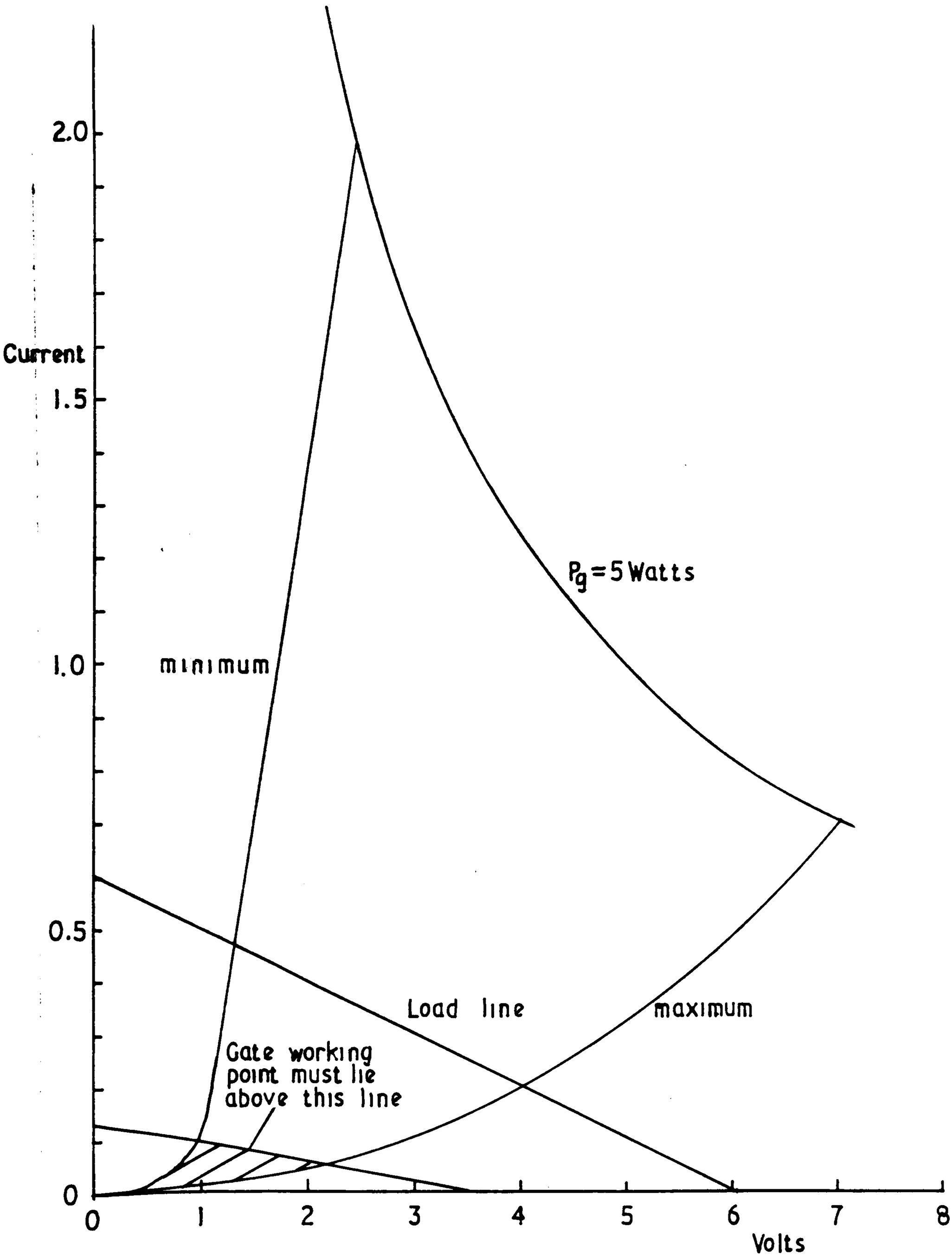


Fig 4.7 Gate characteristic

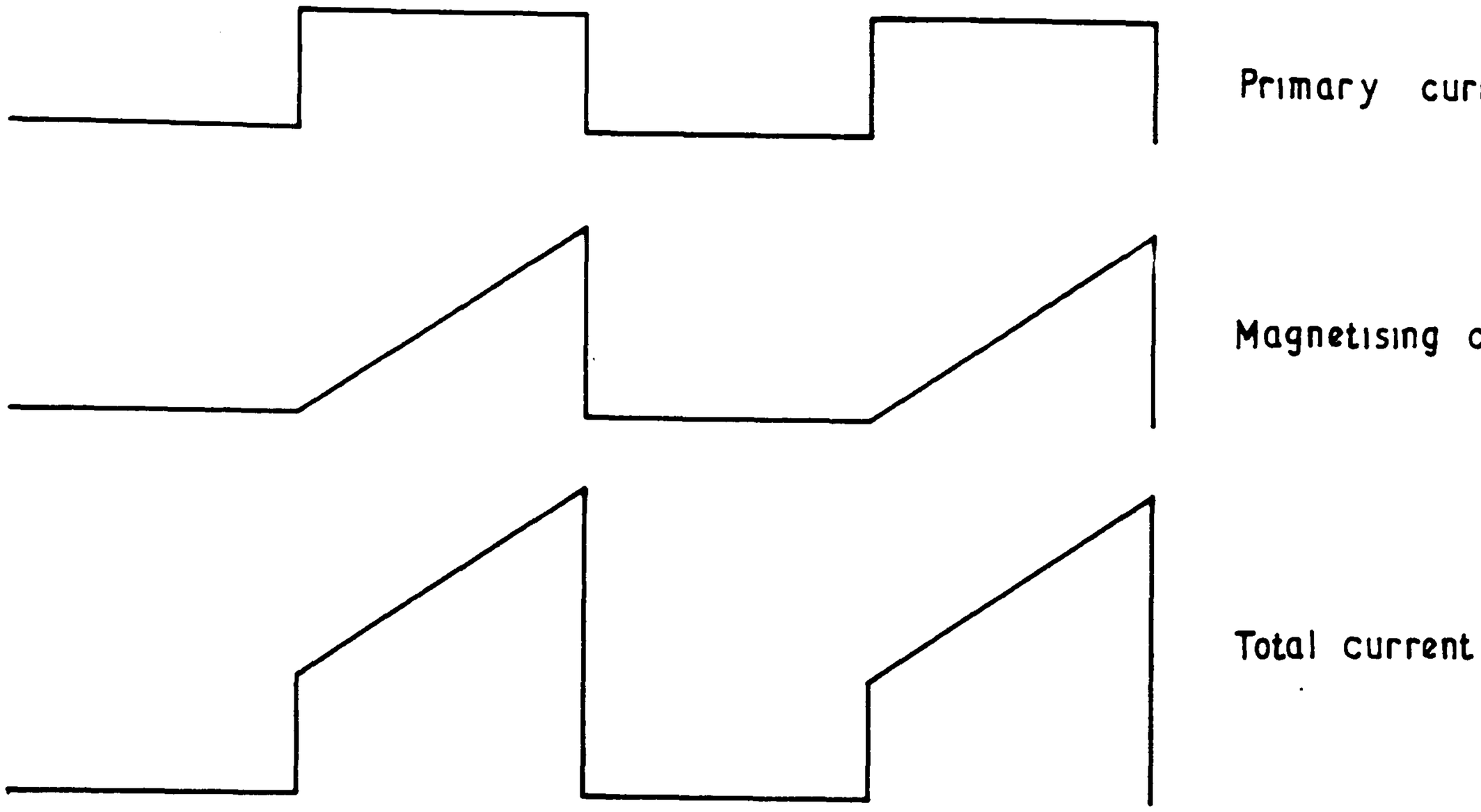


Fig 4.8

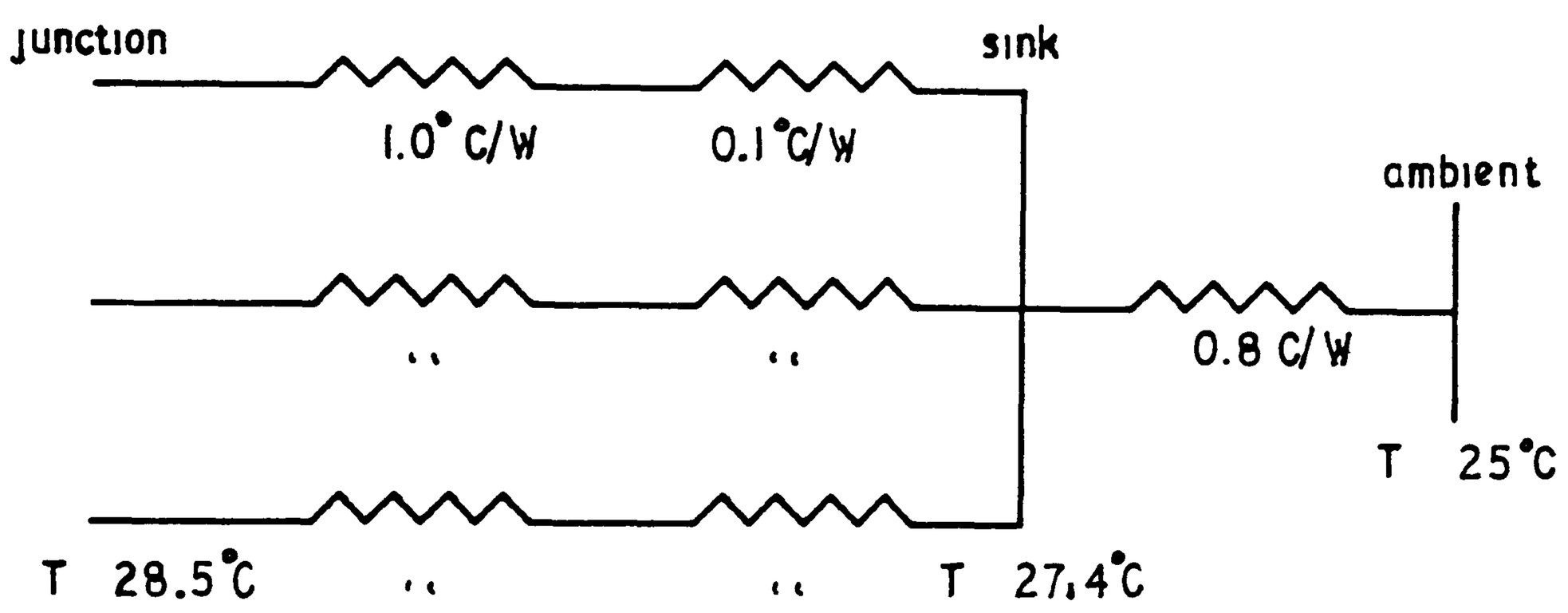


Fig 4.9

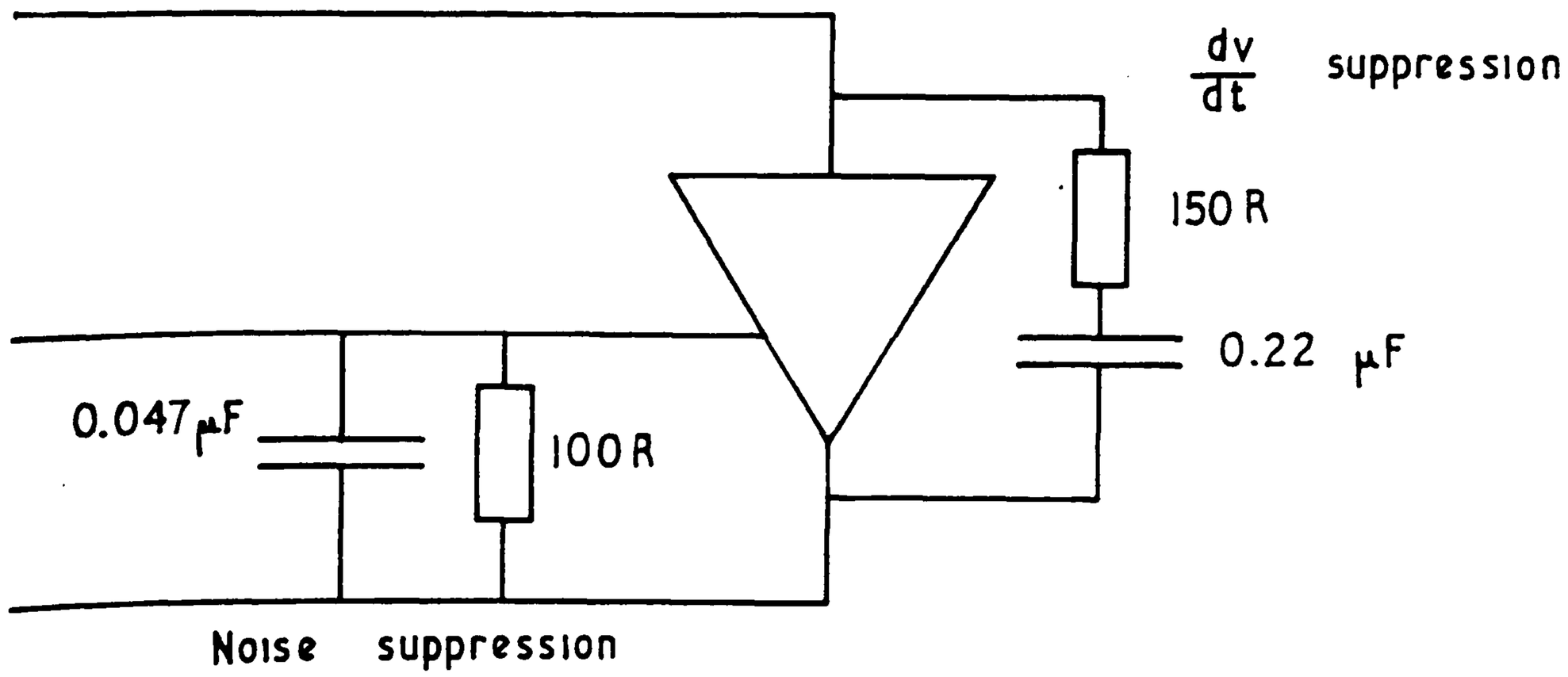


Fig 4.10 Thyristor suppression

Supersynchronous

Subsynchronous

Actual Secondary Emf

↑ 20mm/sec

180° out of phase

In phase

Sec. Emf. Signal Generator

Fig 5.1

Supersynchronous

Subsynchronous

↑ 20mm/se

Sec. Emf. Signal Generator

In phase

In phase

Current

Fig 5.2

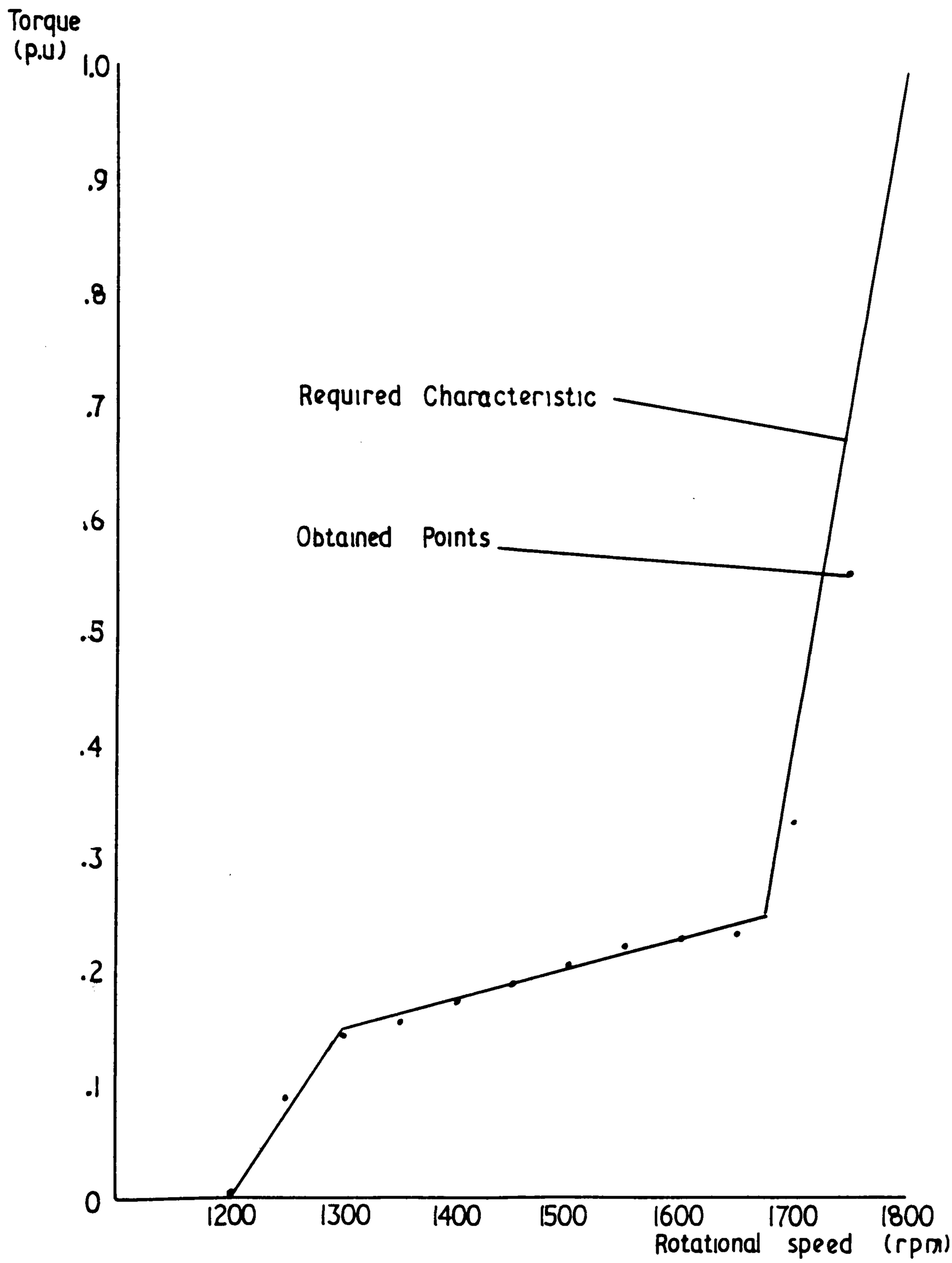
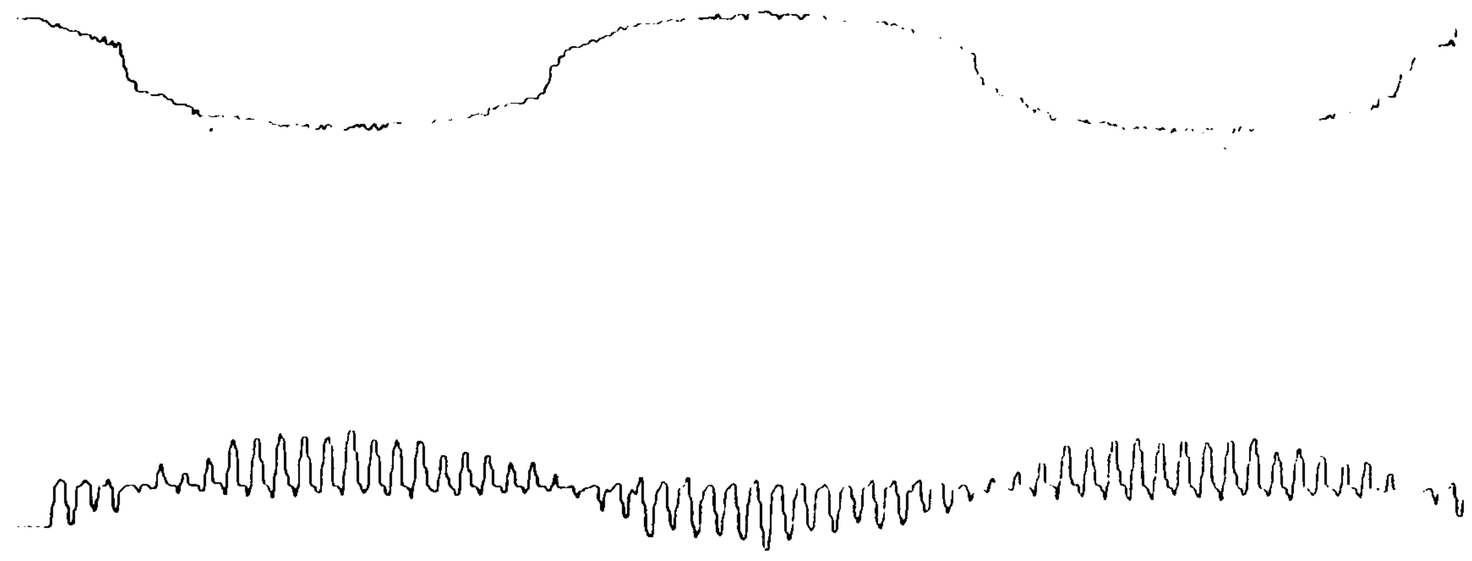
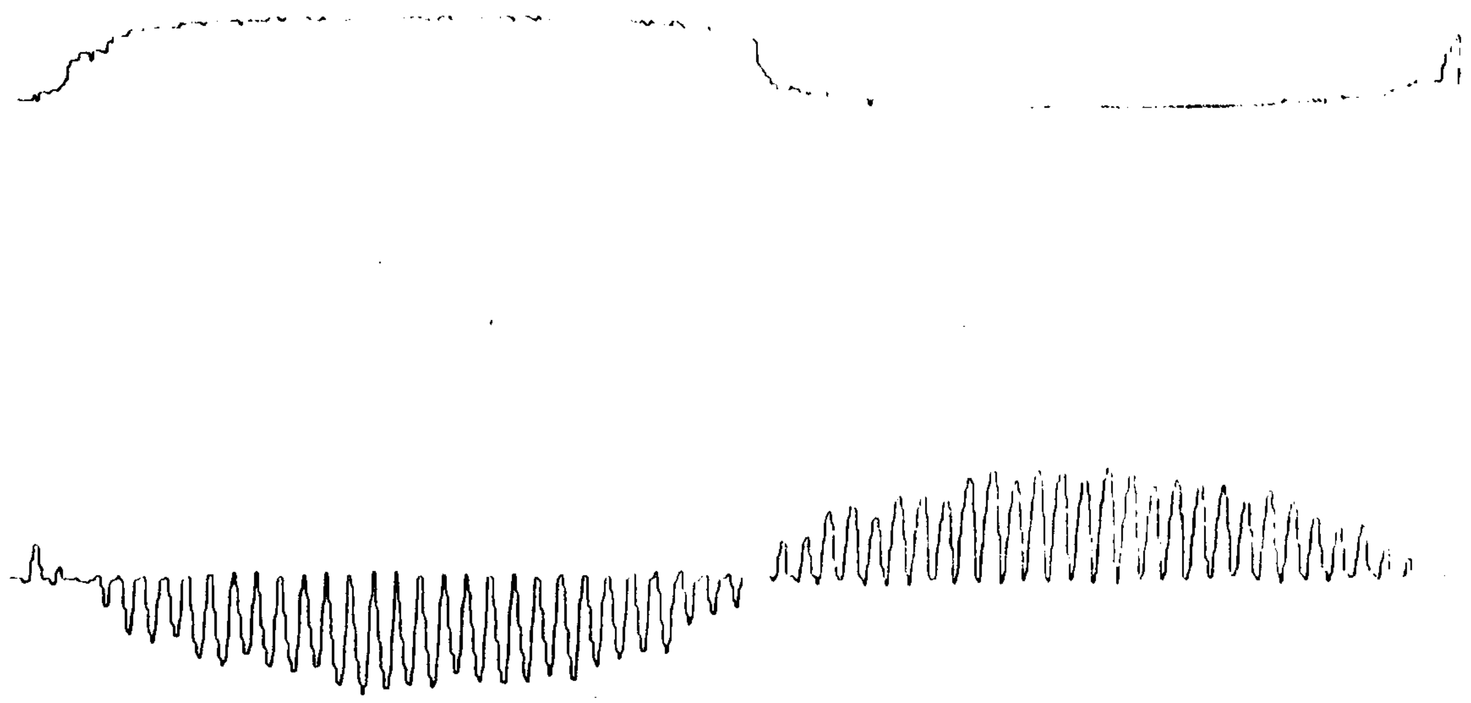


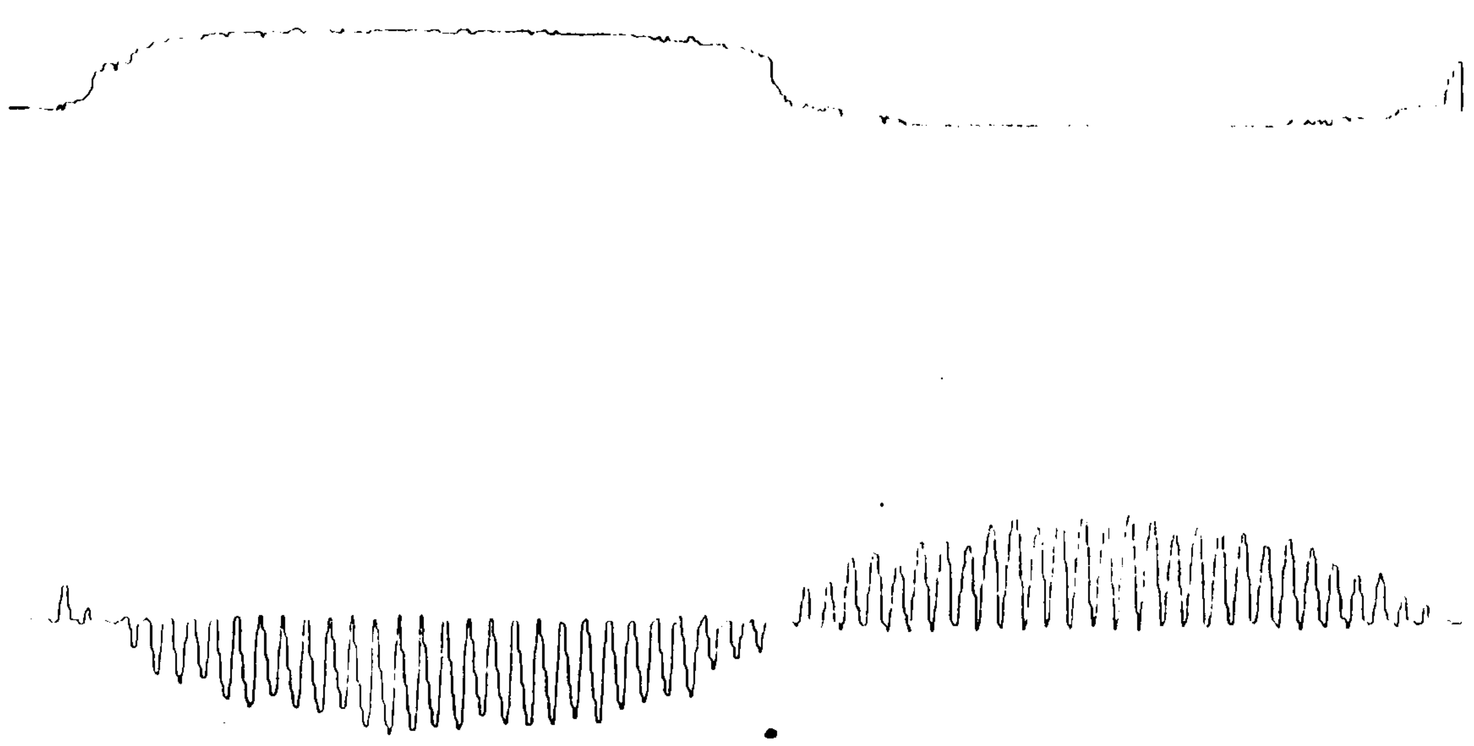
Fig 5.3 Torque vs speed
with page changing



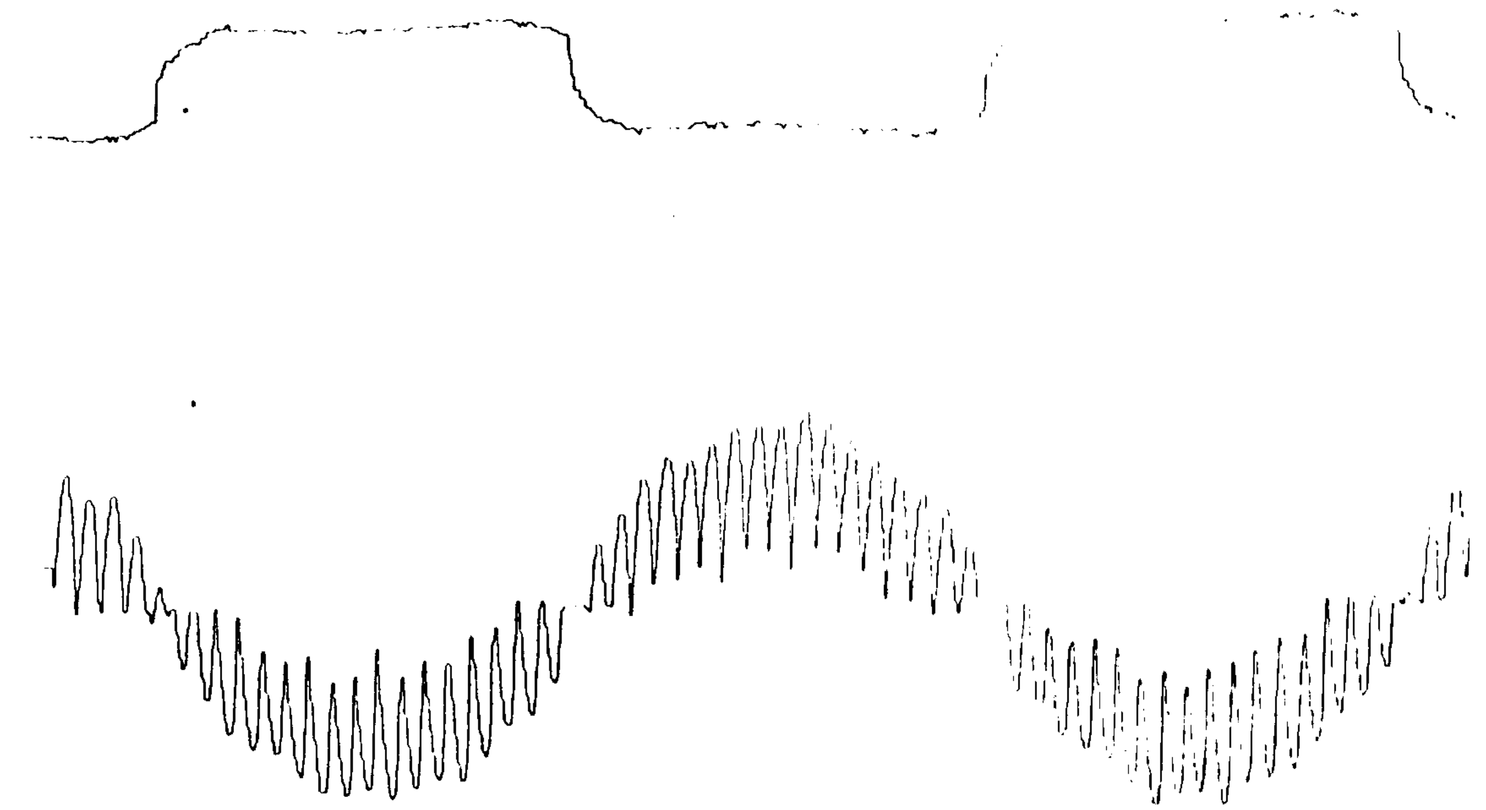
a) 1250 rpm



b) 1350 rpm

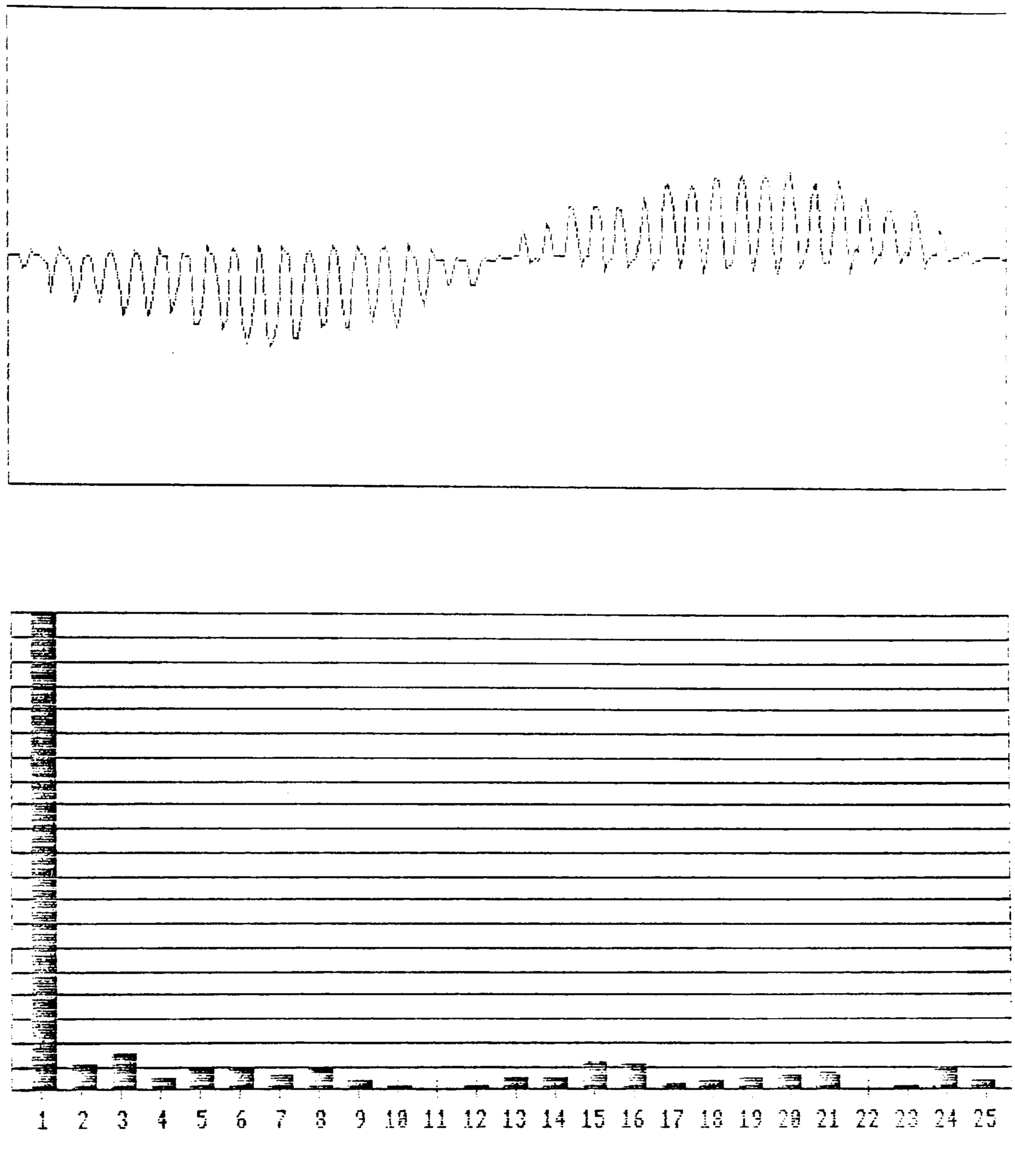


c) 1650 rpm



d) 1750 rpm

Fig 5.4



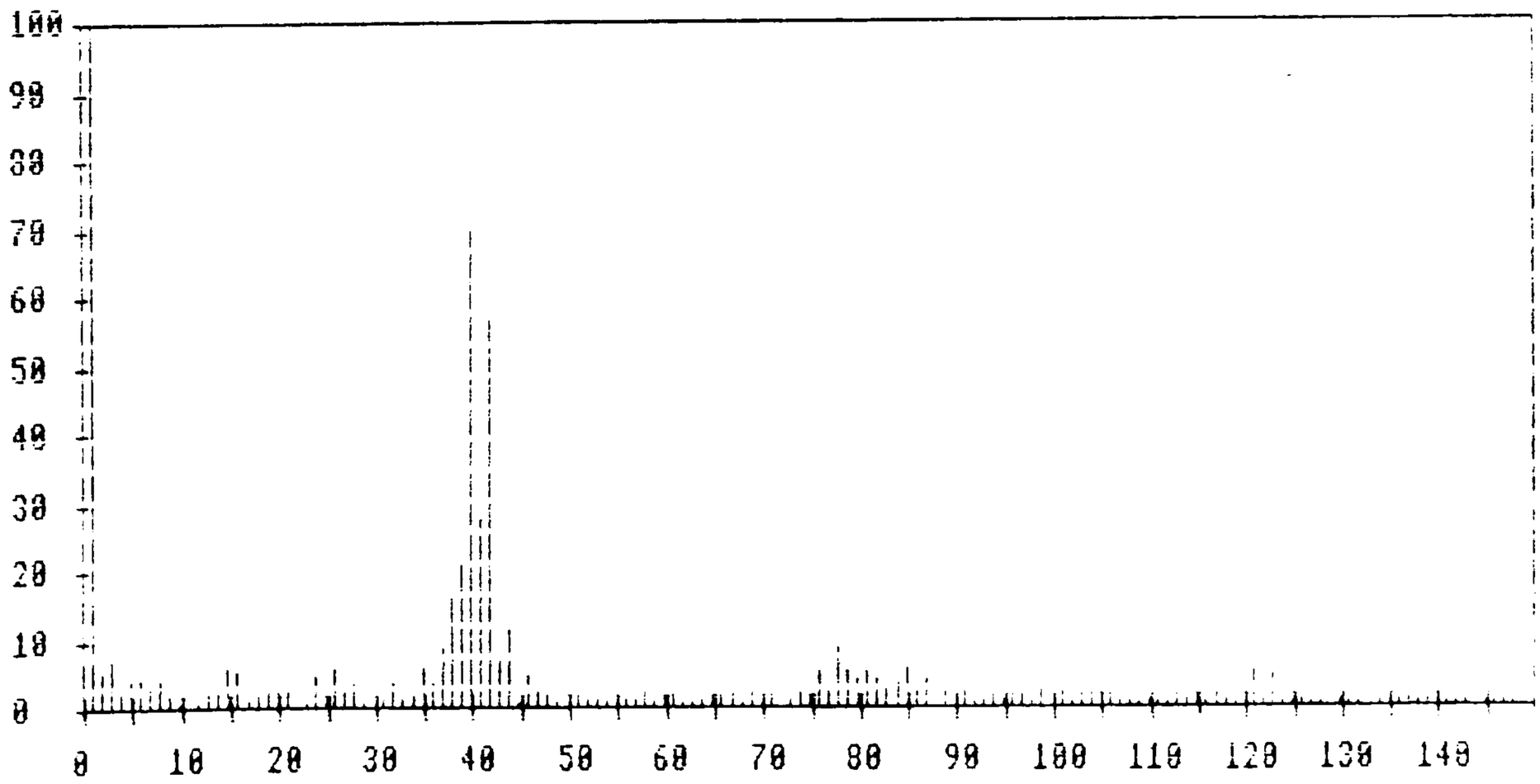


Fig 5.5a 1275 rpm

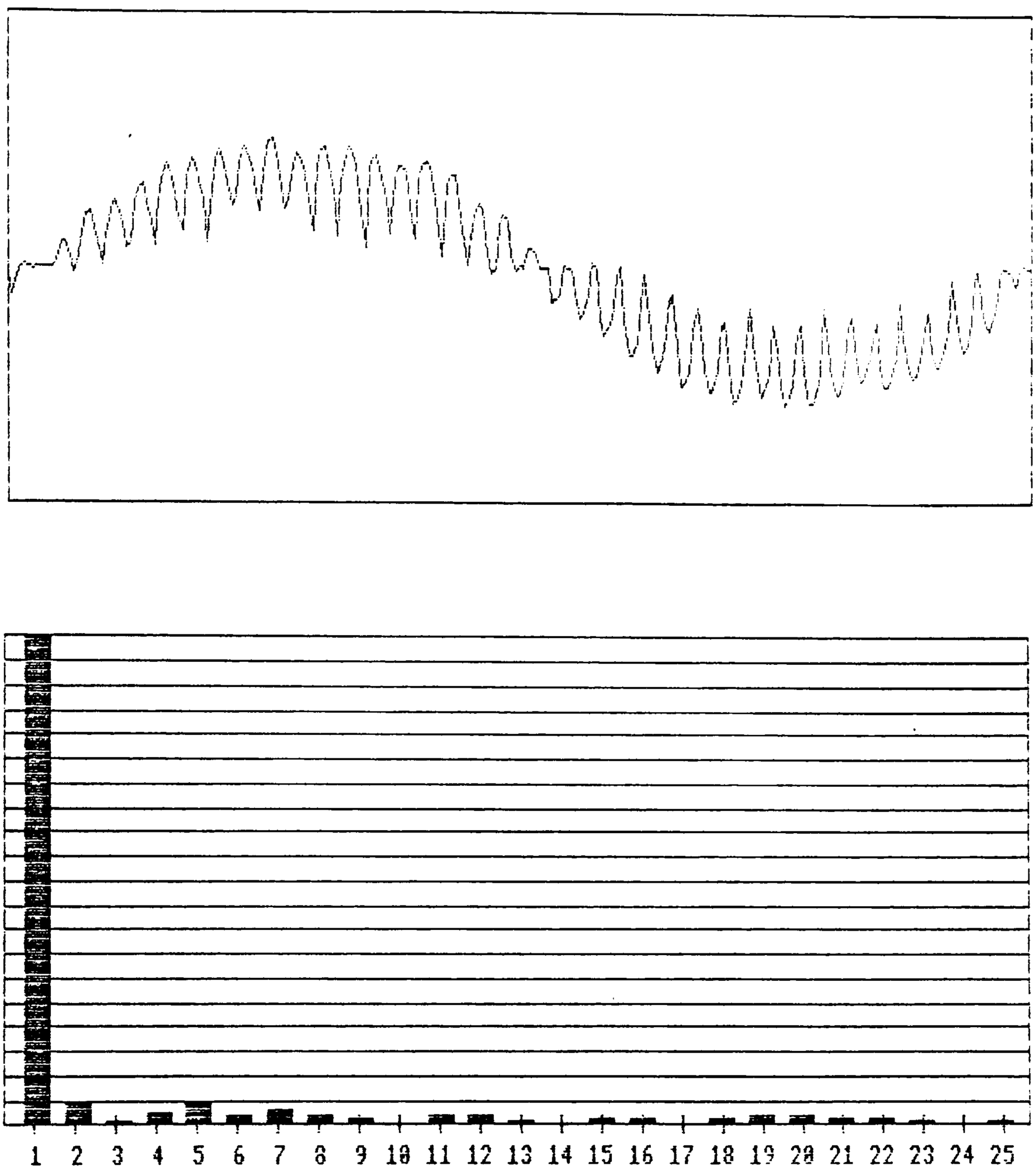


Fig 5.5b 1725 rpm

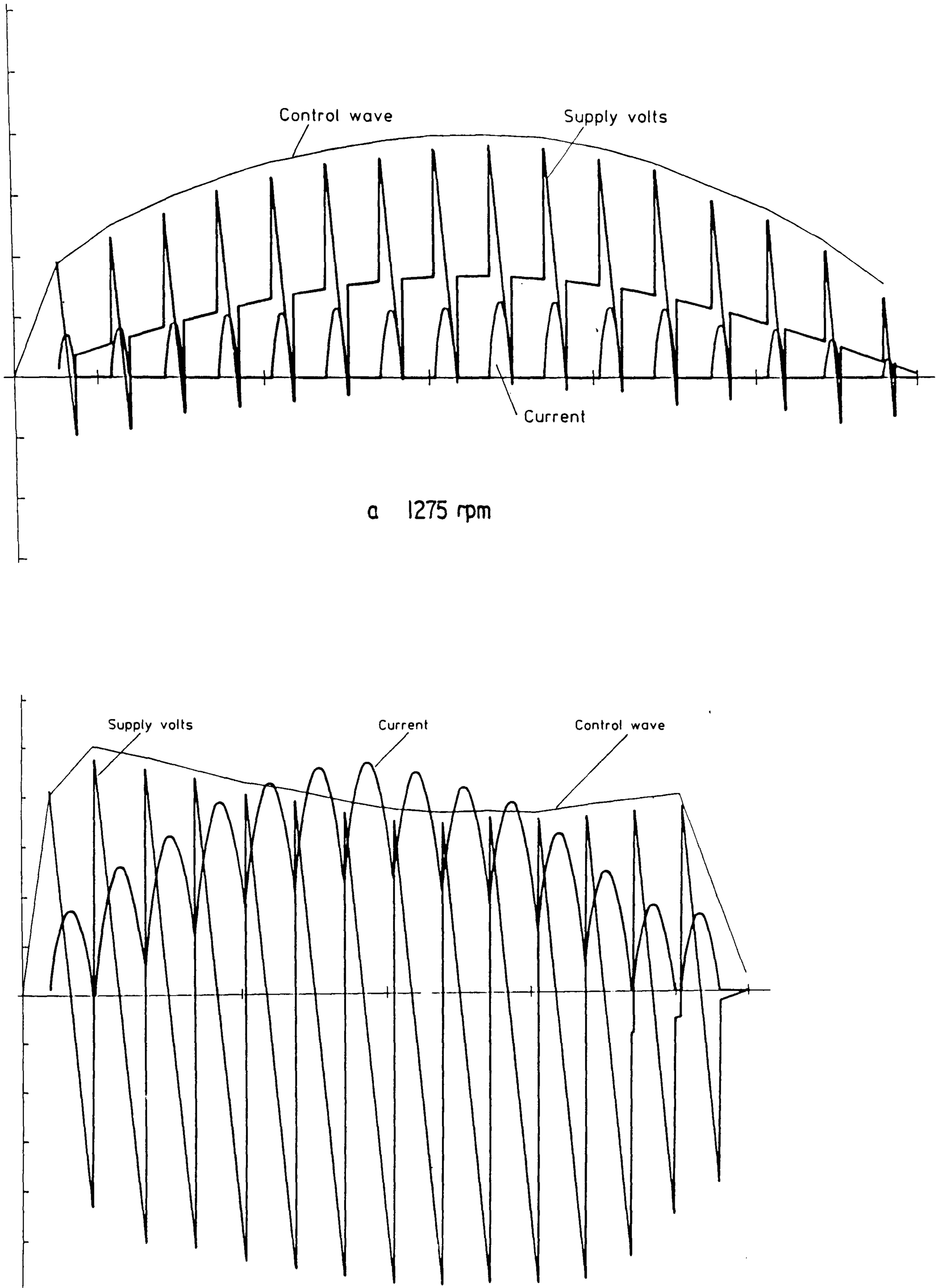
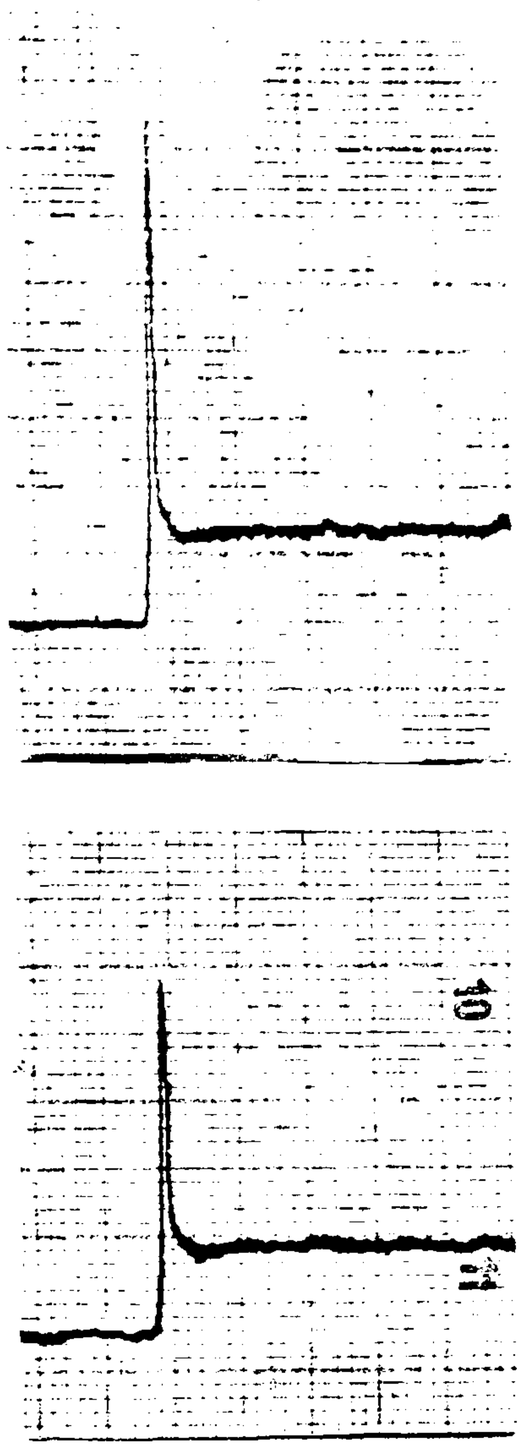
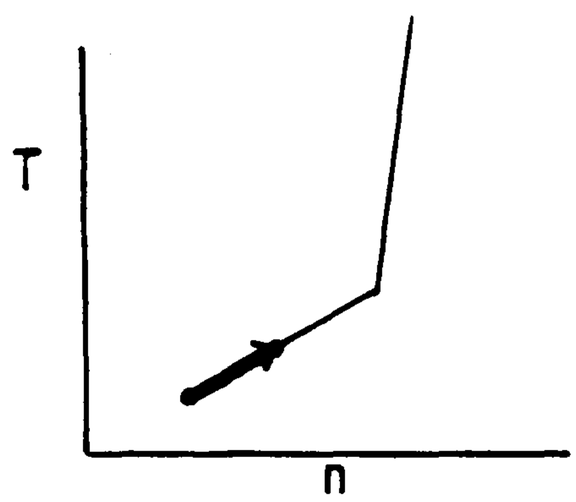


Fig 5.6 Computer predicted waveforms

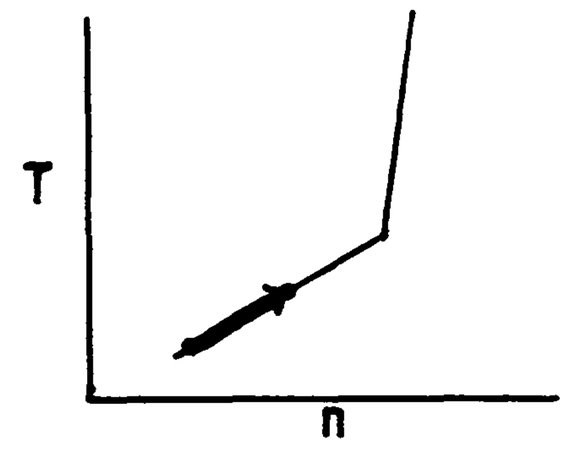
Fig 5.7 Steady State Torques



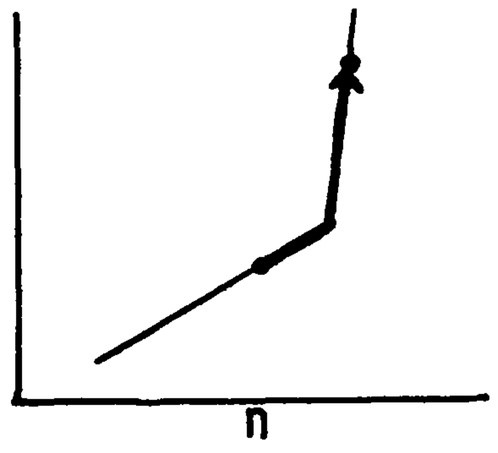
a 1250 1450 rpm Fixed page



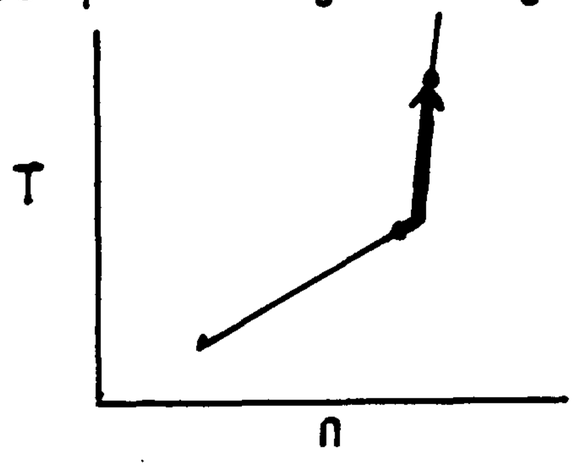
b 1250 1450 rpm Page changing



c 1550 1750 rpm Page changing



d 1650 1750 rpm Page changing



e 1675 1775 rpm Page changing

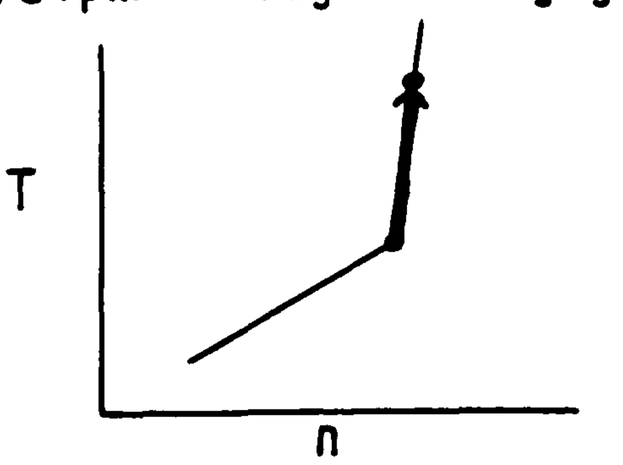


Fig 5.8

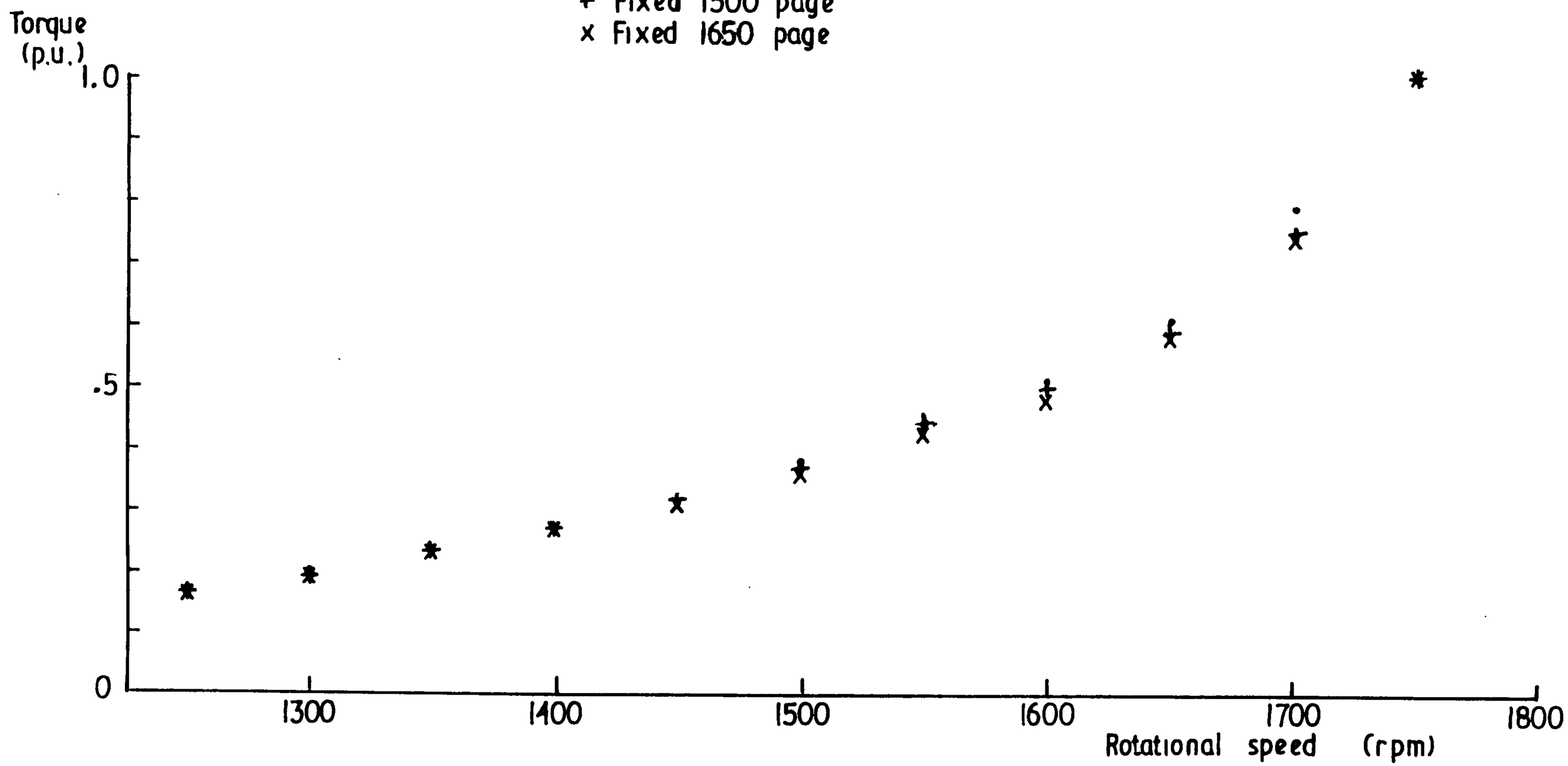


Fig 5.9 Torque vs speed (fixed page operation)

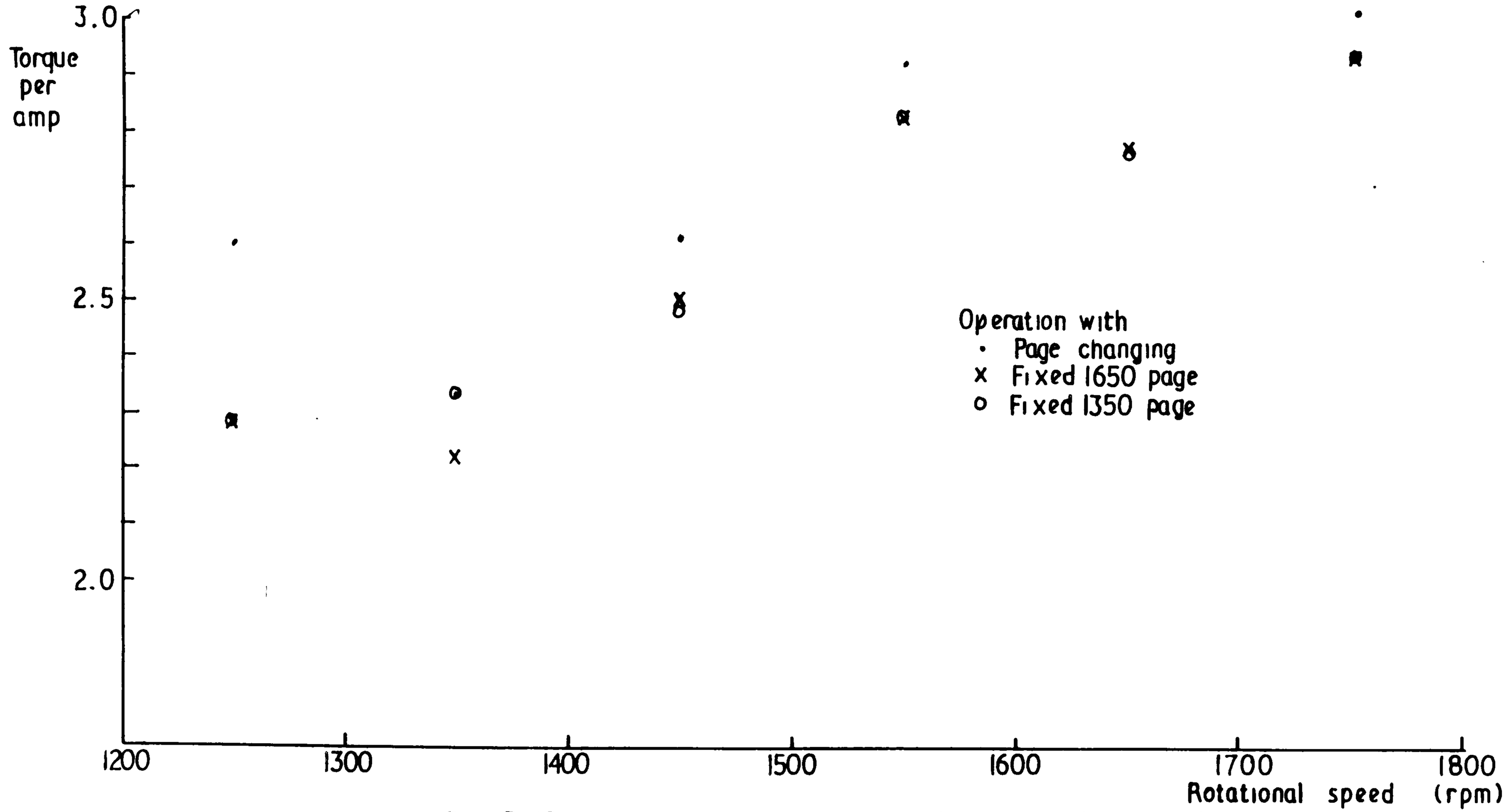


Fig 5.10 Torque per amp vs speed (on reqd T-n characteristic)

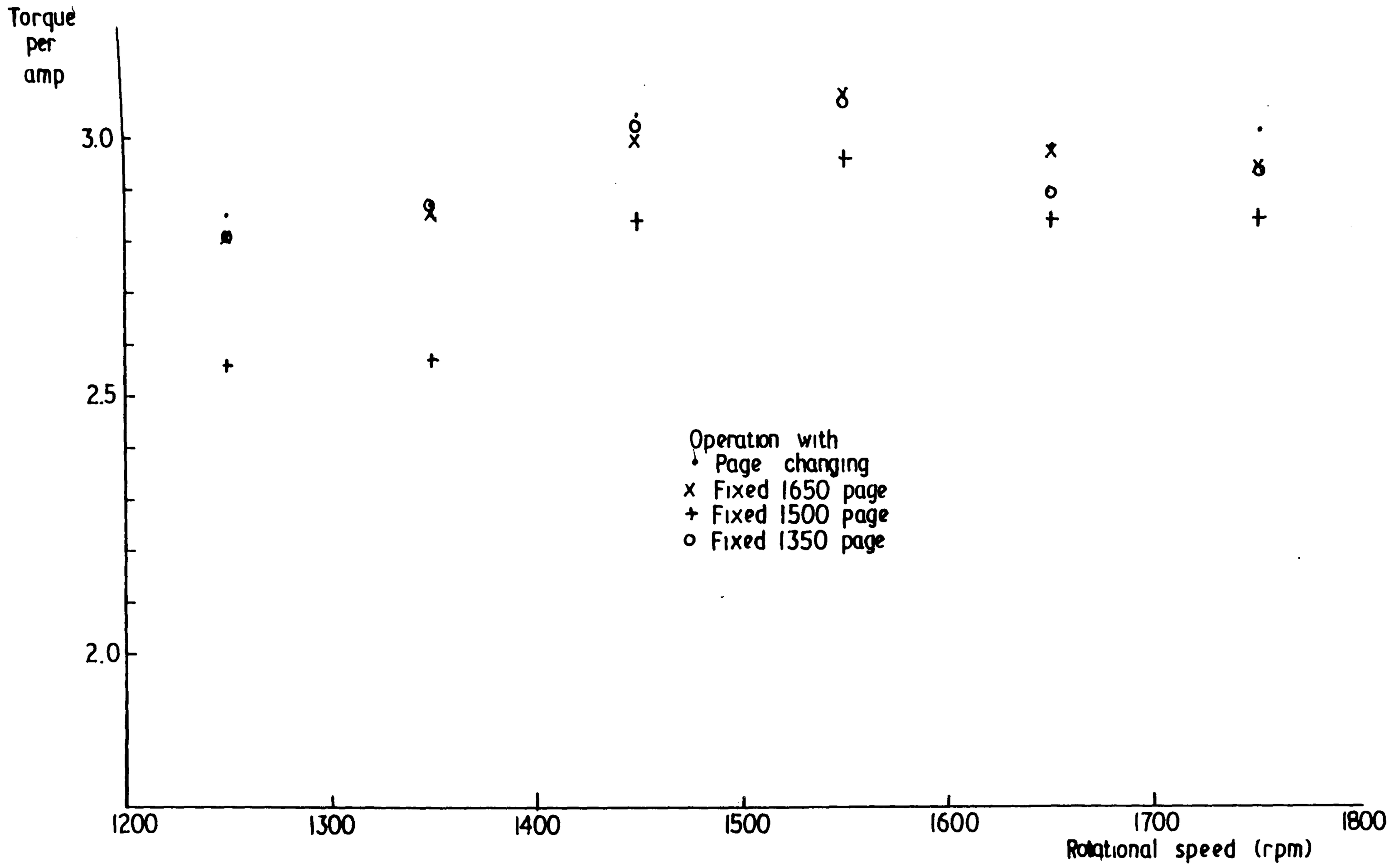


Fig 5.11a Torque per amp vs speed (T = 1.0 p.u.)

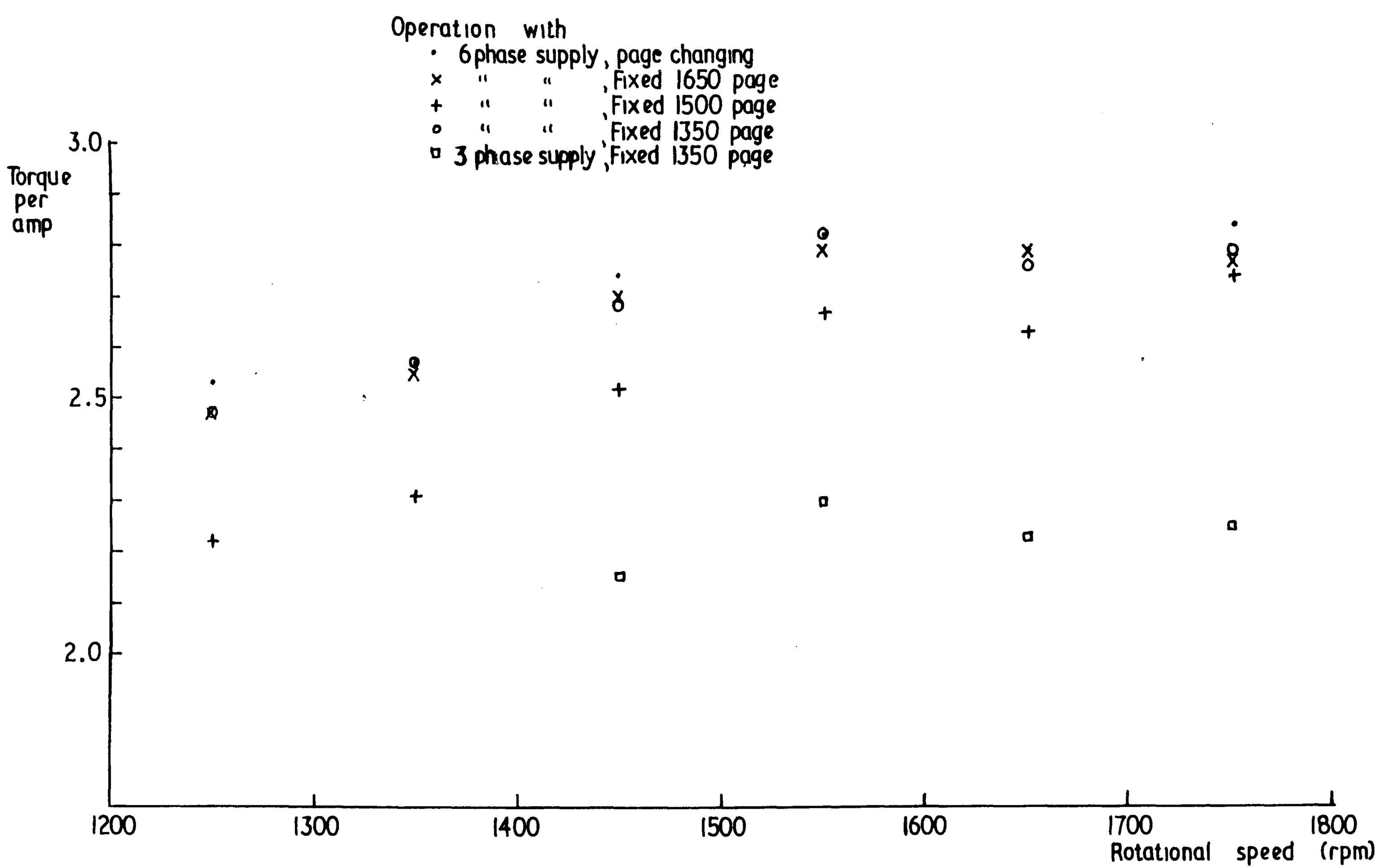
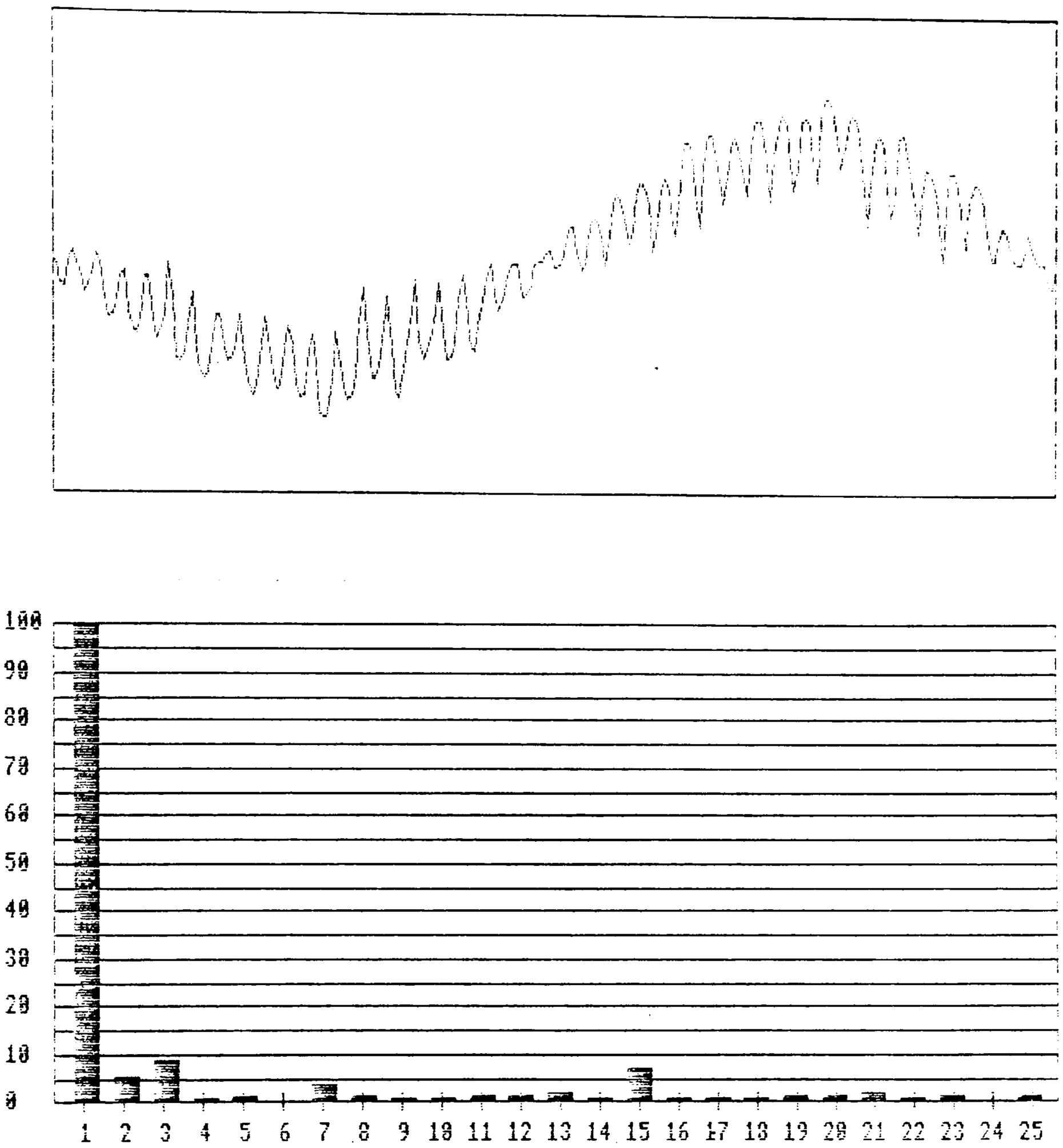


Fig 5.11 b Torque per amp vs speed (T = 0.5 p.u.)



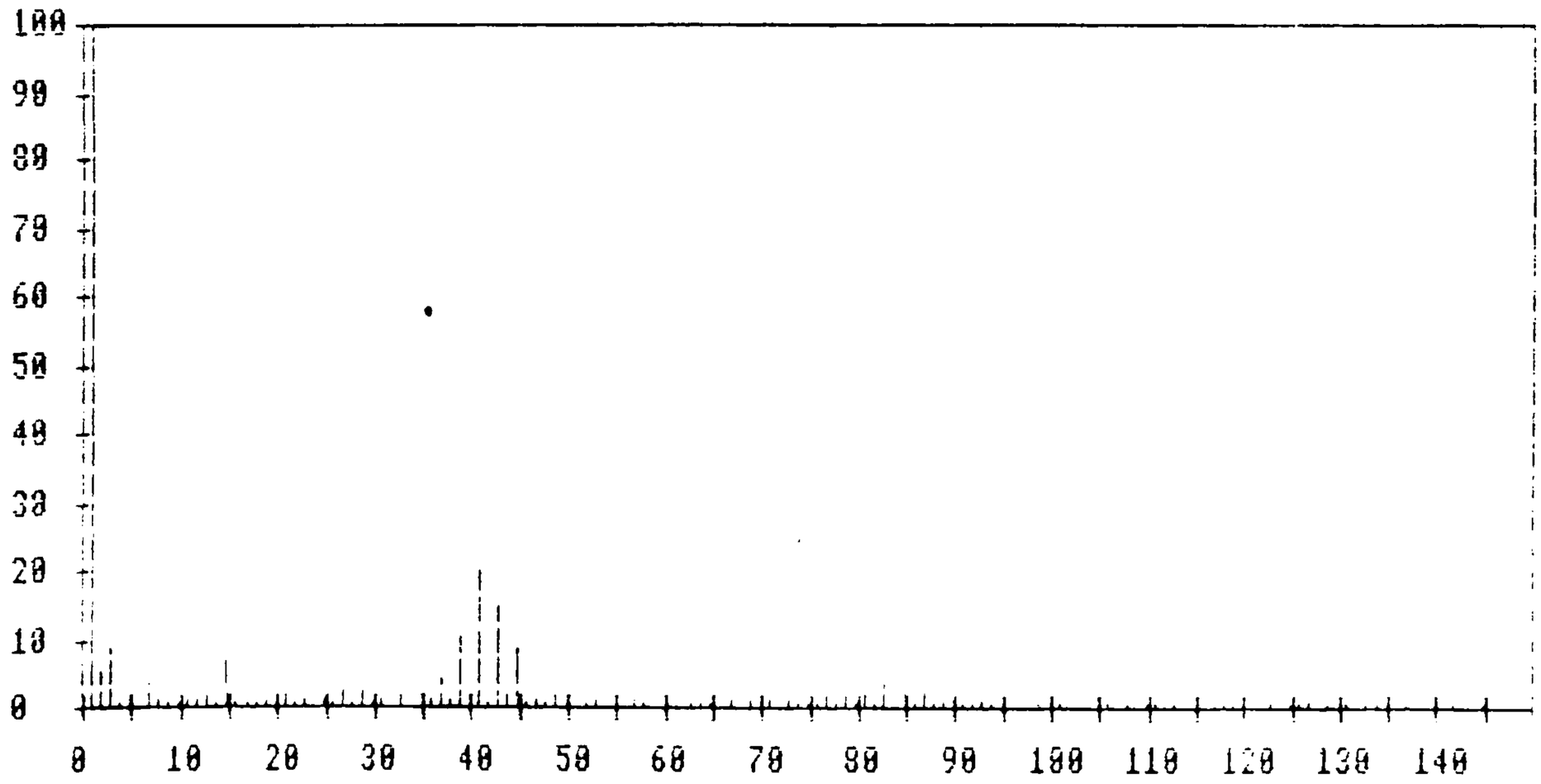


Fig 5.12a 1275 rpm Fixed 1350 page

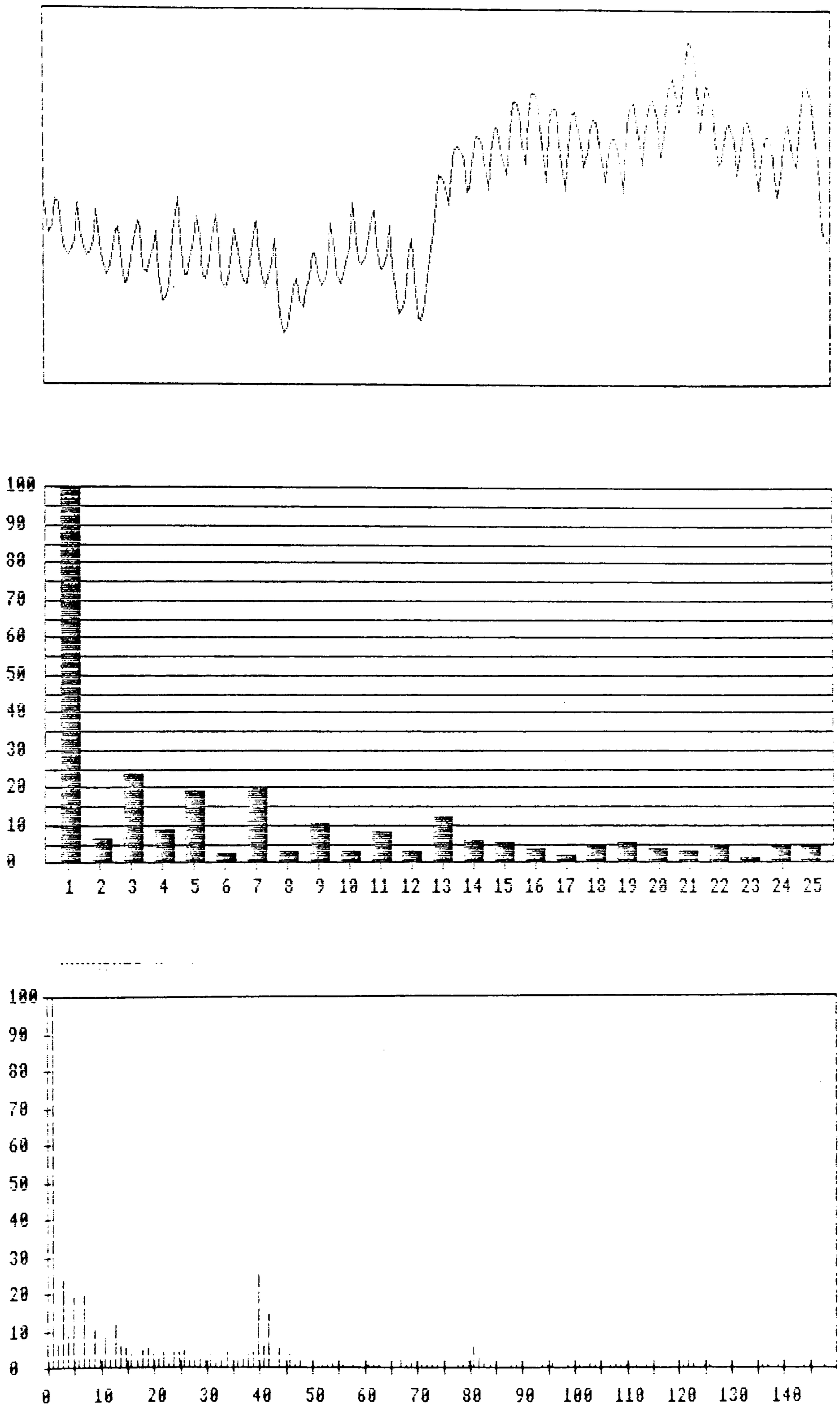
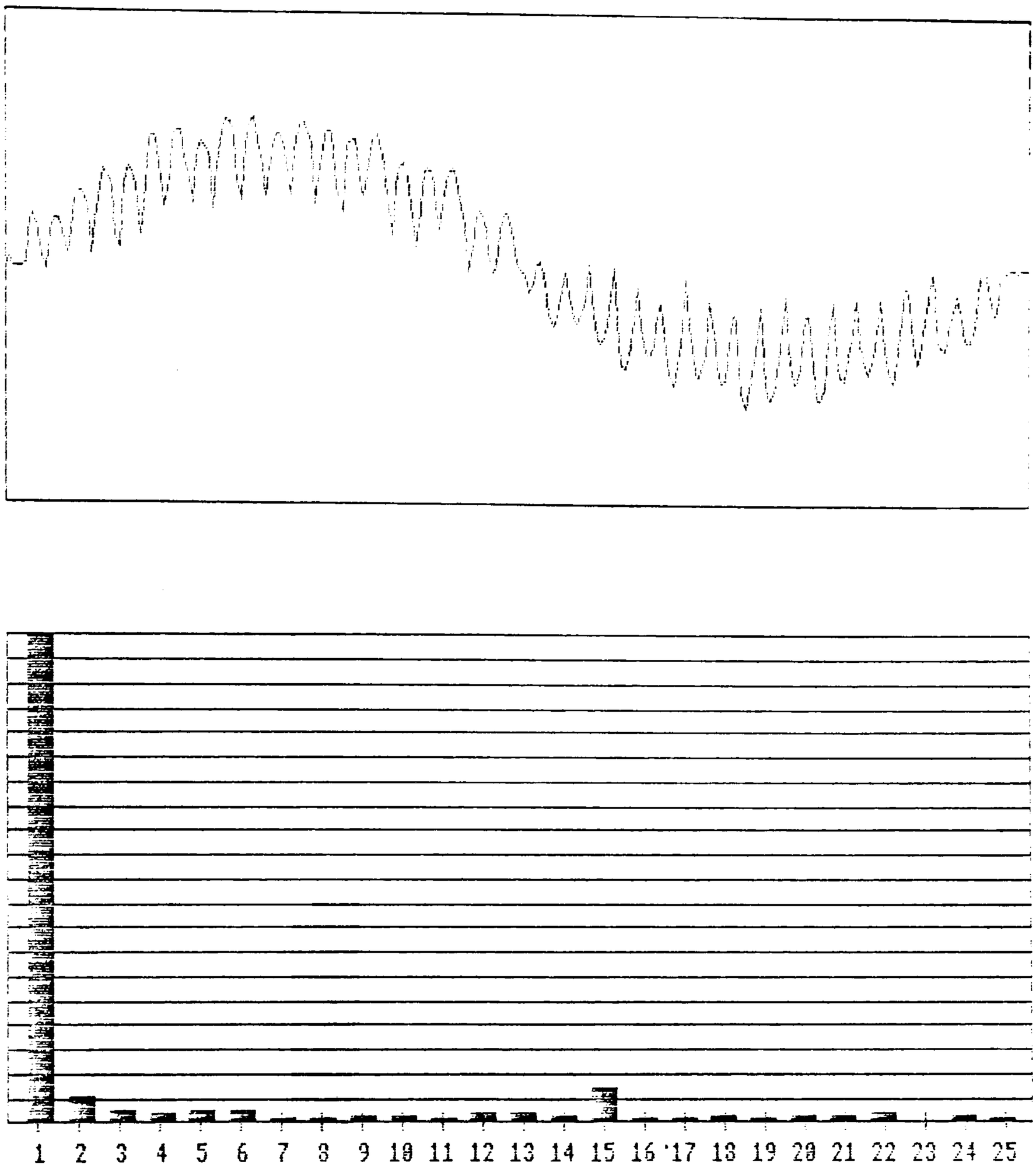


Fig 5.12b 1275 rpm Fixed 1500 page



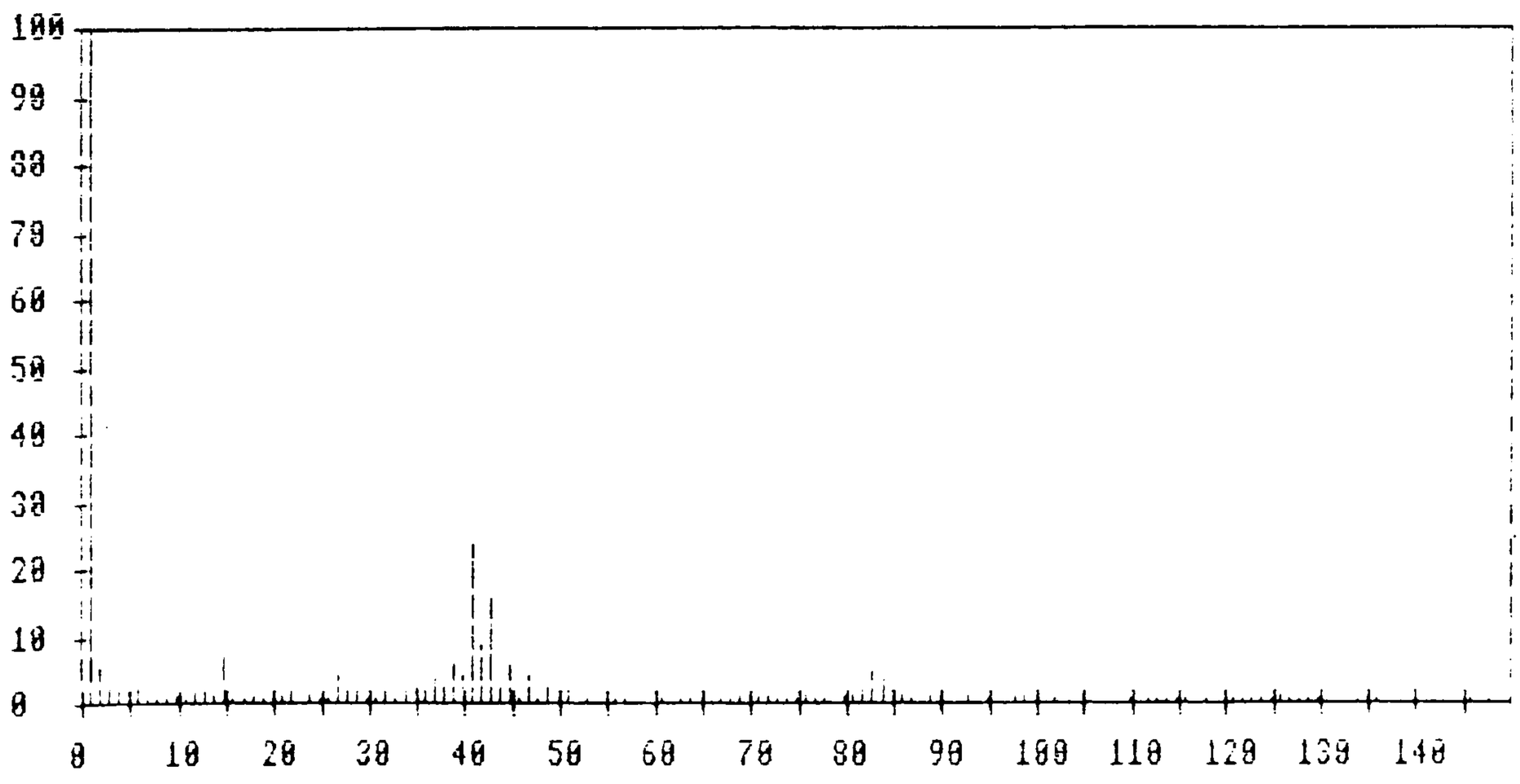


Fig 5.12c 1275 rpm Fixed 1650 page

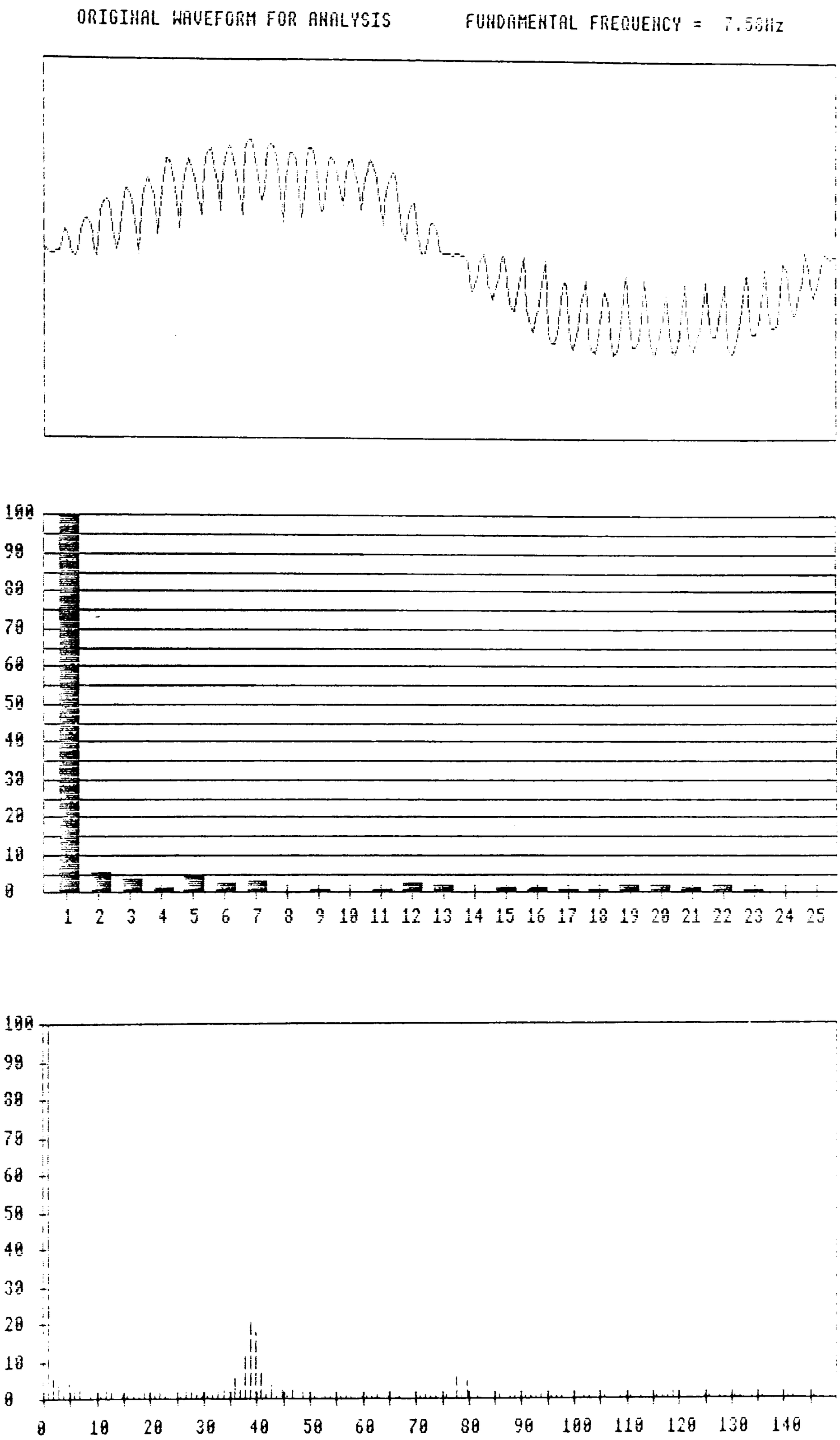


Fig 5.12d 1275 rpm Page changing

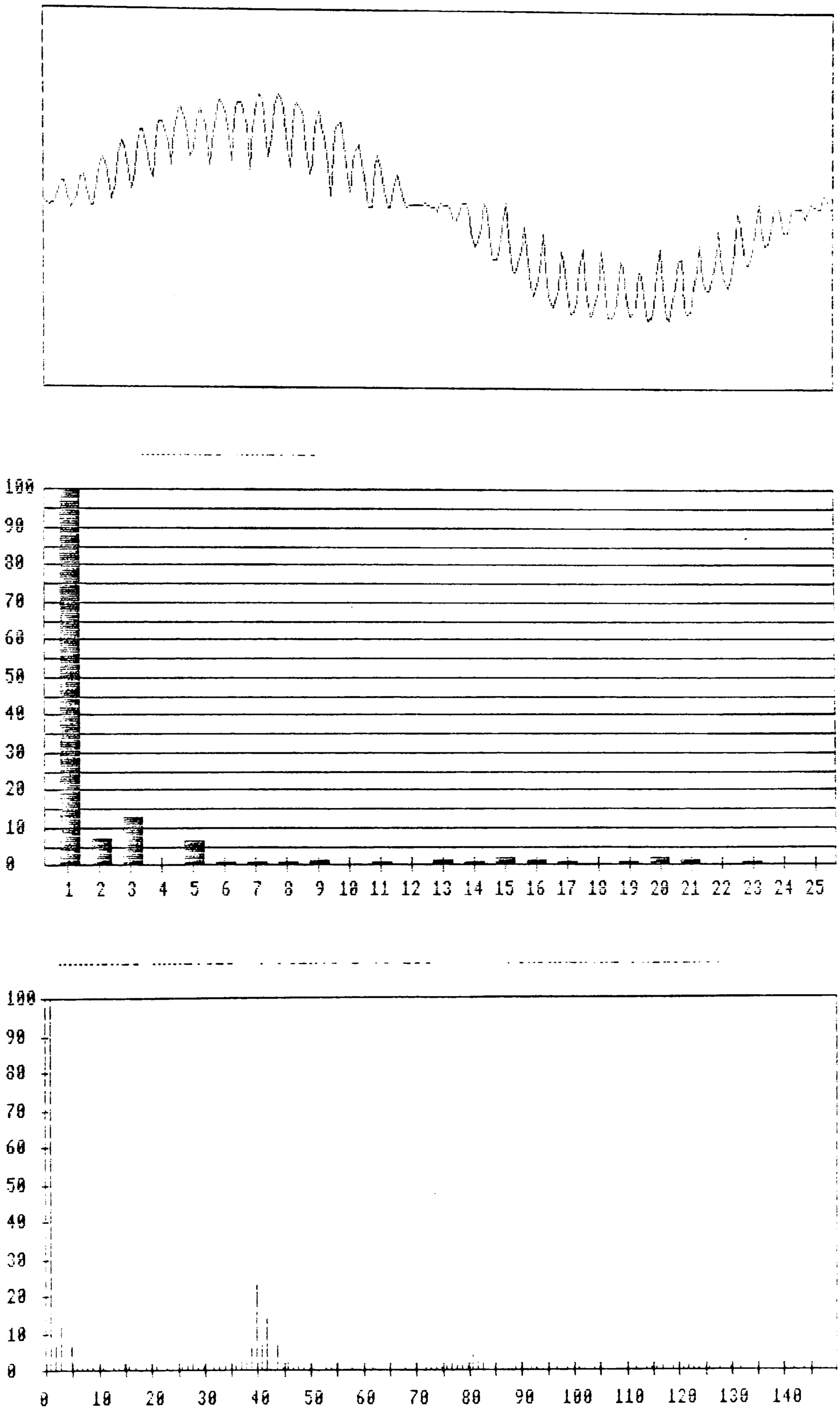


Fig 5.12e 1725 rpm Fixed 1350 page

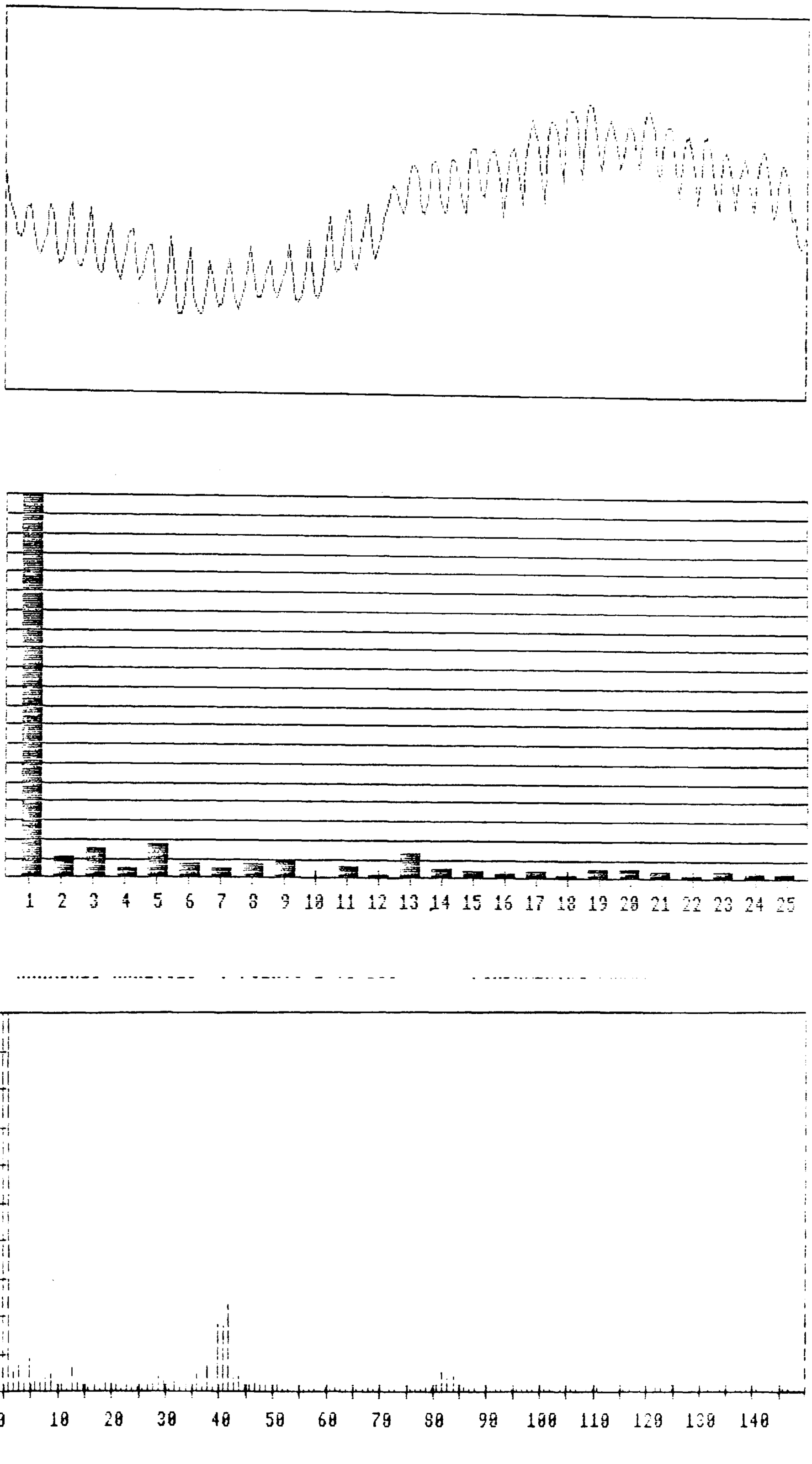


Fig 5.12f 1725 rpm Fixed 1500 page

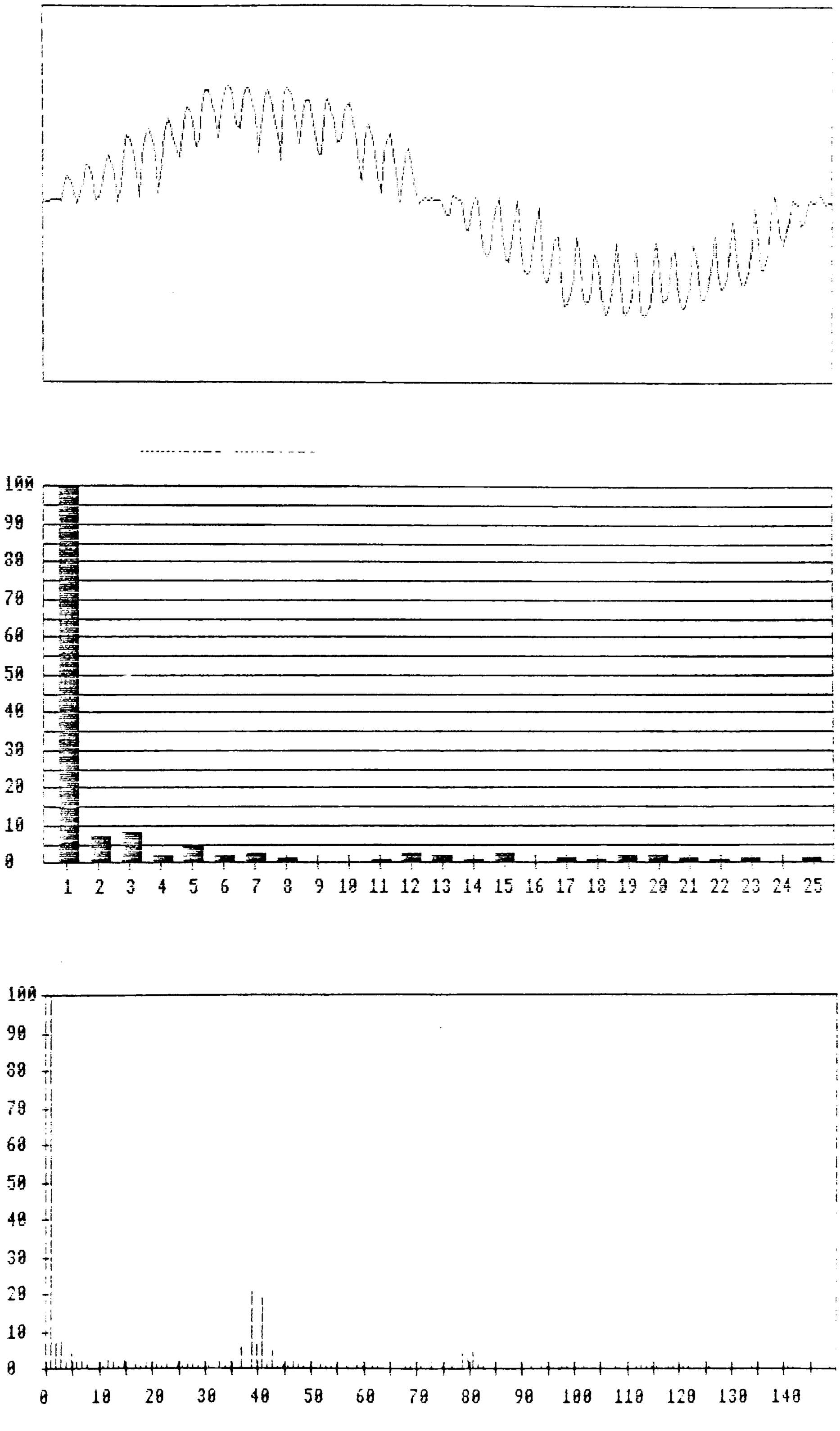


Fig 5.12g 1725 rpm Fixed 1650 page

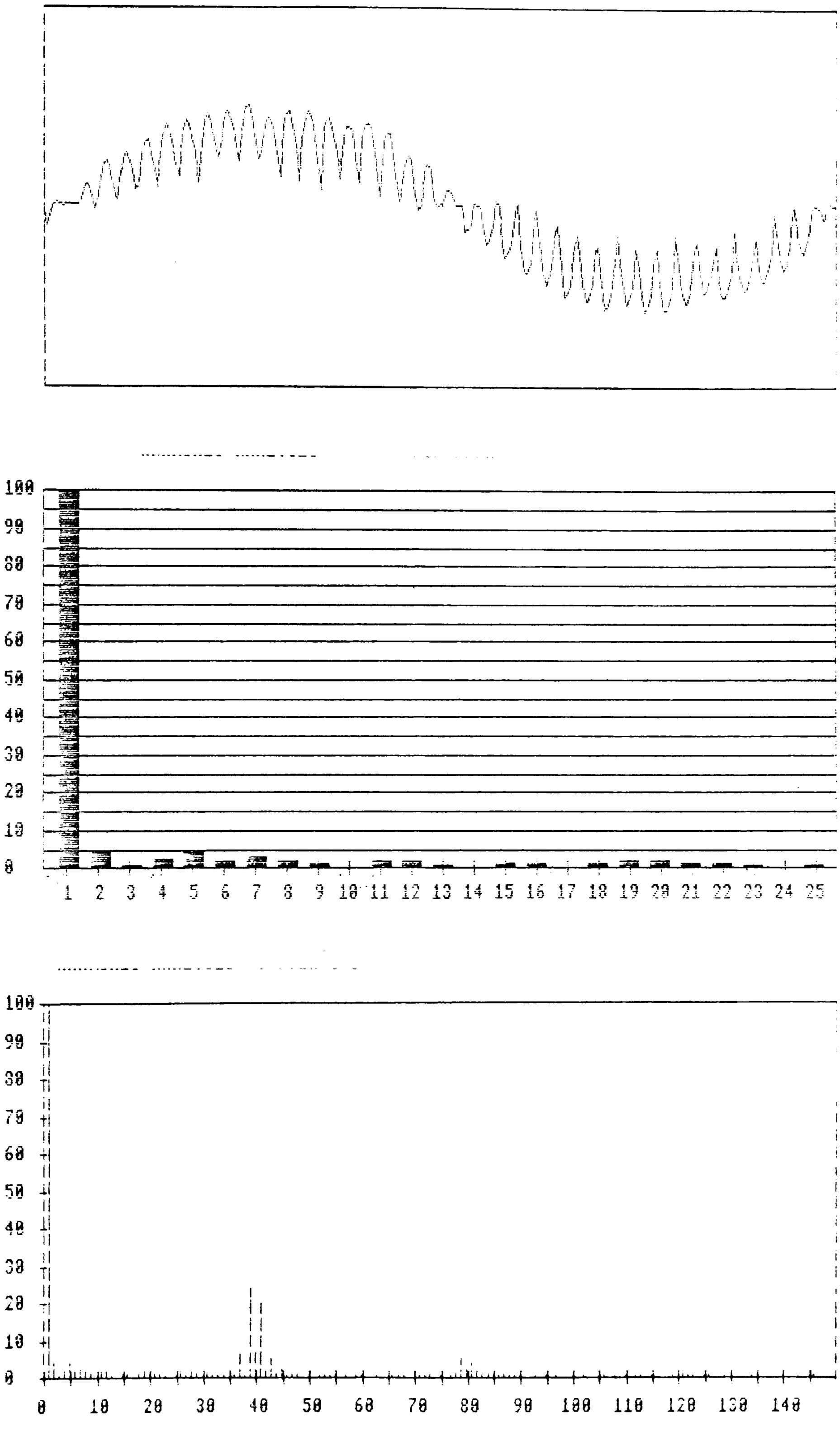
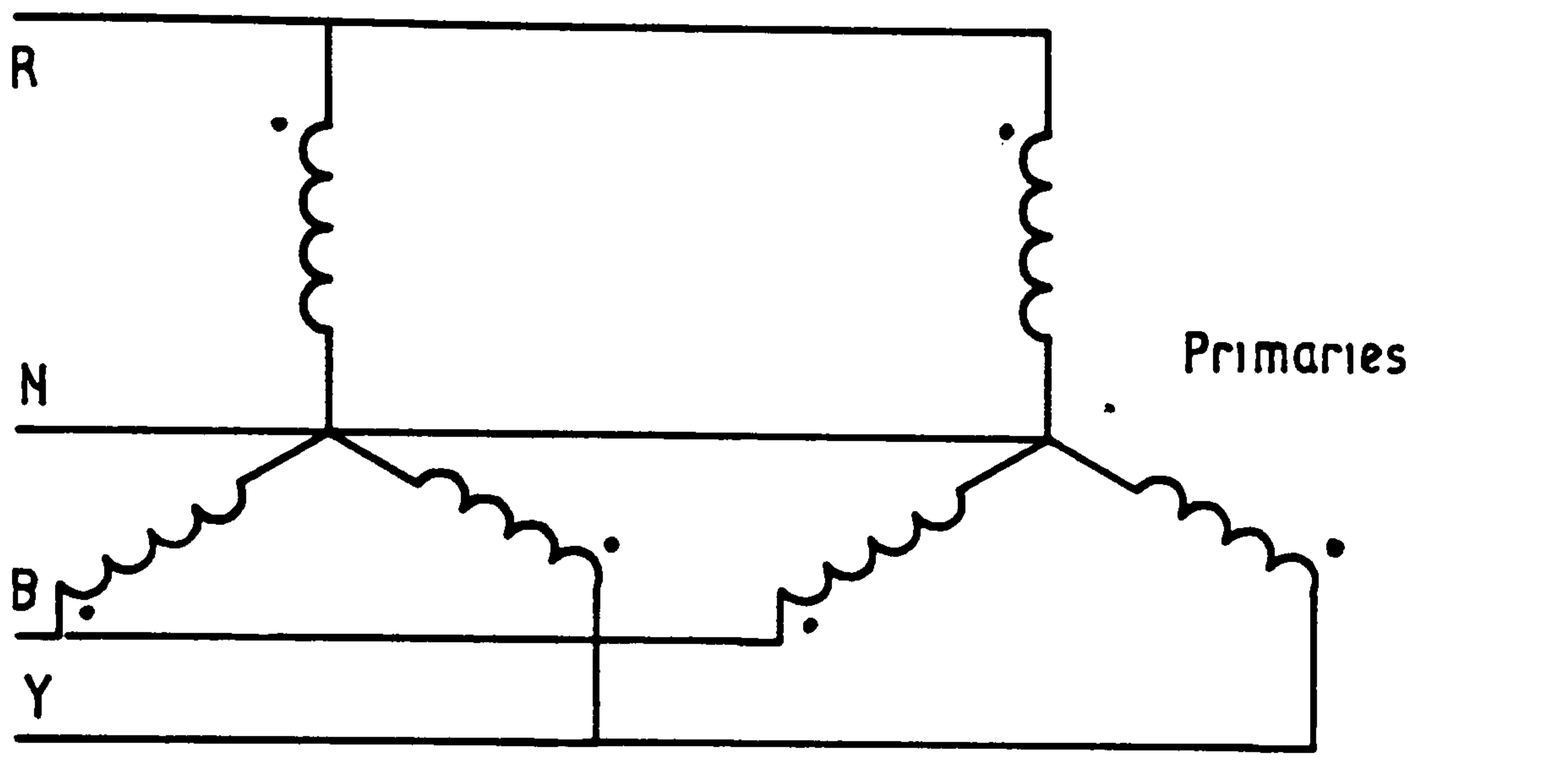
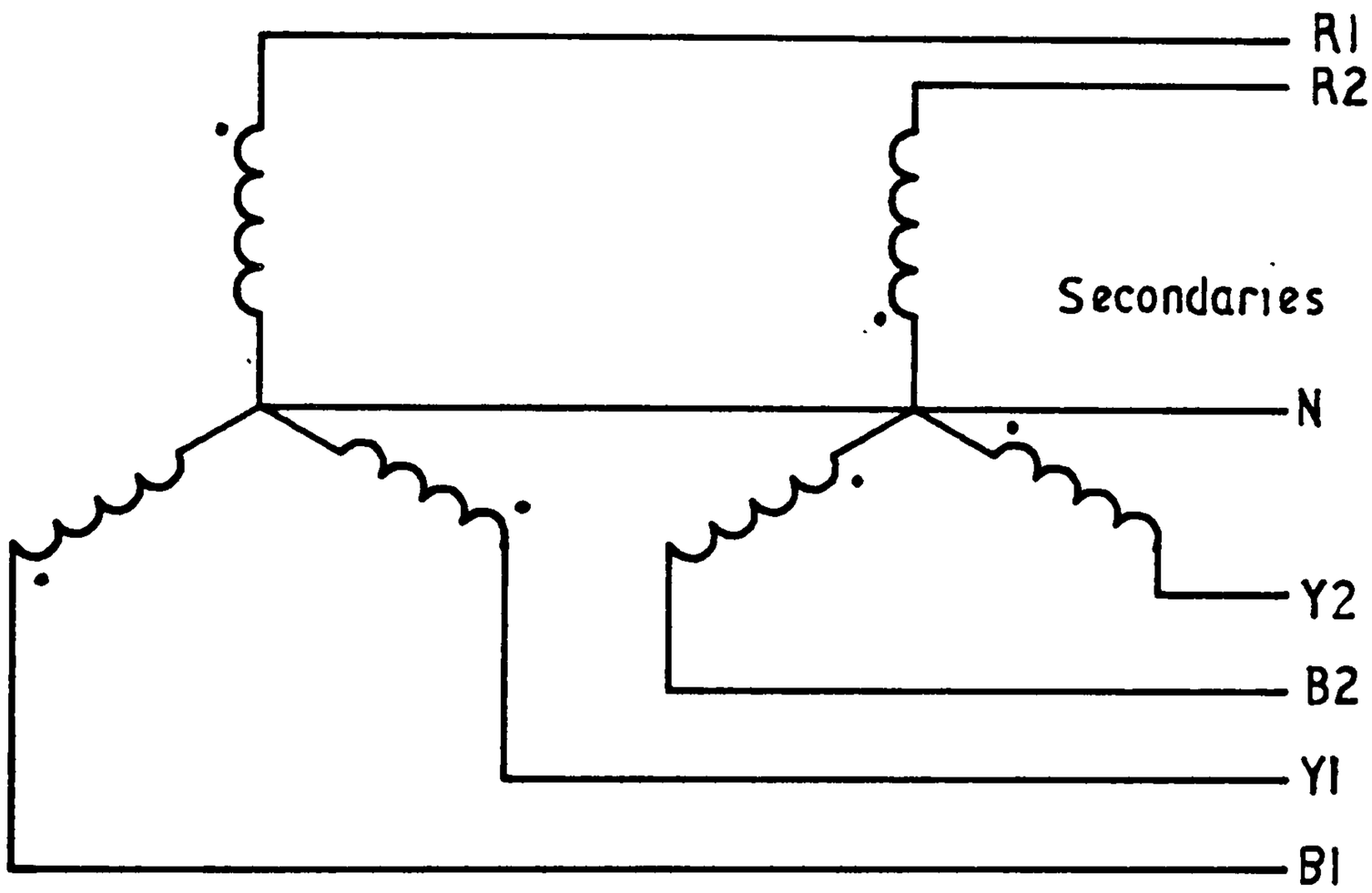


Fig 5.12h 1725 rpm Page changing





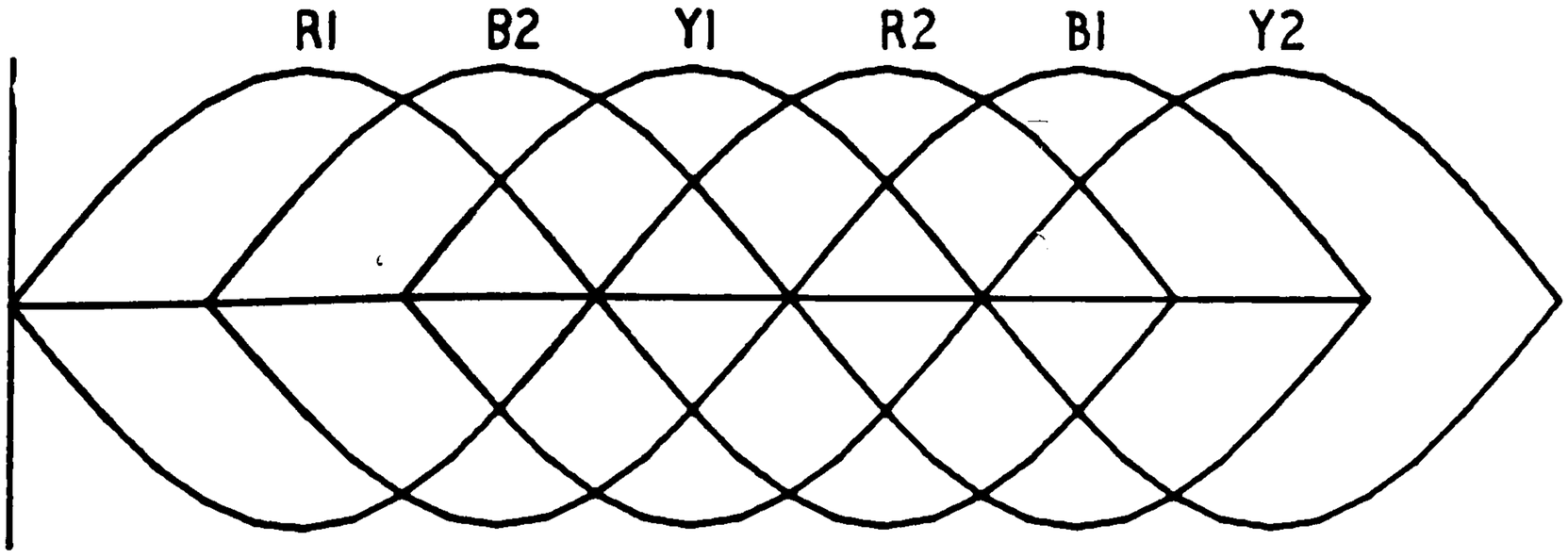


Fig 5.13 Six phase supply

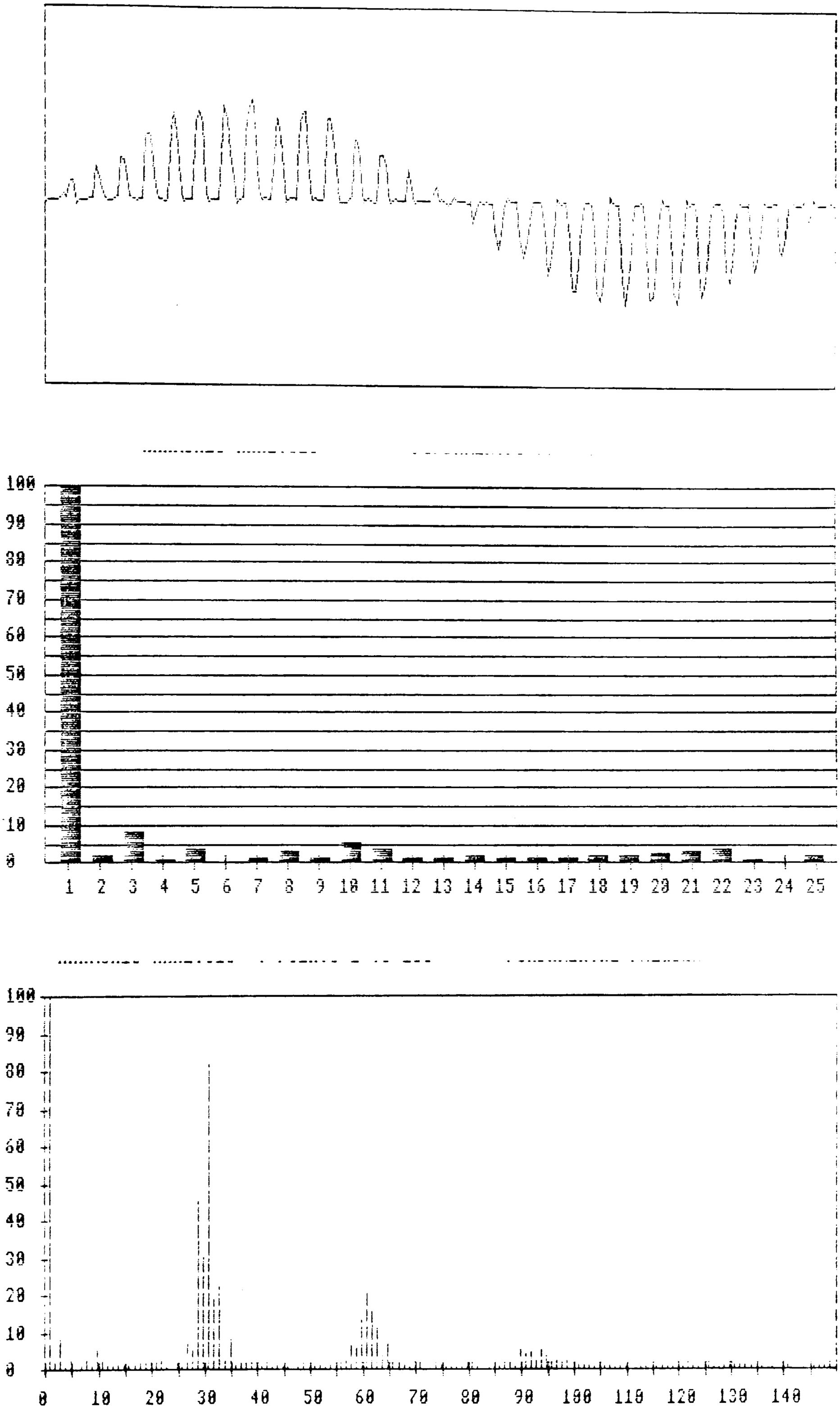


Fig 5.14a 1350 rpm 3 phase supply

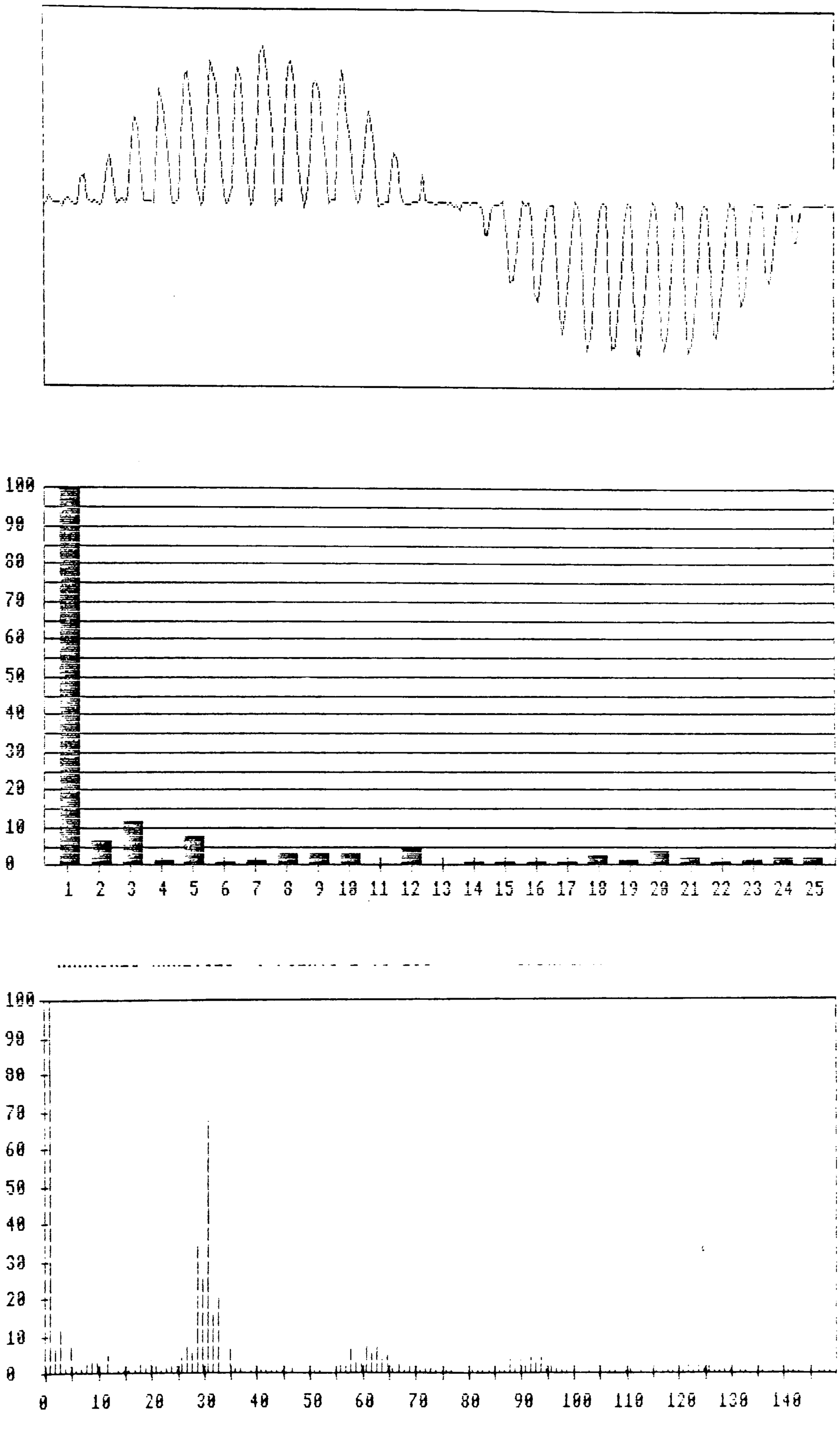
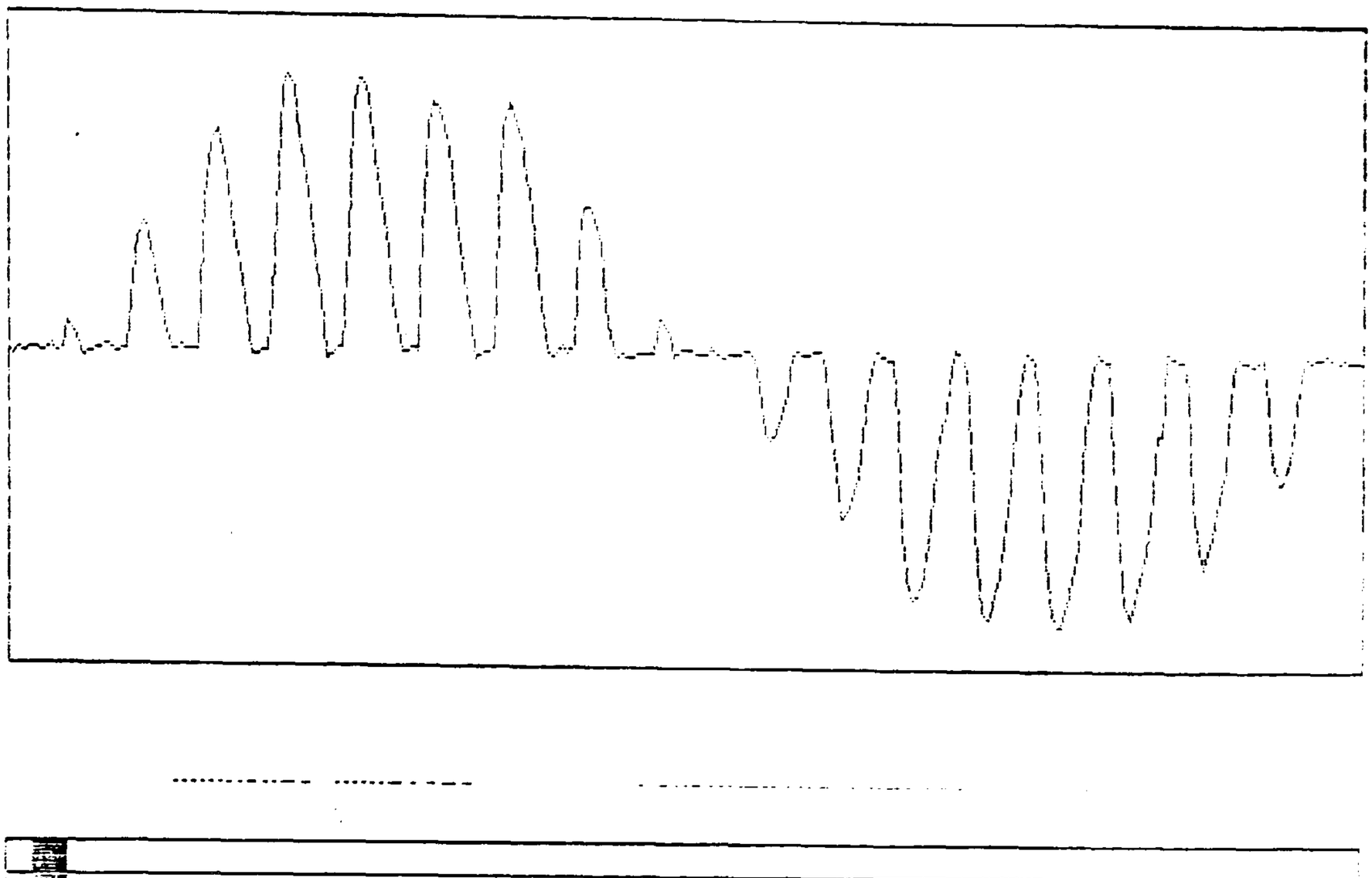
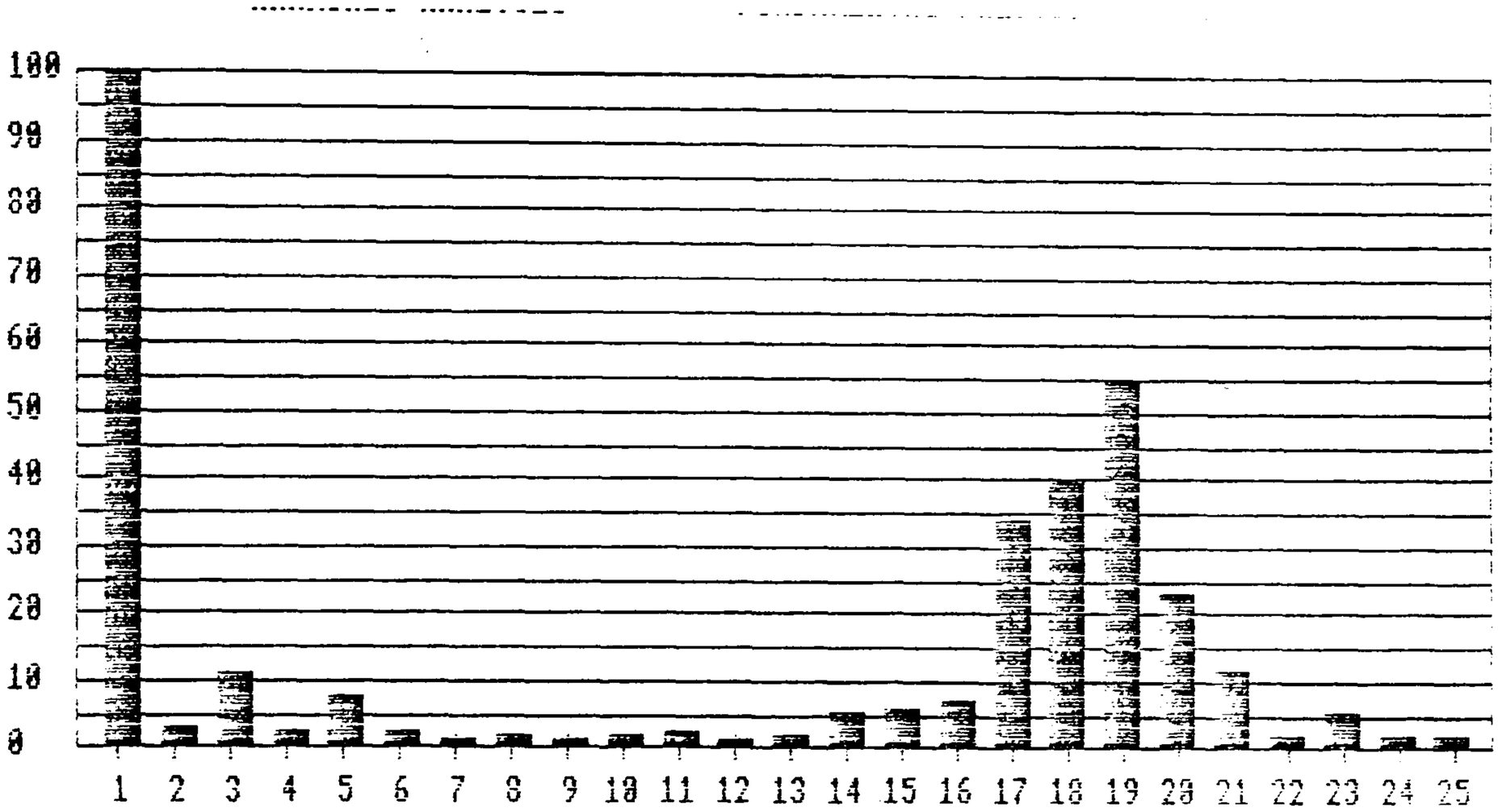


Fig 5.14b 1650 rpm 3 phase supply





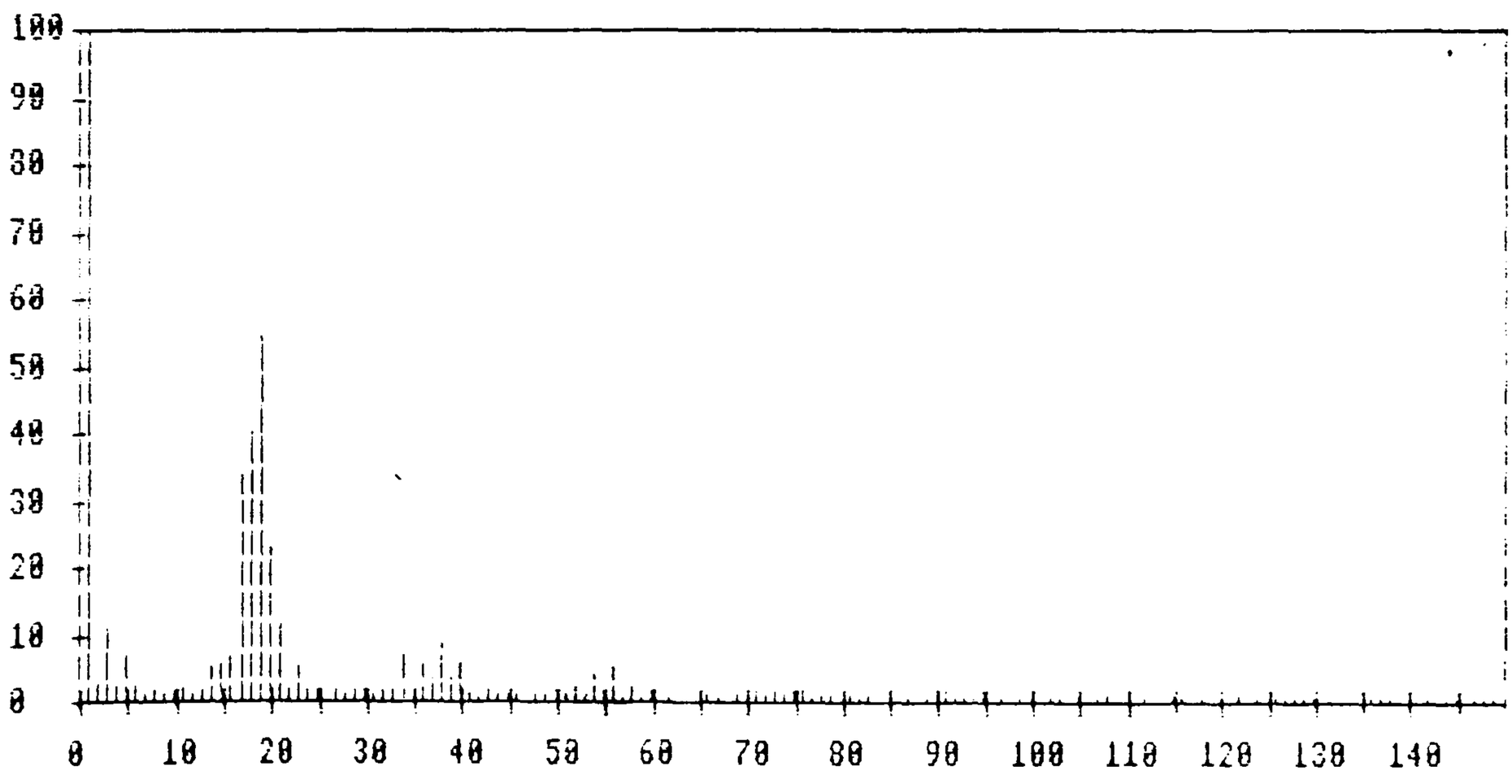


Fig 5.14c 1750 rpm 3 phase supply

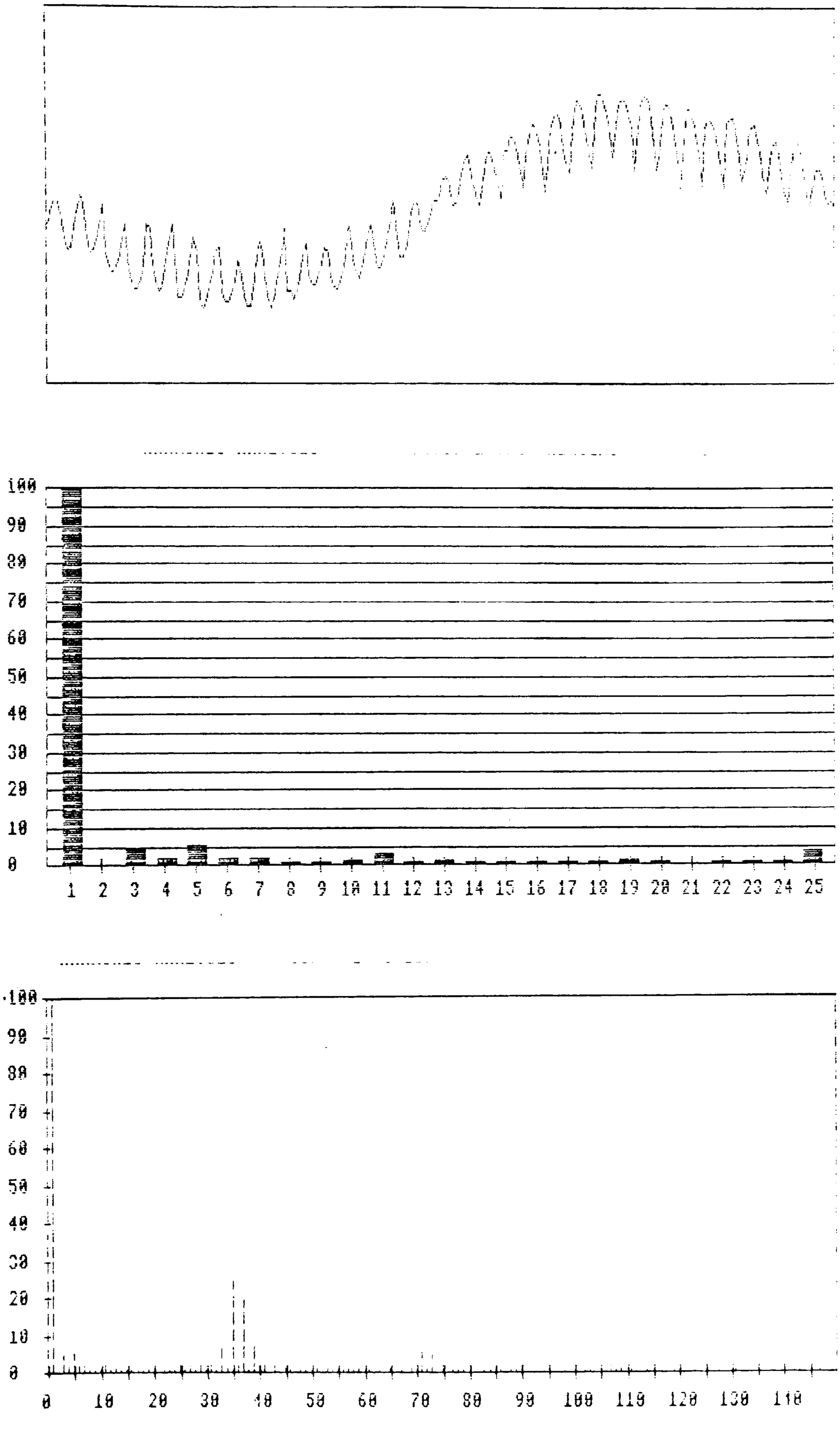


Fig 5.14d 1750 rpm 6 phase supply

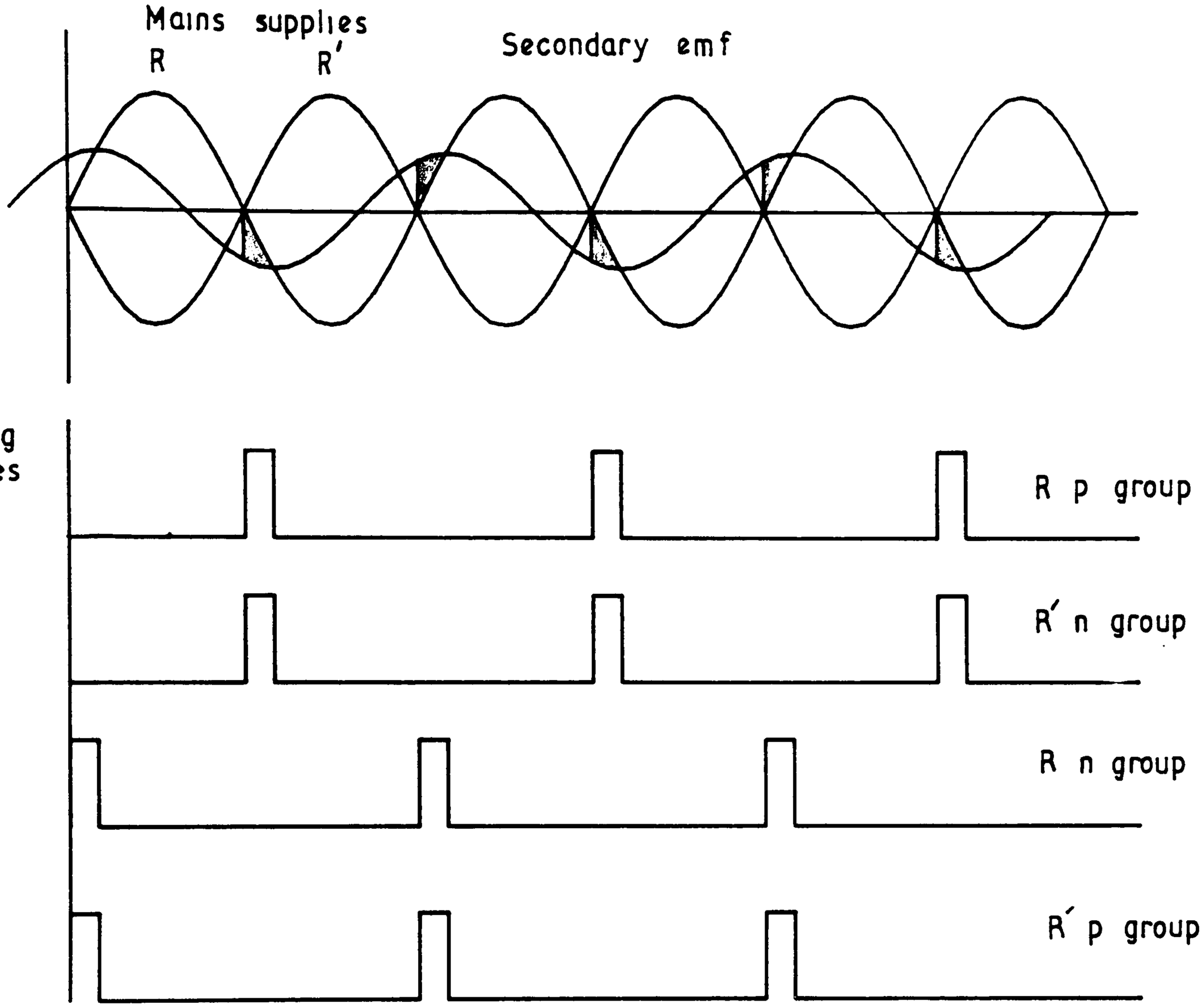


Fig 5.15 Firing pulses at standstill

Fig 5.16 Secondary current at standstill

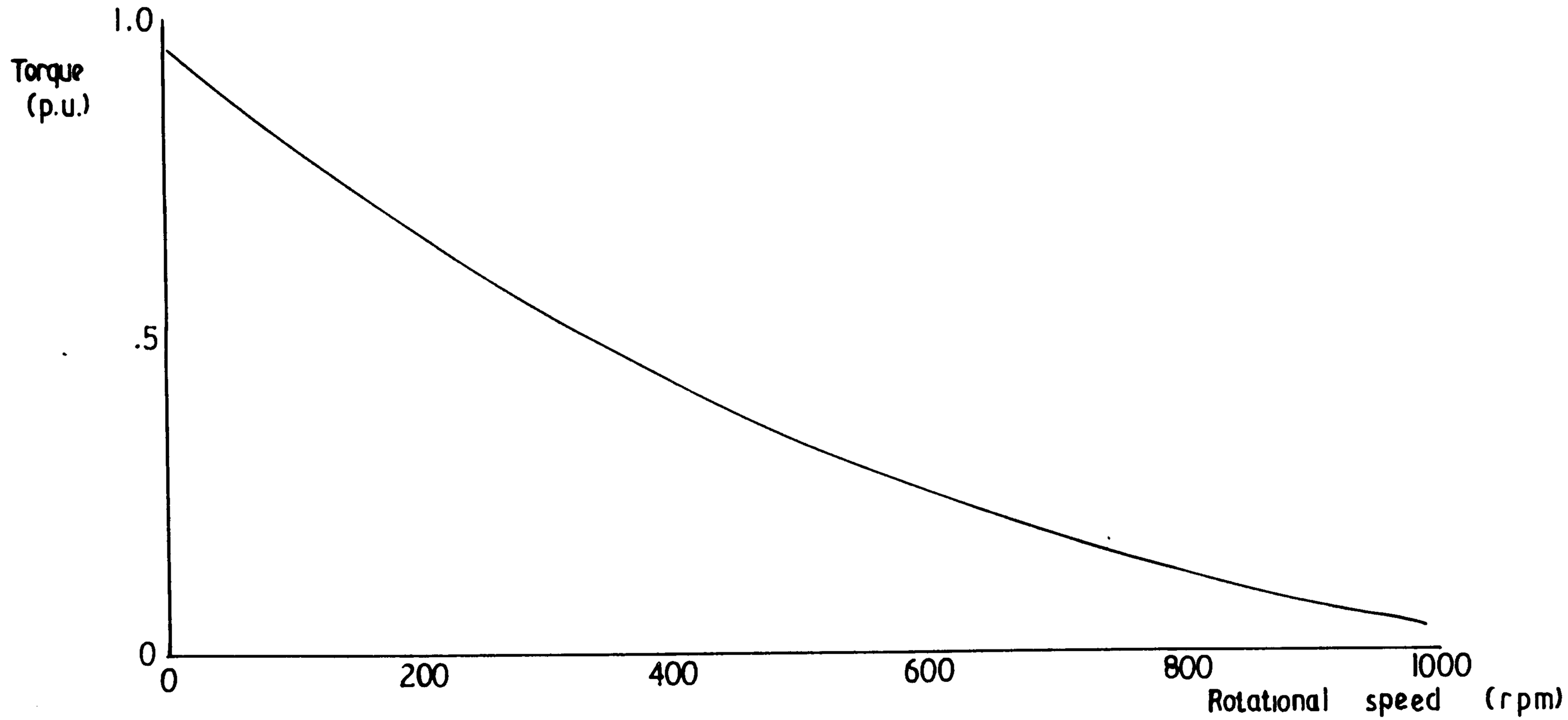
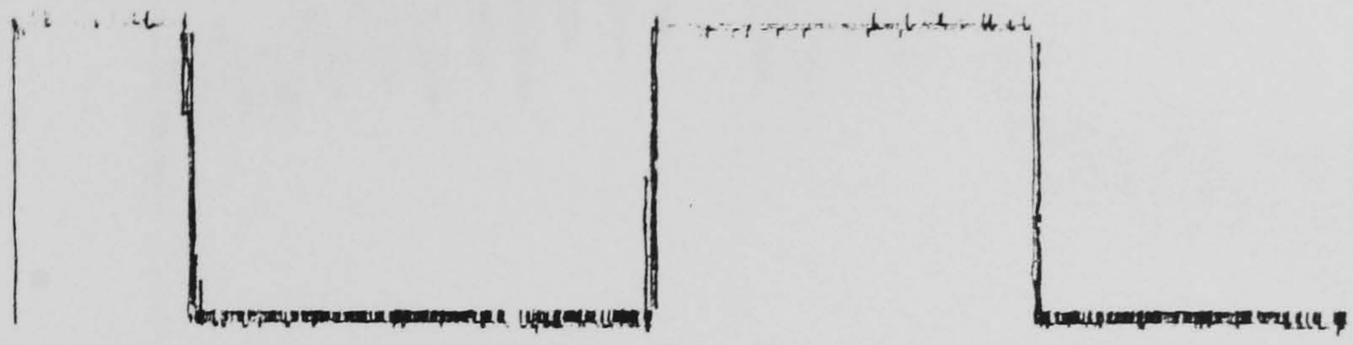
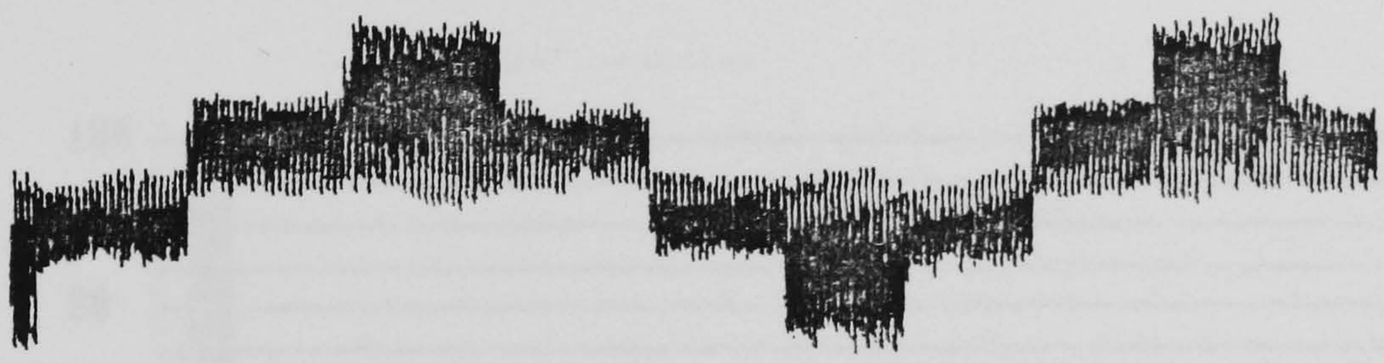


Fig 5.17 Torque vs speed under starting up conditions

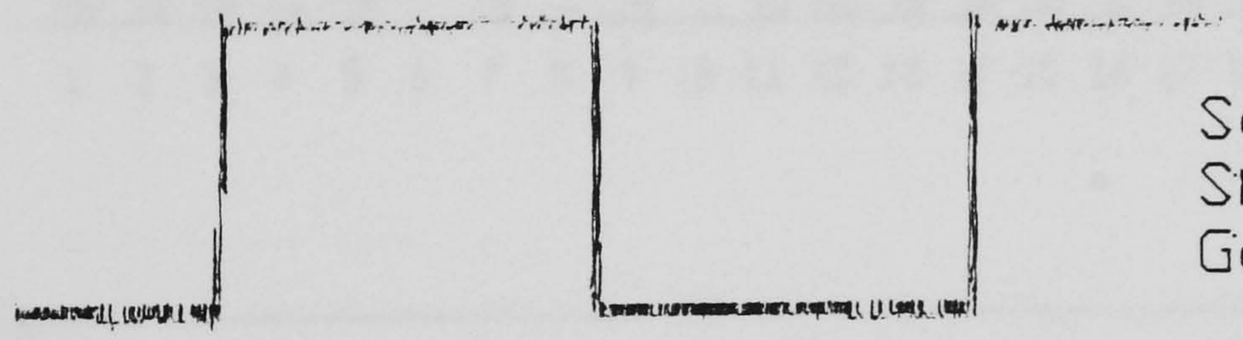


Sec. Emf
Signal
Generator

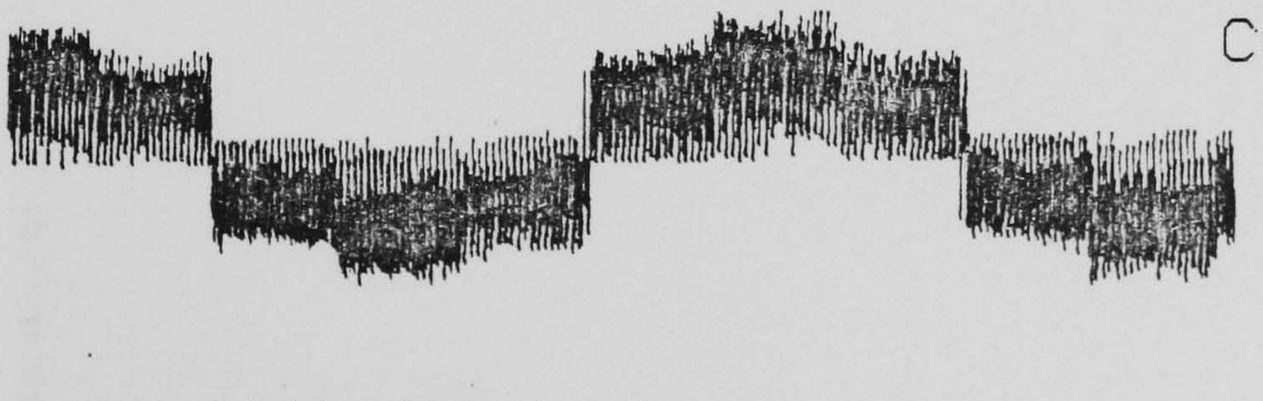


Current

Without Neutral



Sec. Emf
Signal
Generator



Current

With Neutral

Fig 5.18 Effect of Neutral

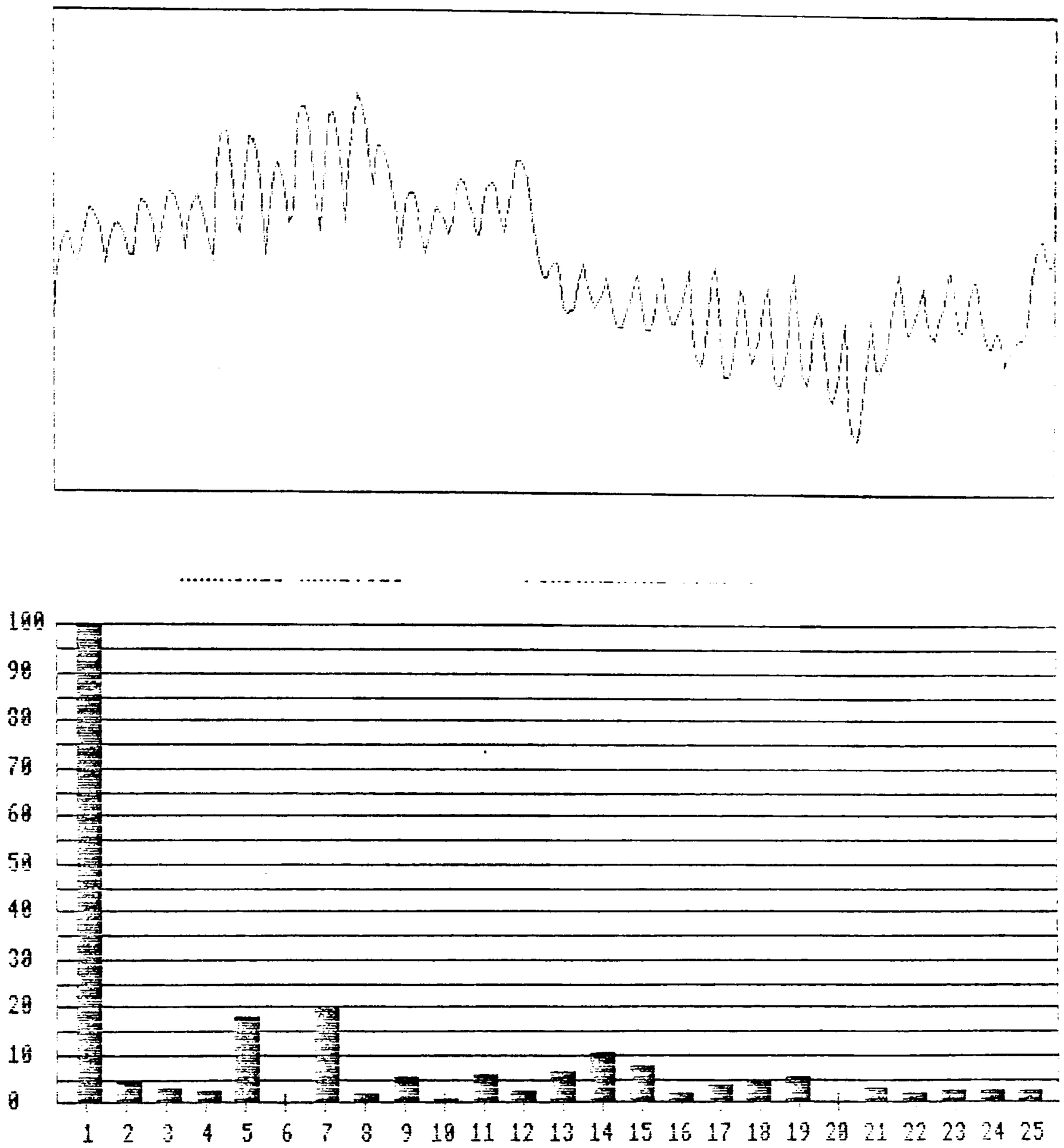


Fig 5.19a 1250 rpm Without neutral

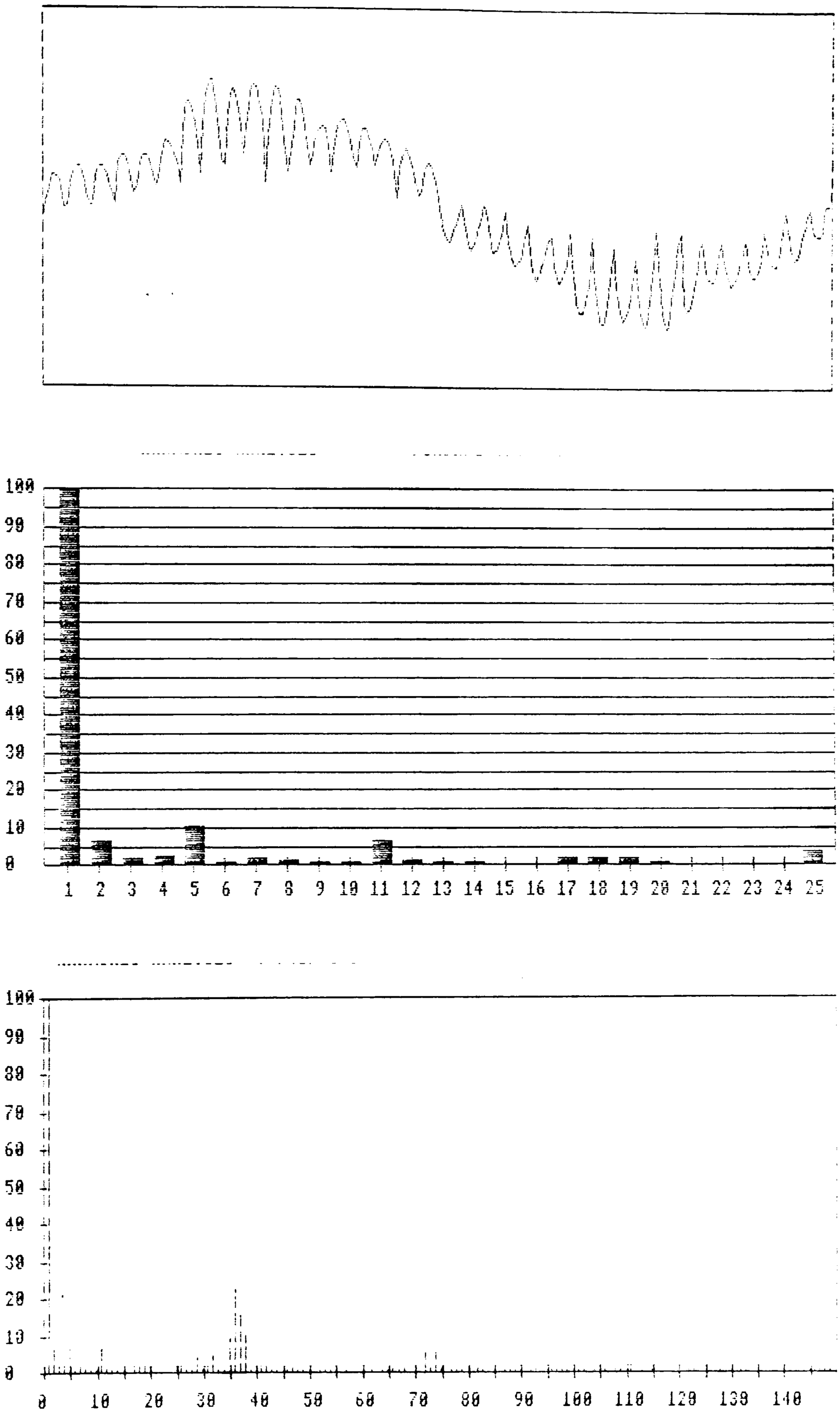


Fig 5.19b 1750 rpm Without neutral

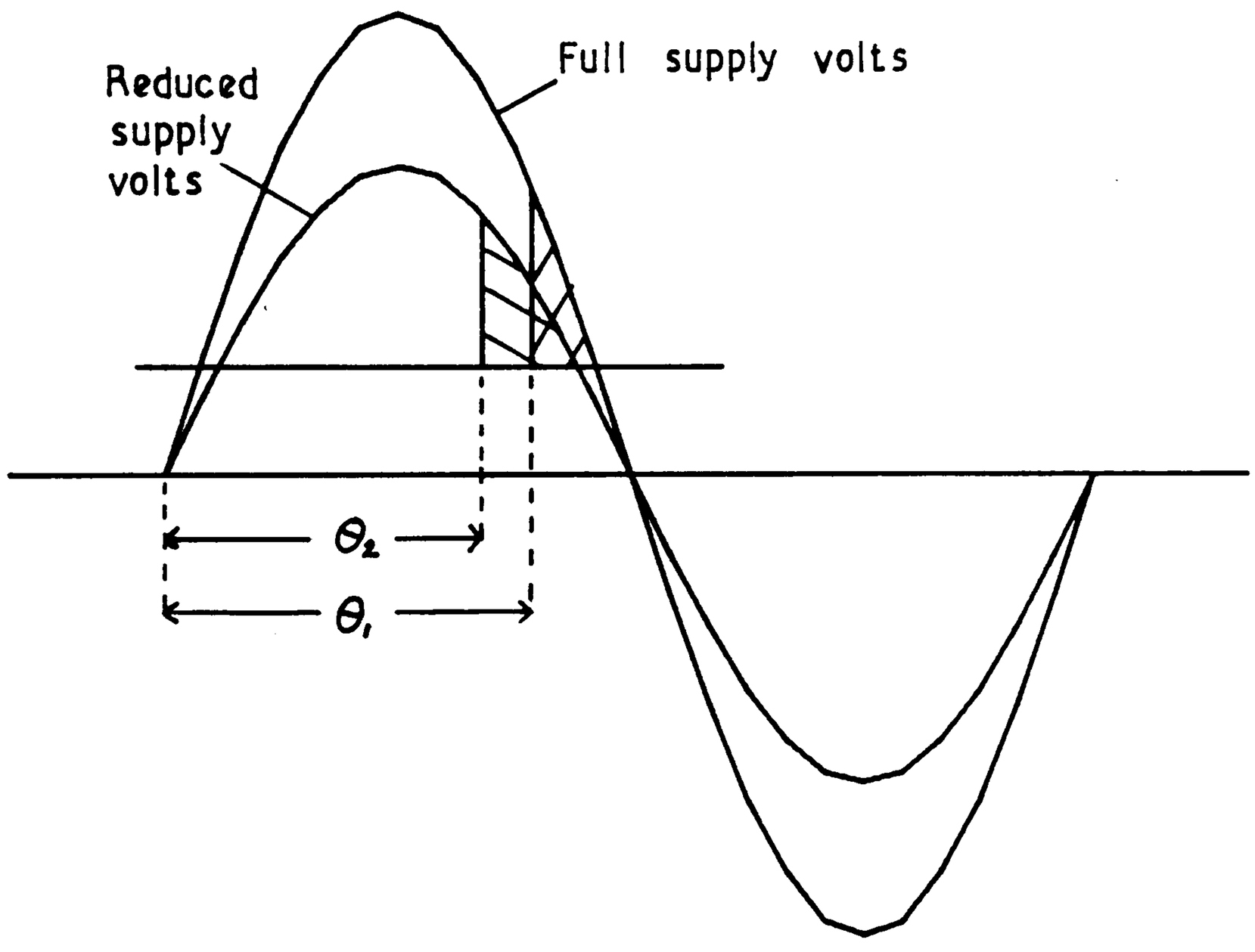


Fig 5.20 Effect of TX volts

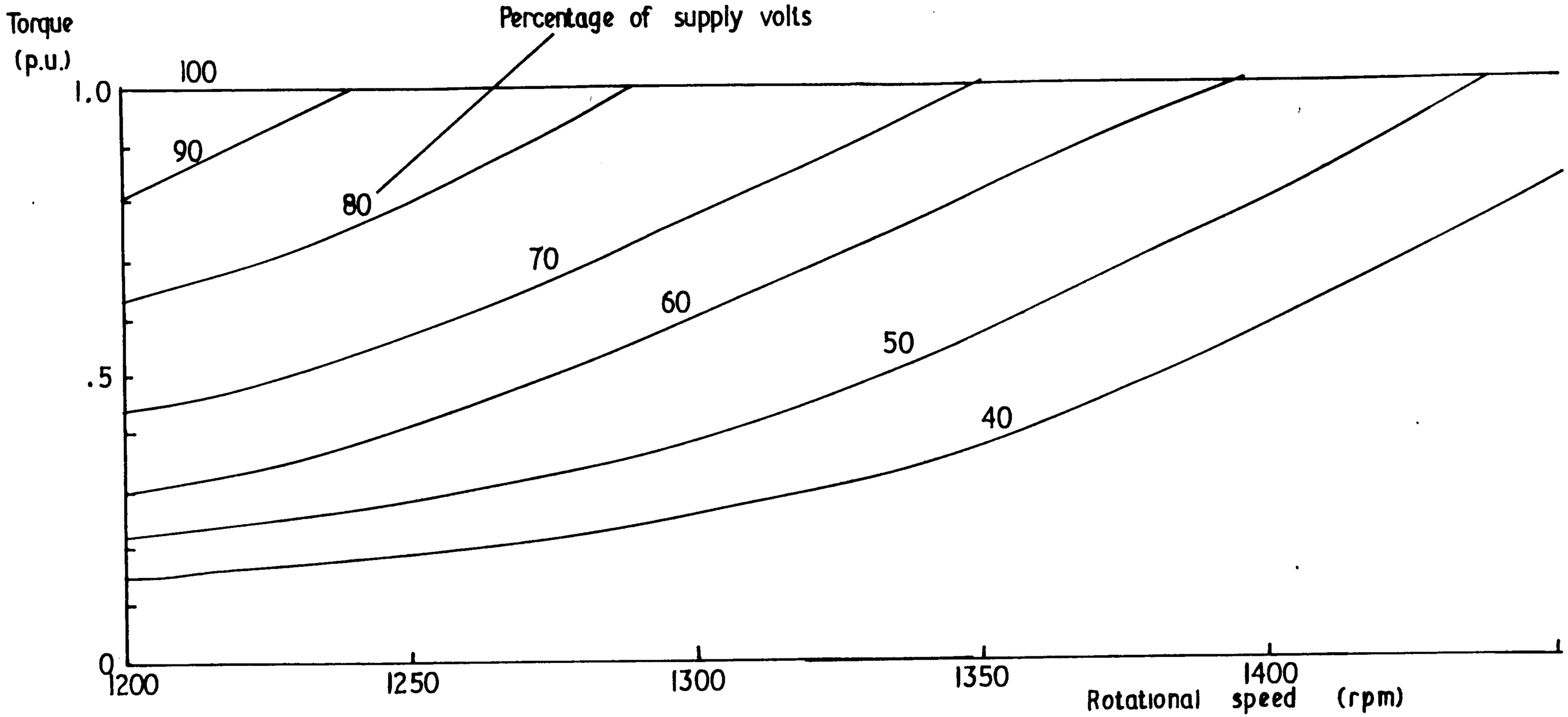


Fig 5.21 Torque vs speed for varying TX volts

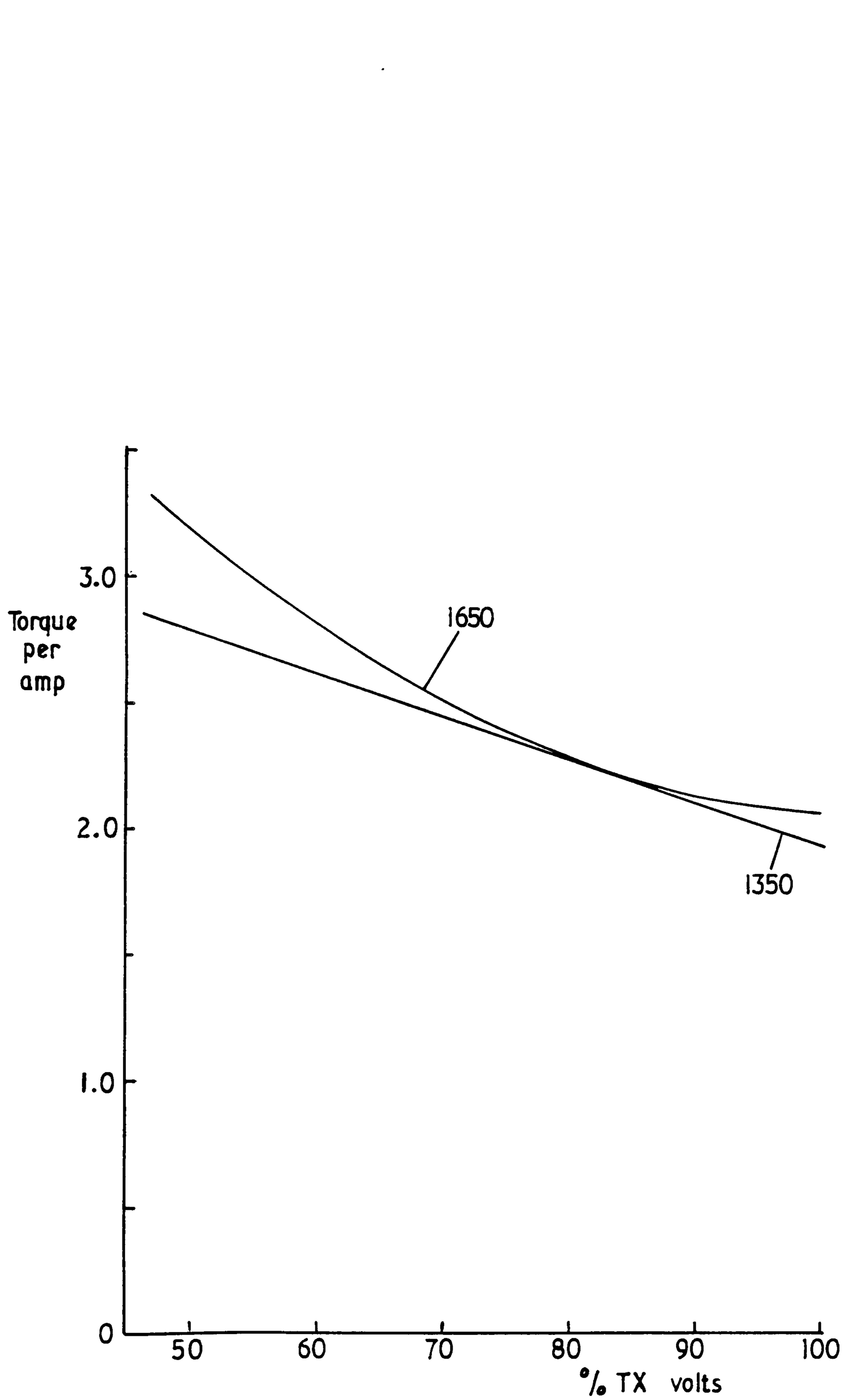


Fig 5.22 Torque per amp vs TX supply volts
T= 0.5 p.u. at 2 speeds

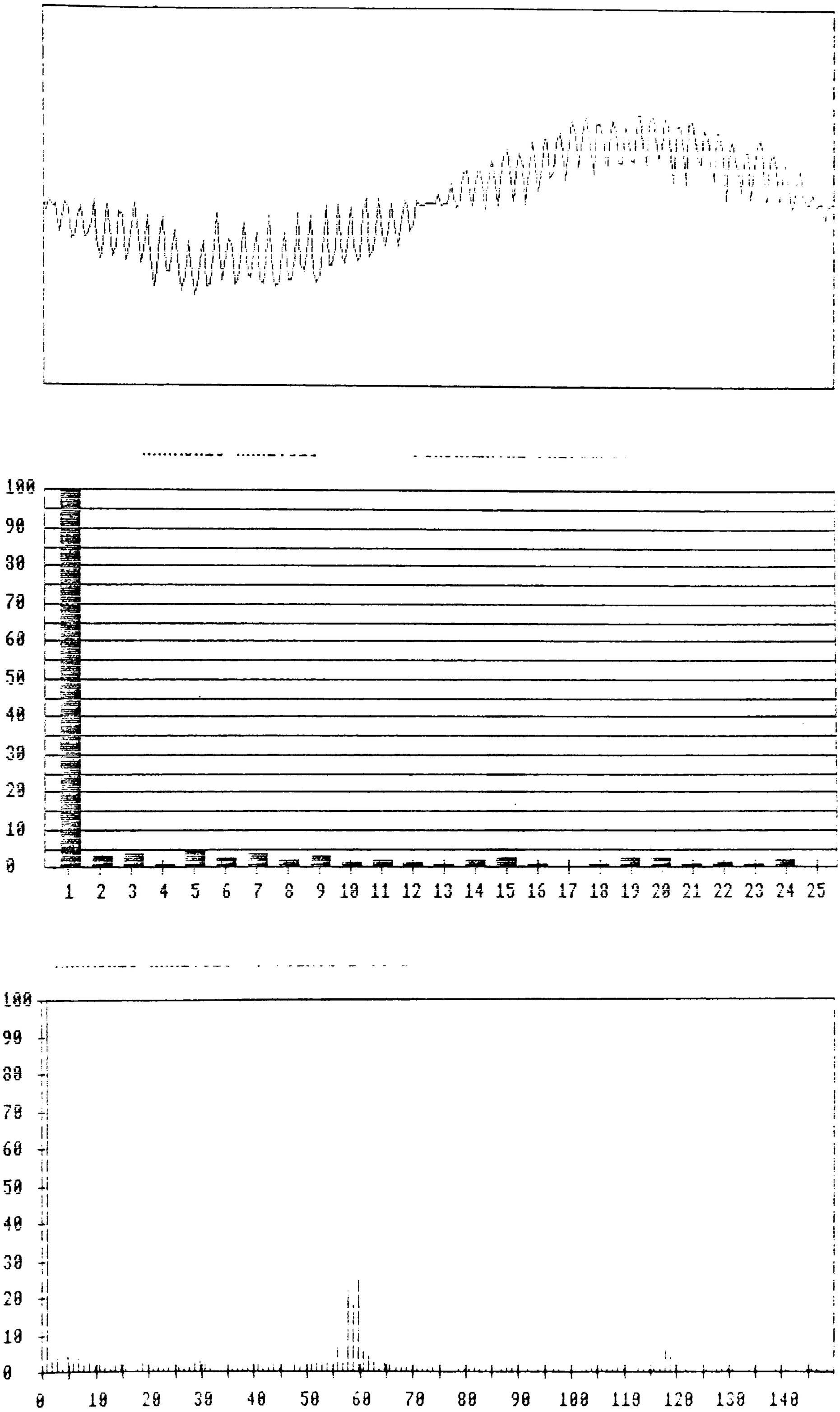
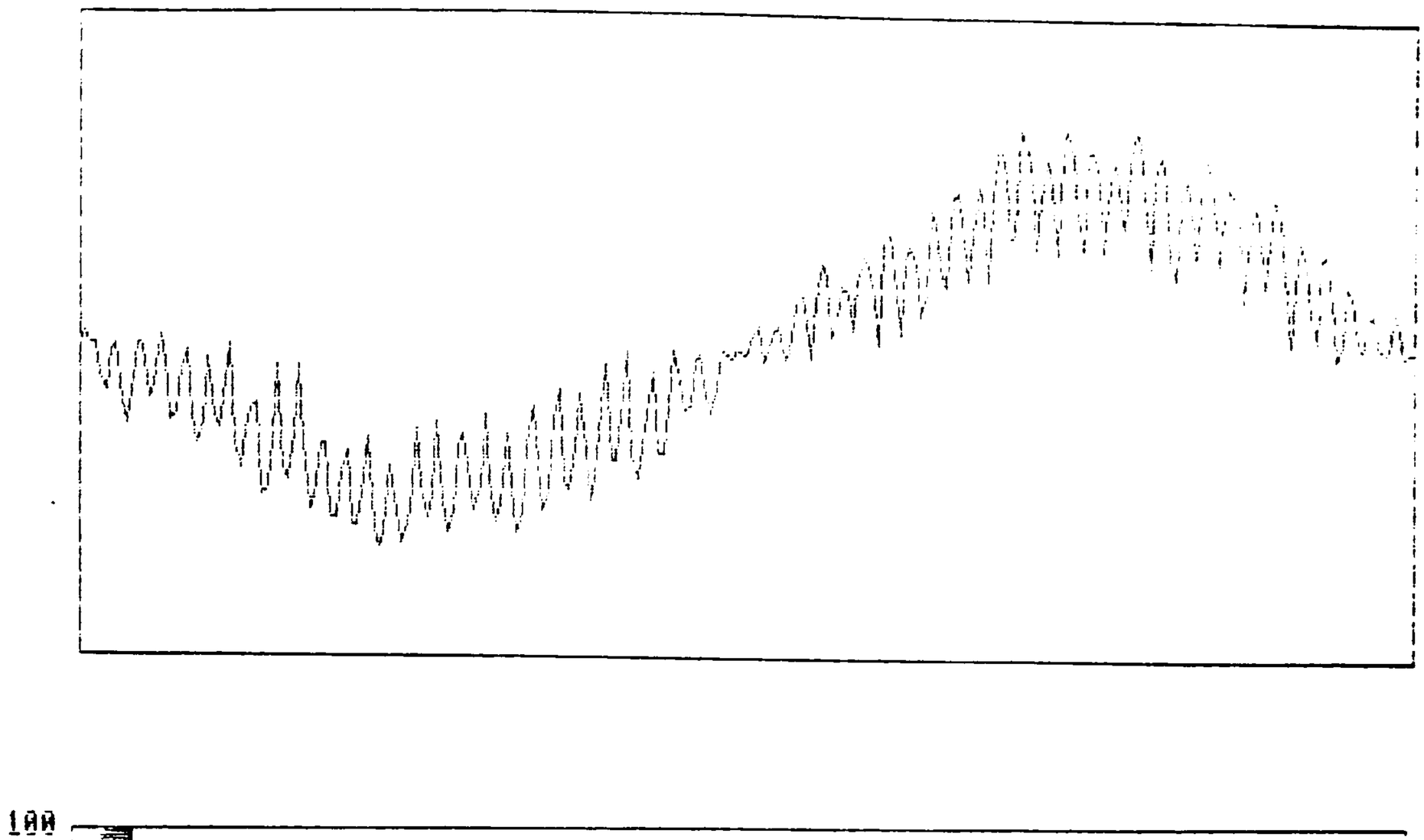
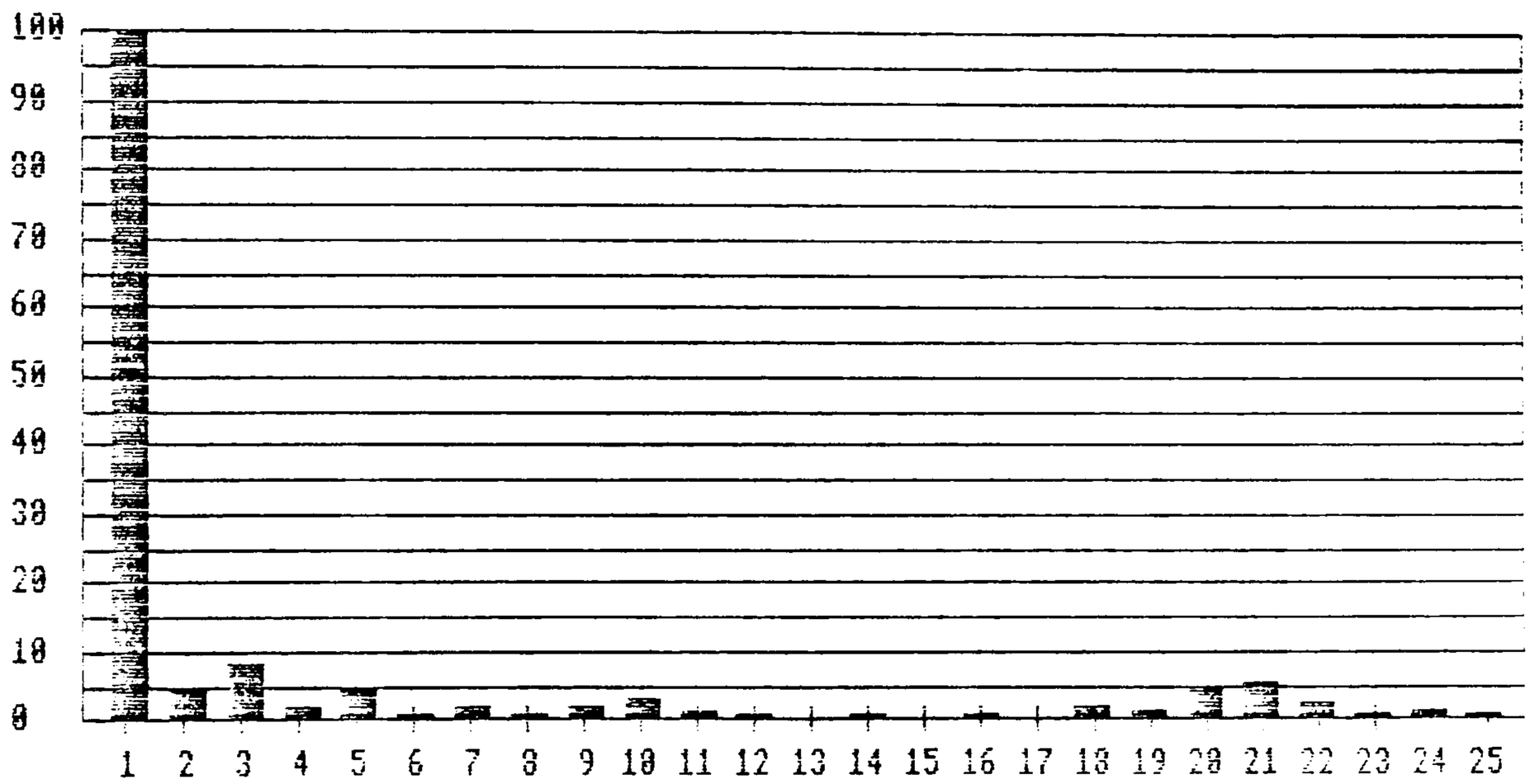


Fig 5.23a 1650 rpm 100% TX volts





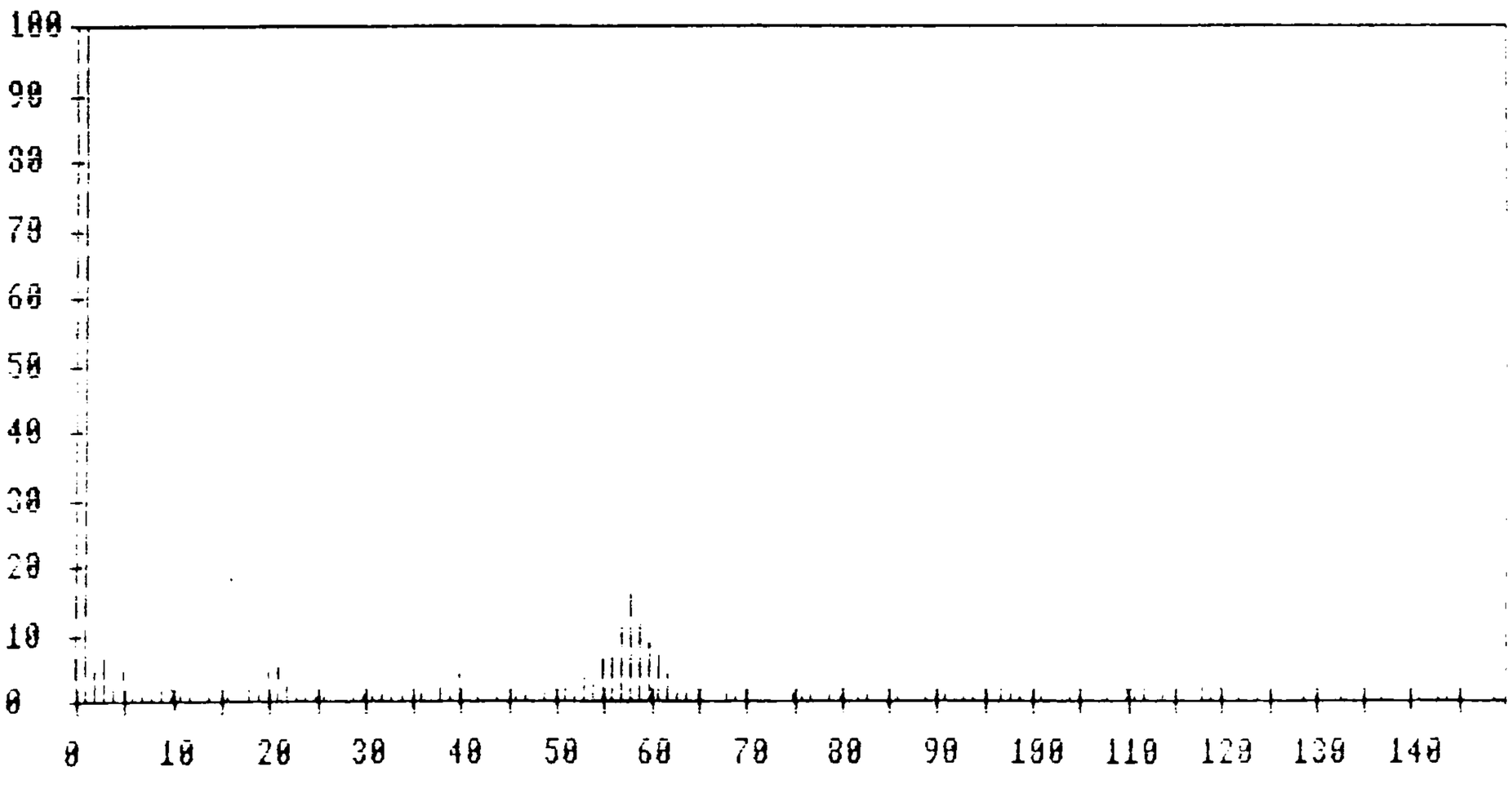


Fig 5.23b 1650 rpm 50% TX volts

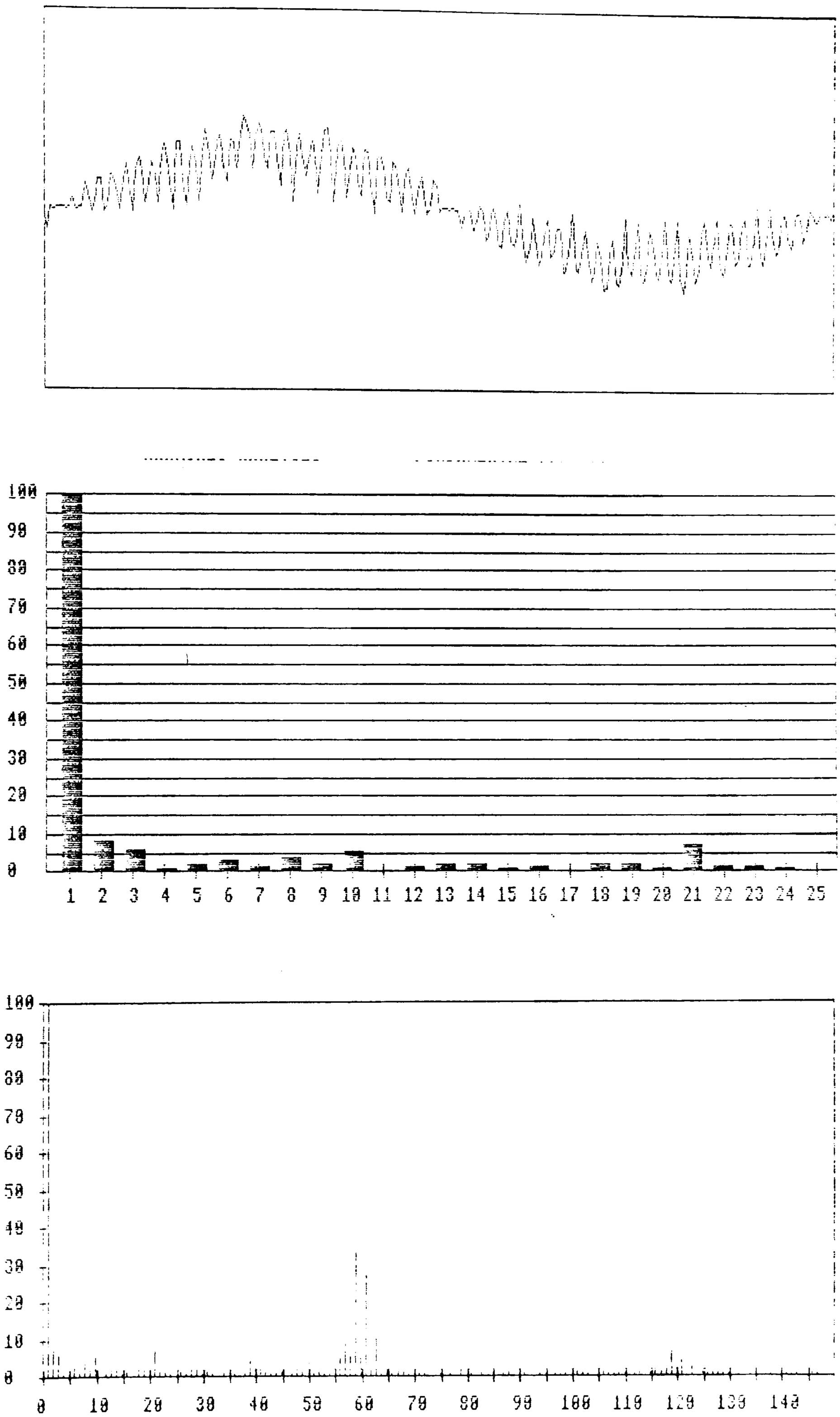


Fig 5.23c 1350 rpm 100% TX volts

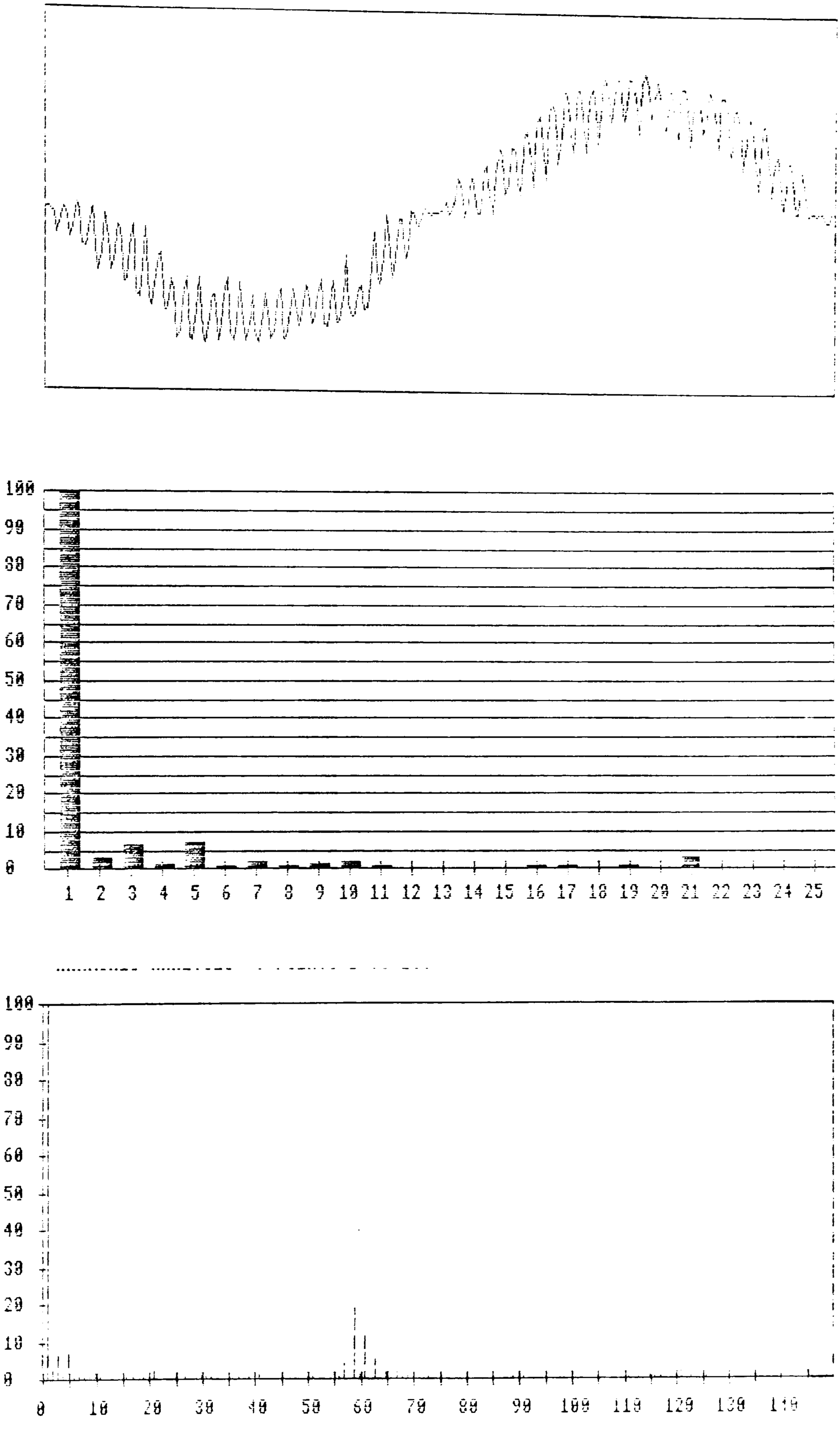


Fig 5.23d 1350 rpm 50% TX volts

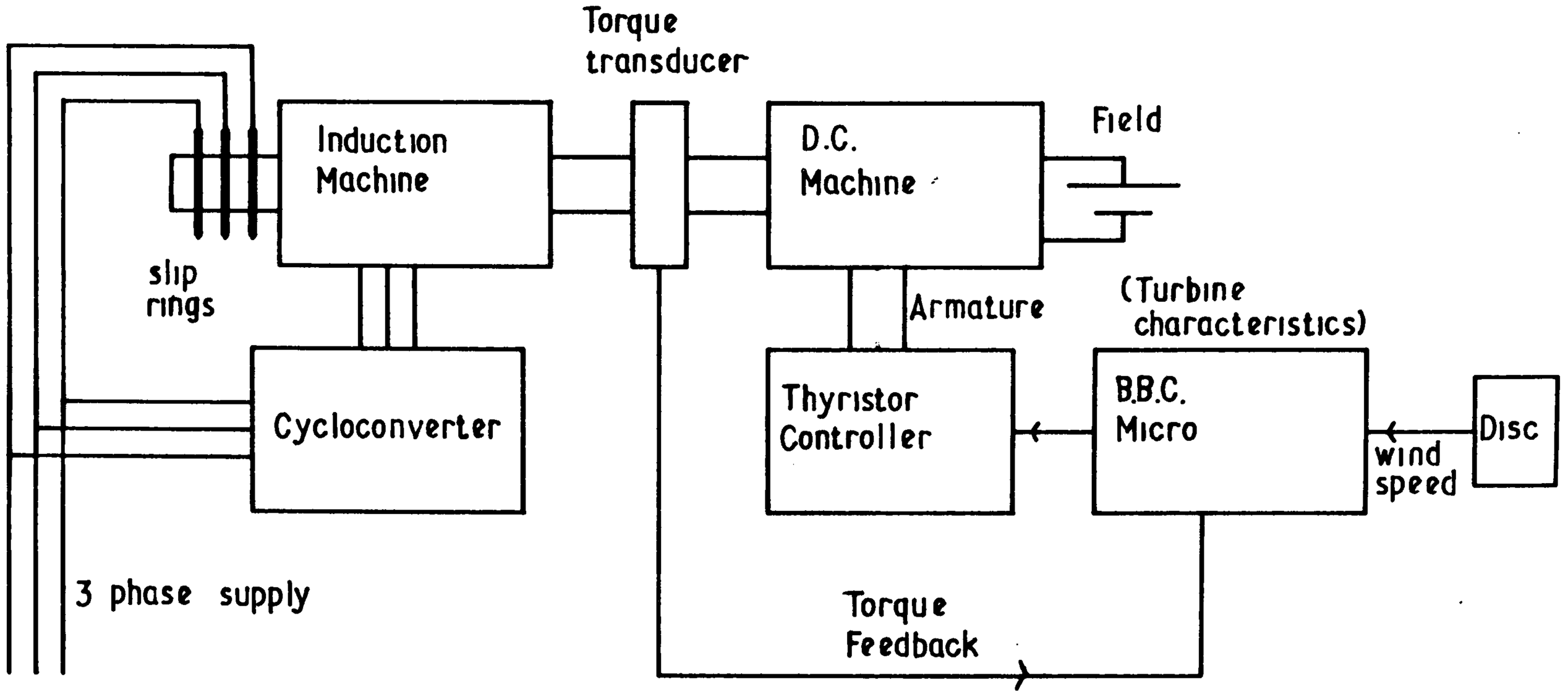

Torque
transducer
Induction
Machine
D.C.
Machine
Field
slip
rings
Armature
(Turbine
characteristics)
Cycloconverter
Thyristor
Controller
B.B.C.
Micro
Disc
wind
speed
3 phase supply
Torque
Feedback

Fig A1.1

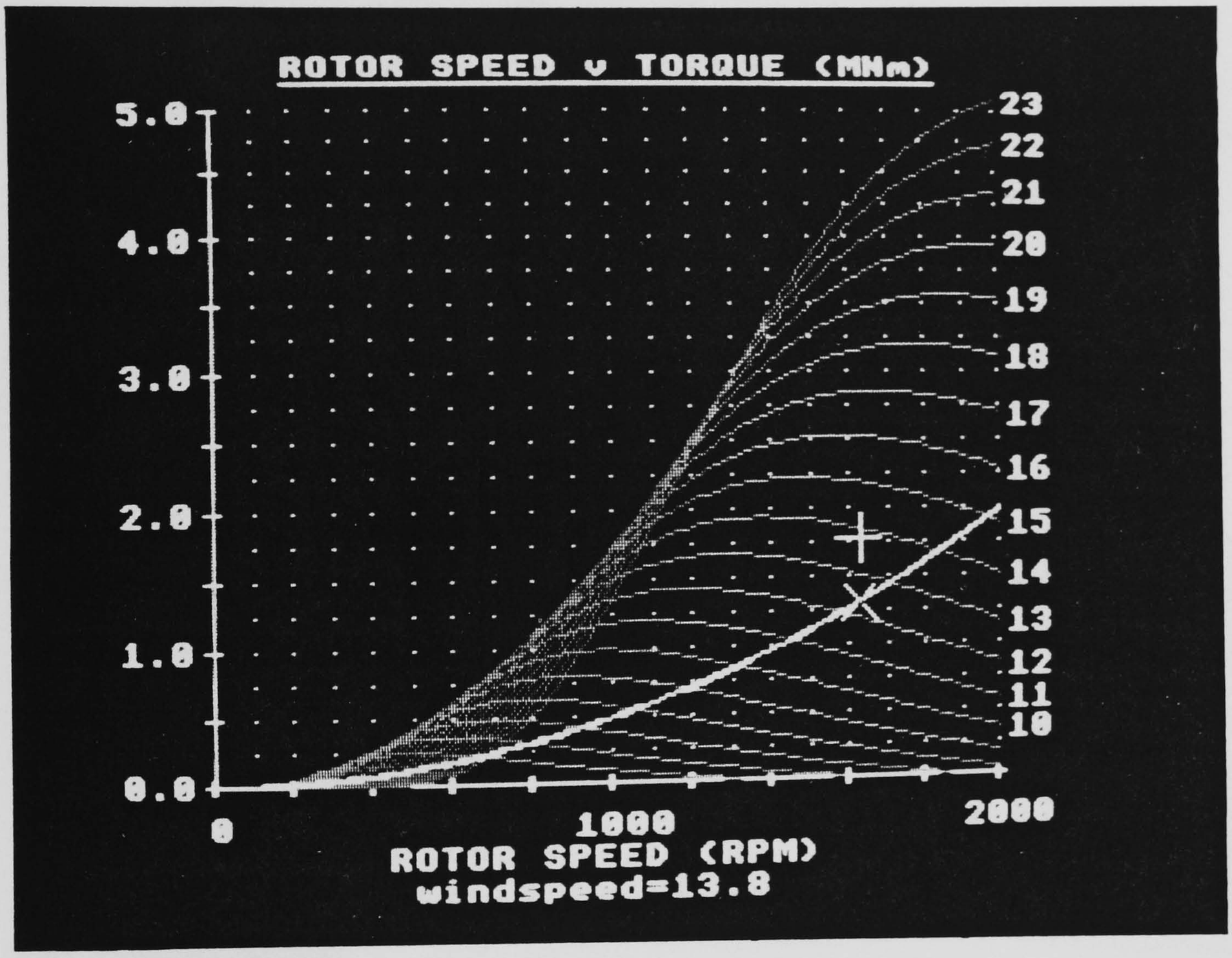


Fig A1.2 WTS screen output

```
>L.
   10 printer$="off":graph=1:old=4:first=0
   12 demand=500
   20 MODE 7:*DRIVE2
   50 REM WIND TURBINE DATA
   52 inertia=6.9E6
   54 radius=45.7
   56 synchub=1.5              :REM HUB SPEED AT SYNCH. ROT. SPEED
   58 gbratio=1000/synchub     :REM GEAR BOX RATIO
   60 gbeff=.8                 :REM GEAR BOX EFFICIENCY
   62 CPmax=.42                :REM Cp MAXIMUM
   64 lamCPmx=9                :REM LAMBDA AT CP MAX
   66 scale=1.9242*CPmax*2002225*radius^5/(gbratio^2*lamCPmx^3*29.4)
   67                          :REM FROM TORQUE SPEED VALUES
   70 REM LINE 1050 NEEDS TO BE REWRITTEN WITH THE CORRECT EQUATION FOR CP IN
   80 REM DISC DATA
   82 title$="WIND2"
   84 pages$="30"
   88 cutout=1850
  100 CLS
  110 VDU 23;8202;0;0;0;
  120 ?&FE62=255:?&FE60=0
  130 CLOSE#0
  200 GOSUB 10000:REM MANUAL/AUTO
  210 IF mode$="auto" GOSUB 11000:REM START PAGE
  220 GOSUB 15000
  230 REM RUN UP TO 500 RPM
  240 rotor=500
  250 ?&FE60=500*224/2000+32
  260 IF ADVAL(1)*.0305<450 GOTO 260
  300 REM MAIN PROG
  305 IF mode$="manual":rotor=demand
  306 IF mode$="manual":IF INKEY(-33):IF wind<25.4:wind=wind+.2
  307 IF mode$="manual":IF INKEY(-120):IF wind>4:wind=wind-.2
  308 IF mode$="manual" GOTO 380
  310 FOR data=1TO490
  320 SOUND 1,-10,200,1
  330 IF data=485 THENSOUND1,-15,230,25
  340 INPUT#Z,wind2
  350 FOR interp=0TO9
  360 rotor=demand
  370 wind=wind1+interp*(wind2-wind1)/10
  380 IF ADVAL(1)*.0305>cutout THEN GOSUB 30000
  400 PROCcalcs
  460 ?&FE60=demand*224/2000+32
  470 GOSUB 14000
  480 IF mode$="manual" GOTO 500
  490 NEXT interp
  500 IF printer$="off" GOTO 540
  510 VDU2,21:@%=&20208
  520 PRINT;ADVAL(1)*.0305,rotor,wind,Cp,torque/1000000,load/1000000,accel/100
00,power/1000000,"   "demand
  530 VDU 6,3
  540 IF INKEY(-90)THEN printer$="off"
  550 IF INKEY(-106)THEN printer$="on"
  555 IF mode$="manual" GOTO 300
```

Fig A1.3 Wind Turbine Simulator Programme

```
 560 wind1=wind2
 565 rotor=demand
 570 NEXT data
 600 CLOSE#0
 605 update$="yes"
 610 page$=STR$(VAL(page$)+1)
 620 IF page$=pages$ THEN GOTO 30000
 630 file$="WIP"+page$
 640 GOTO 300
1000 REM CALCULATIONS
1010 DEF PROCcalcs
1015 hubsp=rotor/gbratio
1020 gamma=(wind*2.2374)/hubsp
1040 lambda=2.2374*radius/gamma
1050 Cp=0.5*(gamma-5.6)*EXP(-.17*gamma)
1060 REM Torque CALC. T=.5*rho*Cp*wind^2*pi*R^3/lamda rho=1.225:pi=3.14
1070 torque=Cp*wind*wind*1.9242*radius*radius*radius/lambda
1080 REM GET LOAD:scale as scaling factor:torval is actual measured torque
1085 torval=ADVAL(2)/692
1090 IF torval>30 THEN torval=torval+((torval-30)/9)
1095 load=torval*scale
1100 REM Power CALC. power=torque*
1110 power=load*hubsp
1120 accel=torque-load
1130 REM demand speed
1140 demand=((accel*.2)/inertia)*gbratio+rotor
1150 ENDPROC
10000 REM WINDDATA OR MANUAL
10010 CLS
10020 PRINT:PRINT
10030 PRINTCHR$(141)"     WIND TURBINE SIMULATOR"
10040 PRINTCHR$(141)"     WIND TURBINE SIMULATOR"
10050 PRINT:PRINT
10060 PRINTCHR$(141)"PLEASE ENTER REQUIRED RUNNING MODE:"
10070 PRINTCHR$(141)"PLEASE ENTER REQUIRED RUNNING MODE:"
10080 PRINT:PRINT:PRINT
10090 PRINTCHR$(141)"   A. ORKNEY WIND DATA"
10100 PRINTCHR$(141)"   A. ORKNEY WIND DATA"
10110 PRINT:PRINT
10120 PRINTCHR$(141)"   B. MANUAL CONTROL OF WIND"
10130 PRINTCHR$(141)"   B. MANUAL CONTROL OF WIND"
10140 PRINT:PRINT:PRINT
10150 PRINTCHR$(141)"PLEASE TYPE'A'OR'B'TO CONTINUE"
10160 PRINTCHR$(141)"PLEASE TYPE'A'OR'B'TO CONTINUE"
10170 IF INKEY(-66) THEN mode$="auto":GOTO 10200
10180 IF INKEY(-101) THEN mode$="manual":wind=4:update$="NO":GOTO 10200
10190 GOTO 10170
10200 CLS
10210 PRINT:PRINT:PRINT
10220 PRINTCHR$(141)"SELECT GRAPH SIZE"
10230 PRINTCHR$(141)"SELECT GRAPH SIZE"
10240 PRINT:PRINT
```

Fig A1.3 continued

```
10250 PRINTCHR$(141)"      1.  NORMAL SIZE"
10252 PRINTCHR$(141)"      1.  NORMAL SIZE"
10260 PRINT
10270 PRINTCHR$(141)"      2.  TWICE SIZE"
10272 PRINTCHR$(141)"      2.  TWICE SIZE"
10280 IF INKEY(-49) THEN graph=1:RETURN
10290 IF INKEY(-50) THEN graph=2:RETURN
10300 GOTO 10280
11000 REM GET STARTING PAGE
11010 CLS
11020 PRINT:PRINT:PRINT:PRINT
11030 PRINTCHR$(141)" START PAGE FROM ";title$;" (01-";pages$")"
11040 PRINTCHR$(141)" START PAGE FROM ";title$;" (01-";pages$");:VDU 11
11045 *FX15,0
11050 page1$=GET$
11055 IF page1$="0" GOTO 11070
11060 IF VAL(page1$)*10>VAL(pages$) OR VAL(page1$)=0 GOTO 11050
11070 PRINT page1$;:VDU10,8
11080 PRINT page1$;:VDU11
11090 page2$=GET$
11100 page$=page1$+page2$
11110 IF VAL(page$)>VAL(pages$) GOTO 11090
11120 PRINT page2$;:VDU10,8
11130 PRINT page2$;
11140 file$="WIP"+page$
11150 Z=OPENIN(file$)
11160 INPUT#Z,wind1
11170 update$="NO"
11180 RETURN
14000 REM UPDATE GRAPH
14020 REM REMOVE POINT
14030 IF first=1 GOSUB 14500
14040 @%=&20104
14050 GCOL 0,0
14060 MOVE 720,30:PRINTold
14100 REM PLOT POINT
14110 Xaxis=150+rotor/2
14120 Yaxis=150+torque*160*graph/1000000
14122  Yaxis2=150+load*160*graph/1000000
14130 GOSUB 14500
14140 GCOL 0,3
14145 @%=&20104:MOVE 720,30:PRINTwind
14150 old=wind
14160 first=1
14170 RETURN
14500 REM PLOT
14510 MOVE Xaxis-30,Yaxis
14520 PLOT 10,60,0
14530 MOVE Xaxis,Yaxis-30
14540 PLOT 10,0,60
14550 MOVE Xaxis-21,Yaxis2-21
14560 PLOT 10,43,43
14570 MOVE Xaxis+21,Yaxis2-21
14580 PLOT 10,-43,43
14600 RETURN
15000 REM GET PICTURE
15005 Xaxis=0:Yaxis=0
15010 MODE 1
15015 *DRIVE 0
15020 CLS
```

Fig A1.3 continued

```
15030 IF graph=1:*LOAD PIC1
15040 IF graph=2:*LOAD PIC2
15050 VDU5
15060 MOVE 370,70
15070 PRINT"ROTOR SPEED (RPM)"
15075 MOVE 400,30:PRINT"windspeed="
15080 *DRIVE 2
15090 IF mode$="auto" RETURN
15100 GCOL 0,2
15110 MOVE 10,30:PRINT"F0=INCREASE"
15120 MOVE 900,30:PRINT"F9=DECREASE"
15130 RETURN
30000 CLS
30002 MODE7
30005 PRINT:PRINT:PRINT:
30010 PRINT CHR$(141)"OVER SPEED AUTO CUTOUT    "
30012 PRINT CHR$(141)"OVER SPEED AUTO CUTOUT    "
30020 ?&FE60=0
30024 FOR K=1 TO 3 .
30025 FOR I=100 TO 150 STEP2
30026 SOUND 1,-15,I,1
30027 NEXT I
30028 NEXT K
30030 END
```

Fig A1.3 continued

```
 L.
  90 MODE7
  95 *FX15,0
 100 DIM A(1024)
 150 CLOSE#0
 300 MODE7
 305 VDU 23,1,0;0;0;
 310 CLS:PRINT:PRINT:PRINT
 320 PRINT "DATA INPUT FROM SCOPE OR DISC?"
 330 PRINT:PRINT "TYPE S OR D ":G$=GET$
 340 IF G$="S" THEN 400
 345 IF G$="D" THEN 13000
 350 GOTO 330
 400 REM COLLECTION OF DATA
 500 CLS:VDU 23,1,0;0;0;:@%=&20205
 600 PRINT
 700 PRINTCHR$(141);"DATA COLLECTION FROM SCOPE"
 800 PRINTCHR$(141);"DATA COLLECTION FROM SCOPE"
 900 PRINT:PRINT:PRINT:
1000 PRINT" The wave form on the digital scope     must be stored at the maxi
m          amplitude possible (ie. clipping       is not quite occuring."
1100 PRINT
1200 PRINT" When thewaveform is suitably stored   press'SPACE-BAR'to continue

1300 G=GET
1400 FORI=1TO7:VDU11:NEXT
1500 FORI=1TO7:PRINTTAB(38)" ":NEXT
1600 FORI=1TO9:VDU11:NEXT
1700 PRINT:PRINT:PRINT:PRINT
2100 INPUT "NUMBER OF SAMPLES (2^N)",Samples
2110 VDU 11:PRINTTAB(35)" ":VDU 11
2200 PRINT"TIME FOR CYCLE OF FUNDAMENTAL"
2210 INPUT"WAVEFORM  (MICROSECONDS)    ",Cycle
2220 VDU 11:PRINTTAB(35)" ":VDU 11,11
2300 PRINT"TIME / DIVISION WHEN STORING  "
2310 INPUT"WAVEFORM  (MILLISECONDS)    ",Store
2320 VDU 11:PRINTTAB(35)" ":VDU 11,11
2350 MPT=Samples*Store*40/Cycle
2400 PRINT"TIME / DIVISION FOR PLAY BACK >"MPT
2410 INPUT"OF THE WAVEFORM  (SECONDS)    ",Playback
2420 VDU 11:PRINTTAB(35)" ":VDU 11
2500 T=Cycle*Playback/(Store*1000)
2600 FOR I=1TO4:PRINTTAB(30)"     ":NEXTI
2700 VDU 11,11,11,11,11,11
3000 PRINT
3100 PRINT"   TIME PERIOD   = ";T"  SECONDS     "
3200 PRINT
3300 PRINT"    SAMPLING RATE = ";Samples/T"  HZ         "
3400 PRINT:PRINT:PRINT
3500 PRINT"          To input the data press"
3600 PRINT
3700 PRINT"                    'PEN-START'"
```

Fig A1.4 Fourier Analysis Programme

```
3800 PRINT
3900 PRINT"              on the oscilloscope"
3950 IF ADVAL(4)/16<1000 GOTO 3970
3960 GOTO 3950
3970 FOR I=1TO7:VDU11:NEXT
3971 FOR I=1TO7:PRINTTAB(38)" ":NEXT
3972 FOR I=1TO19:VDU11:NEXT
3980 VDU31,17,1:PRINTCHR$(141)"    COLLECTING DATA"
3981 VDU31,17,2:PRINTCHR$(141)"    COLLECTING DATA"
3990 PRINTTAB(3,12)"CLOCK          =         SECONDS"
4000 REM MAIN PROG
4010 X=T-1
4020 TIME=0
4050 FOR I=1TO Samples
4100 IF TIME>(T*I*100/Samples):A(I)=ADVAL(3):NEXT
4150 IF T-TIME/100<=X:PRINTTAB(20,12);X:X=X-1
4200 IF I<Samples GOTO 4100
4300 FOR I=1TO4:VDU11:NEXTI
4310 FOR I=1TO4:PRINTTAB(38)" ":NEXT
4320 FOR I=1TO4:VDU11:NEXTI
5000 REM DRAW WAVEFORM
5005 MODE4
5006 colour=6
5007 VDU 19,1,colour,0,0,0
5010 GCOL 0,3
5014 PRINTTAB(6,3)"THIS IS THE WAVEFORM STORED"
5020 MOVE 140,200
5030 DRAW 140,800
5040 DRAW 1164,800
5050 DRAW 1164,200
5060 DRAW 140,200
5400 MOVE 141,(A(1)/128)+250
5500 FOR I=1 TO Samples-1
5600 DRAW I*(1024/Samples)+140,(A(I)/128)+250
5700 NEXT
5710 PRINTTAB(7,28)"PRESS SPACE-BAR TO CONTINUE"
5998 G=GET
5999 MODE7
6000 CLS:VDU 23,1,0;0;0;
6001 PRINT:PRINT:PRINT
6002 PRINT"THE WAVEFORM IS NOW STORED."
6003 PRINT"DO YOU WISH TO :"
6004 PRINT:PRINT"(A) ANALYSE IT NOW"
6005 PRINT"(B) SAVE IT ONTO THE CURRENT DISC"
6006 PRINT"(C) GETANOTHER WAVEFORM FROM SCOPE"
6007 PRINT"(D) GET ANOTHER WAVEFORM FROM DISC"
6008 PRINT"(E) EXIT":G$=GET$
6009 IF G$="A" THEN 6015
6010 IF G$="B" THEN 12000
6011 IF G$="C" THEN 400
6012 IF G$="D" THEN 13000
6013 IF G$="E" THEN CLS:END
6014 GOTO 6009
6015 CLS:PRINT:PRINT
6016 PRINTCHR$(141);"ANALYSIS IN PROGRESS"
6020 PRINTCHR$(141);"ANALYSIS IN PROGRESS"
10000 DIM B(1024),C(1024)
```

Fig A1.4 continued

```
10050 PROCsignalin
10060 DEF PROCdft
10110 FOR J%=1TOP%:B(J%)=B(J%)/P%:C(J%)=C(J%)/P%:NEXT J%
10160 PROCdfteval("dft")
10170 ENDPROC
10180 DEF PROCinvdft
10190 PRINT"Inverse DFT to yield ";Nb" signal samples."
10200 PROCdfteval("invdft")
10210 ENDPROC
10220 DEF PROCdfteval(A$)
10230 REM Reorder sequence according to Fig.12.8
10240 R%=P%/2:Q%=P%-1
10260 J%=1:FOR L%=1 TO Q%:IF L%>J% OR L%=J% THEN GOTO 10350
10290 T=B(J%):V=C(J%):B(J%)=B(L%):C(J%)=C(L%):B(L%)=T:C(L%)=V
10350 K%=R%
10360 IF K%>=J% THEN GOTO 10400
10370 J%=J%-K%:K%=K%/2
10390 GOTO 10360
10400 J%=J%+K%
10410 NEXT L%
10440 REM Calculate FFT accordind to Fig.12.5
10450 FOR M%=1TON%:W=1:X=0:S%=2^M%:K%=S%/2:Y=COS(PI/K%)
10510  IF A$="dft"THENZ=-SIN(PI/K%) ELSE Z=SIN(PI/K%)
10520 FOR J%=1TOK%
10530 FOR L%=J% TO P% STEP S%
10540 H%=L%+K%:T=B(H%)*W-C(H%)*X:V=C(H%)*W+B(H%)*X:B(H%)=B(L%)-T:C(H%)=C(L%)-V:
(L%)=B(L%)+T:C(L%)=C(L%)+V
10610 NEXT L%
10620 Sr=W:W=W*Y-X*Z:X=X*Y+Sr*Z
10650 NEXT J%
10660 NEXT M%
10670 ENDPROC
10680 DEF PROCsignalin
10690 FOR I%=1 TO Samples
10695 B(I%)=A(I%)/16
10700 NEXT I%
10705 @%=10
10709 PRINT
10710 PRINTCHR$(141)"Signal has ";Samples" sample values."
10712 PRINTCHR$(141)"Signal has ";Samples" sample values.":PRINT
10720 N%=1:P%=2
10730 REPEAT:N%=N%+1:P%=P%*2:UNTIL P%>=Samples
10740 PROCdft
10745 D=OPENOUT"ampl.":E=OPENOUT"wavfrm":CLOSE#0
10770 D=OPENOUT"ampl."
10772 PRINT#D,Samples
10773 PRINT#D,Cycle
10775 E=OPENOUT"wavfrm"
10780 P%=INT(P%/2+0.5)
10790 REM Fourier coefficients
10810 FOR J%=1 TO Samples/2
10811 @%=&20308
10820 A=SQR(B(J%)*B(J%)+C(J%)*C(J%))
10850 PRINT#D,A
10860 NEXT J%
10870 IF Samples<257 : step=1:GOTO 10880
10872 step=Samples/256
10880 FOR J%=1 TO 1024 STEP step
```

Fig A1.4 continued

```
10890 PRINT#E,A(J%)
10900 NEXT
10910 CLOSE#0
11000 CHAIN "A.DISP4"
12000 CLS: MODE7
12010 PRINT:PRINT:PRINT
12020 INPUT "FILE NAME FOR DATA STORAGE";flname$
12030 D=OPENOUT(flname$)
12040 PRINT#D,Samples
12050 PRINT#D,Cycle
12060 FOR I = 1 TO Samples
12070 PRINT#D,A(I)
12080 NEXT I
12090 CLS:PRINT:PRINT:PRINT
12100 PRINT"DO YOU WANT TO TAKE ANOTHER WAVEFORM"
12110 PRINT"FROM THE SCOPE OR ANALYSE THIS ONE NOW?"
12120 PRINT"TYPE S OR A";G$=GET$
12130 IF G$="S" THEN 150
12140 IF G$="A" THEN 6015
12150 GOTO12120
13000 CLS:@%=&20205
13010 MODE7
13020 PRINT:PRINT:PRINT
13030 INPUT "DATA FILENAME ";flname$
13031 PRINT:PRINT:PRINT
13032 PRINTCHR$(141);"READING DATA"
13033 PRINTCHR$(141);"READING DATA"
13040 D=OPENIN(flname$)
13050 INPUT#D,Samples
13060 INPUT#D,Cycle
13070 FOR I=1 TO Samples
13080 INPUT#D,A(I)
13090 NEXT I
13100 CLS:GOTO5000
```

Fig A1.4 continued

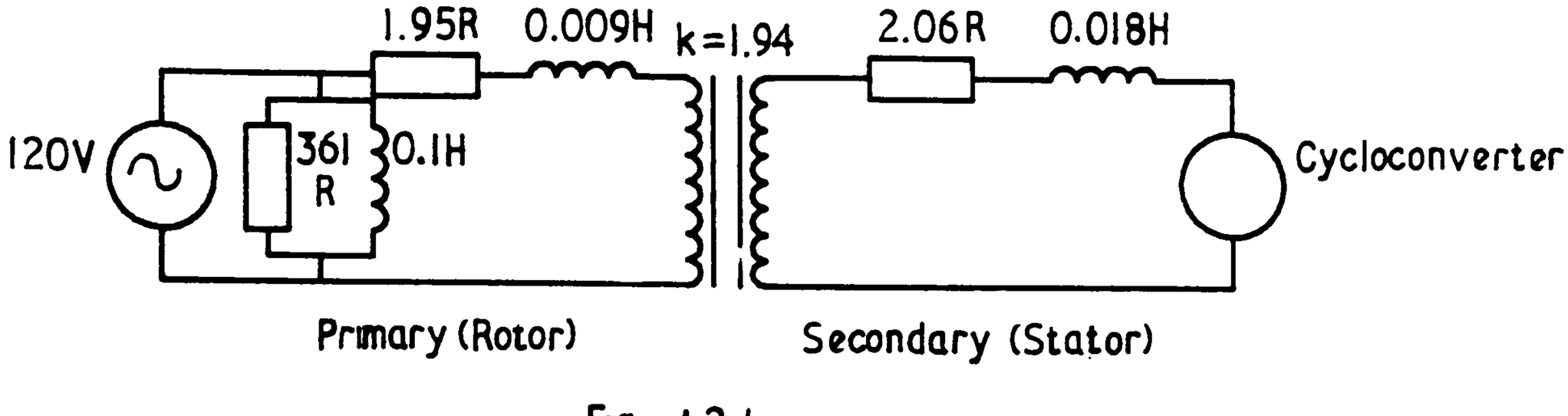


Fig A2.1

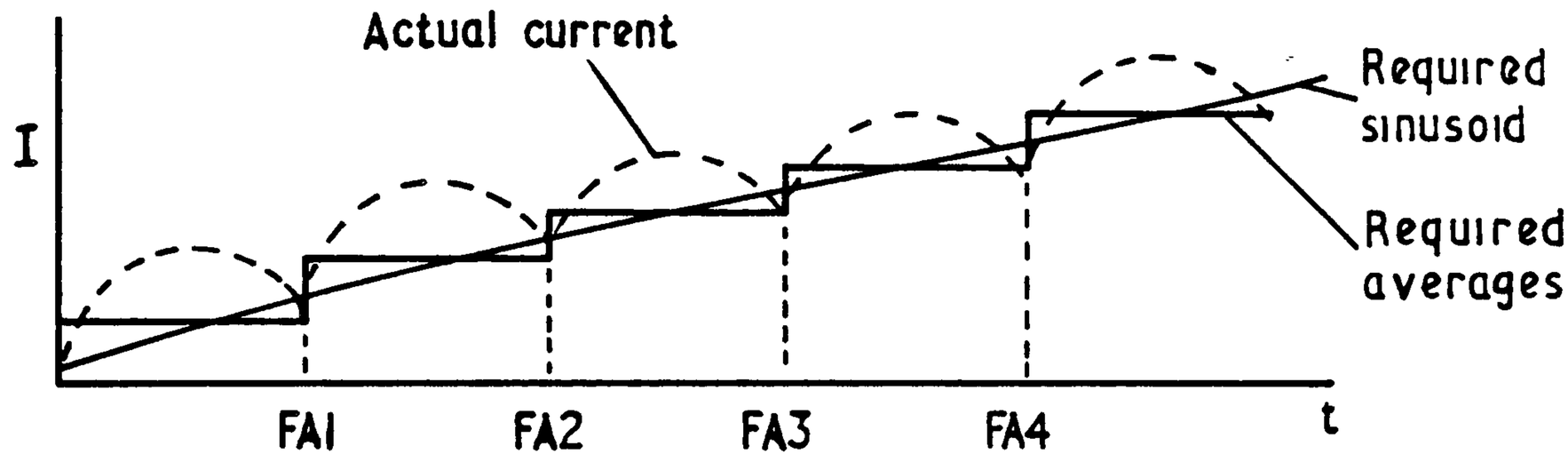


Fig A2.2

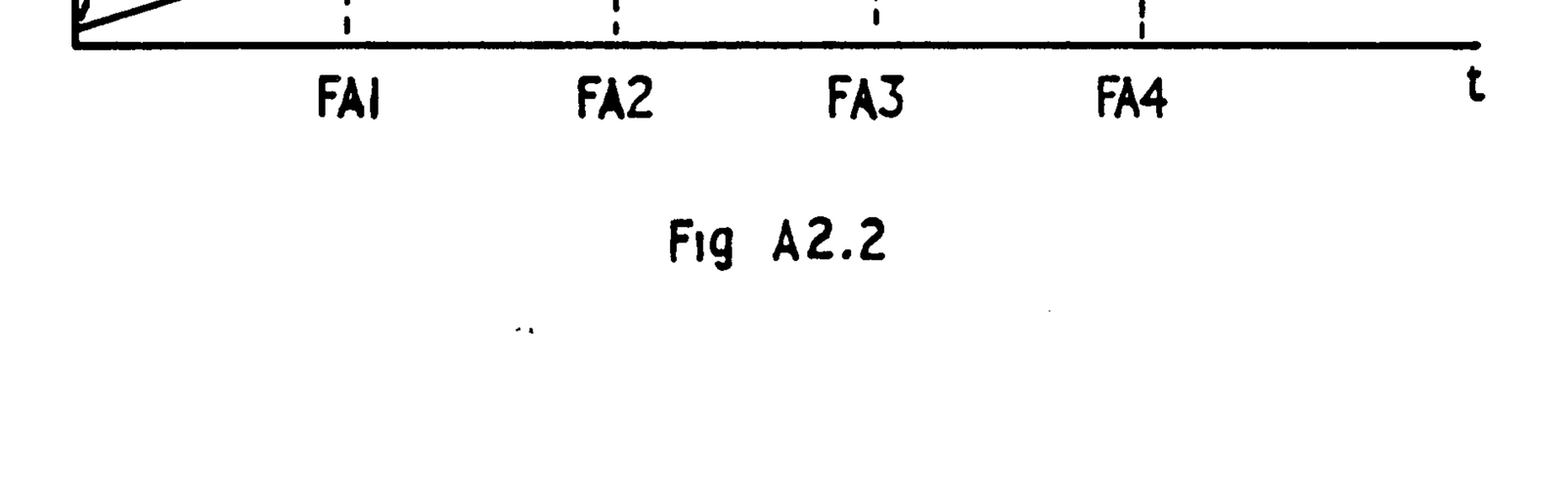


Fig A2.3

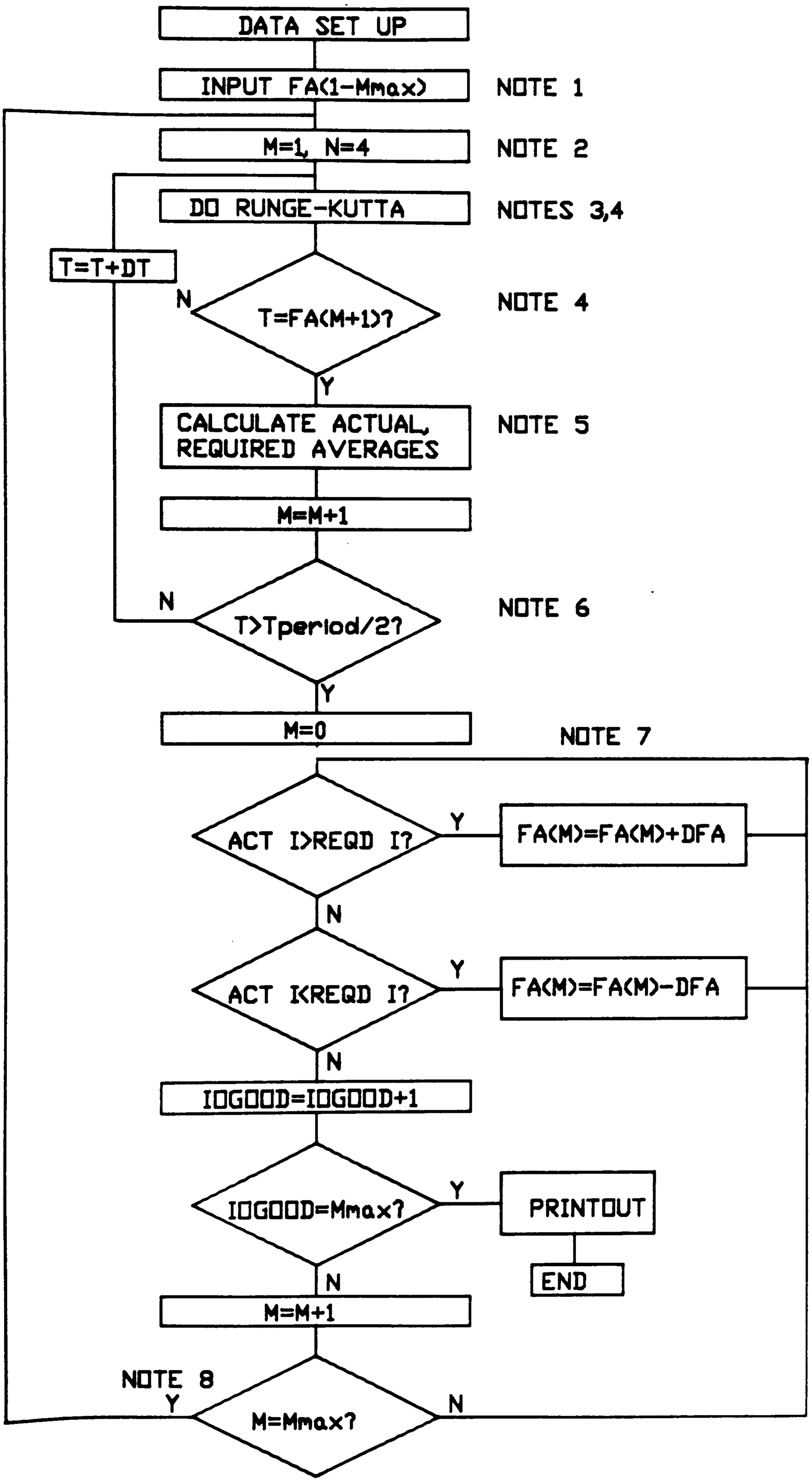


Fig A2.4 Flow Diagram

```
      PROGRAM GUESS       73/73   OPT=0                                FTN 5.1+532        8-/12/1?.

ANSI      1 *               PROGRAM GUESS (INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT)
          2 *         FILE DECLARATION LIST NON- ANSI
          3                 DIMENSION FA(310),SUM(31 ),AAC(31?),RAC(?1.)
          4                 K=1
          5                 PI=3.14159265
          6                 TRAT=1.94
          7                 SLIP=+ .?6
          8                 FSLIP=ABS(SLIP*50.0)
          9                 RES=2. 6+(SLIP*3.298)
         10                 DT=1E-5
         11                 XIND=1.?18
         12                 VPEAK=196.0
         13                 APEAK=1.7
         14                 DO 2 IP=1,18
         15                 READ(5,3) FA(IP)
         16               3 FORMAT(F8.5,2F6.2)
         17               2 CONTINUE
         18                 FA(19)=?.?625
         19                 FA(2?)=?.?666?
         20                 DO 10? J=1,5?
         21               5 DO 1? IRESET=1,150
         22                 SUM(IRESET)=?.?
         23                 SUMSQ=?.?
         24              1? CONTINUE
         25                 M=1
         26                 N=4
         27                 L=(FA(1)/DT)
         28                 XAMPS=  .??2??
         29                 DO 4?,I=L,6251
         30                 T=I*DT
         31       C         RUNGE-KUTTA CALCULATION
         32                 RCUR?=XAMPS
         33                 A1=DT*RUNGE(RCUR?,T,N,PI,RES,XIND,FSLIP,VPEAK,TRAT,SLIP)
         34                 RCUR1=RCUR?+(A1/3)
         35                 A2=DT*RUNGE(RCUR1,(T+(DT/3)),N,PI,RES,XIND,FSLIP,VPEAK,TRAT,SLIP)
         36                 RCUR2=RCUR?+(A1/6)+(A2/6)
         37                 A3=DT*RUNGE(RCUR2,(T+(DT/3)),N,PI,RES,XIND,FSLIP,VPEAK,TRAT,SLIP)
         38                 RCUR3=RCUR?+(A1/8)+(3*A3/8)
         39                 A4=DT*RUNGE(RCUR3,(T+(DT/2)),N,PI,RES,XIND,FSLIP,VPEAK,TRAT,SLIP)
         40                 RCUR4=RCUR?+(A1/2)-(3*A3/2)+(2*A4)
         41                 A5=DT*RUNGE(RCUR4,(T+DT),N,PI,RES,XIND,FSLIP,VPEAK,TRAT,SLIP)
         42                 XAMPS=RCUR?+((A1+(4*A4)+A5)/6)
         43                 IF(XAMPS.LE.?.?)THEN
         44                   XAMPS=?.?
         45                 END IF
         46                 SUMSQ=SUMSQ+((XAMPS**2)*DT)
         47                 SUM(M)=SUM(M)+(XAMPS*DT)
         48                 IF(T.GE.FA(M+1))THEN
         49                   FAM1=FA(M+1)
         50                   FAM=FA(M)
         51                   AAC(M)=SUM(M)/(FAM1-FAM)
         52                   RAC(M)=RGC(FAM1,FAM,FSLIP,PI,APEAK)
         53                   M=M+1
         54                   IF(N.EQ.5)THEN
         55                     N=?
         56                   ELSE
         57                     N=N+1
         58                   END IF
         59                 END IF
         60              4? CONTINUE
         61                 IOGOOD=?
         62                 DO 5? ICHECK=1,18
         63                 IF(ABS(AAC(ICHECK)-RAC(ICHECK)).GT.1.?)THEN
         64                   FINC=?.?0005
         65                 ELSE
         66                   IF(ABS(AAC(ICHECK)-RAC(ICHECK)).GT.?.2)THEN
         67                     FINC=?.??0?2?
         68                   ELSE
         69                     IF(ABS(AAC(ICHECK)-RAC(ICHECK)).GT.?.?5)THEN
         70                       FINC=?.??0?10
         71                     ELSE
         72                       FINC=?.?
         73                       IOGOOD=IOGOOD+1
                                END IF
```

Fig A2.5 Control wave programme

```
      PROGRAM GUESS       73/73   OPT=                          FTN 5.1+552        5-/12/1-.

74                    END IF
75                  END IF
76                  IF(AAC(ICHECK).GT.RAC(ICHECK))THEN
77                    FA(ICHECK)=FA(ICHECK)+FINC
78                  ELSE
79                    FA(ICHECK)=FA(ICHECK)-FINC
80                  END IF
81                  IF(IOGOOD.EQ.18)THEN
82                    DO 45 IOP=1,18
83                    WRITE(7,42) FA(IOP),AAC(IOP),RAC(IOP)
84               42   FORMAT(3F8.5)
85               45   CONTINUE
86                    RMS=SQRT(SUMSQ*2.0*FSLIP)
87                    PRINT*,RMS
88                    STOP
89                  END IF
90               50 CONTINUE
91              100 CONTINUE
92                  DO 55 ICE=1,18
93                  WRITE(7,52) FA(ICE),AAC(ICE),RAC(ICE)
94               52 FORMAT(F8.5,2F8.2)
95               55 CONTINUE
96                  RMS=SQRT(SUMSQ*2.0*FSLIP)
97                  PRINT*,RMS
98                  STOP
99                  END

 1  ANSI       ERROR IN  GUESS


      FUNCTION RUNGE      73/73   OPT=0                          FTN 5.1+552        8-/12/1-.

1                 REALFUNCTIONRUNGE(Y,T,N,PI,RES,XIND,FSLIP,VPEAK,TRAT,SLIP)
2                 RUNGE=(((VPEAK*SIN((100.0*PI*T)-(N*PI/3.0)))-
3                /(TRAT*SLIP*98.0*SIN(2.0*PI*FSLIP*T)))-(Y*RES))/XIND
4                 RETURN
5                 END


      FUNCTION RQC        73/73   OPT=0                          FTN 5.1+552        8-/12/1-.

1                 REAL FUNCTION RQC(FAM1,FAM,FSLIP,PI,APEAK)
2                 X1=(-1/(2.0*PI*FSLIP))*COS(2.0*PI*FSLIP*FAM1)
3                 X2=(-1/(2.0*PI*FSLIP))*COS(2.0*PI*FSLIP*FAM)
4                 RQC=(APEAK*(X1-X2))/(FAM1-FAM)
5                 RETURN
6                 END


      FUNCTION VOLTS      73/73   OPT=0                          FTN 5.1+552        8-/12/1-.

1                 REAL FUNCTION VOLTS(T,N,PI,VPEAK)
2                 VOLTS=VPEAK*SIN((100.0*PI*T)-(N*PI/3.0))
3                 RETURN
4                 END
```

Fig A 2.5 continued