A NEW TWO-SPEED CAPACITOR MOTOR

A dissertation submitted in partial fulfilment
of the requirements for the degree of
MASTER OF ENGINEERING
in
ELECTRICAL MACHINE DESIGN

By

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C E R T I F I C A T E

CERTIFIED that the dissertation entitled "A New Two-Speed Capacitor Motor" which is being submitted by Sri RAJENDRA KUMAR in partial fulfilment for the award of the Degree of Master of Engineering in Electrical Machine Design of University of Roorkee is a record of student's own work carried out by him under my supervision and guidance. The matter embodied in this dissertation has not been submitted for the award of any other Degree or Diploma.

This is further to certify that he has worked for a period of eight months from 1.6.1962 to 31.1.1963 for preparing dissertation for Master of Engineering Degree at the University.

Signature.....

Designation of
the Supervisor.

Dated: 25.2.1967.

Seal

ACKNOWLEDGEMENTS

My sincere thanks are due to Dr. C.S.Jha, Professor and Head of Electrical Engineering Department, Indian Institute of Technology, New Delhi (formerly Reader in Electrical Engineering, University of Roorkee, Roorkee). Under whose kind and able guidance this work was carried out. But for his constant and keen supervision, valuable and helpful suggestions, and unreserved encouragement, this work would not have been a success.

I shall be failing in my duty if I do not record my gratefulness to Prof. C.S.Ghosh, Professor and Head of Electrical Engineering Department, University of Roorkee, Roorkee, for his help in providing the necessary facilities to carry out the experimental work.

Rajendra Kumar

SUMMARY

In the present dissertation the development and operation of a new two-speed single-phase capacitor motor is discussed. Although the most common form of the primary winding for a single-phase induction motor is the asymmetrical 90° - winding, for ratings of 3 to 10 H.P., a standard three-phase winding is gaining favour. If the single-phase induction motor is fitted with a standard three-phase winding, the motor can be operated with suitable switching arrangements at two different speeds, the ratio of the two speeds being 3:1.

The principle of operation of this two-speed motor is the utilization of the third-harmonic torque to give stable operation at one-third speed. The third harmonic field becomes quite significant in certain winding connections and the magnitude of torque developed becomes comparable to the fundamental torque.

Detailed analysis is carried out for the operation of the machine at both the speeds. Generalized rotating field theory, developed by Jha and Brown[17] and based on the extension of the counter-rotating field theory, is used to analyse the performance of the machine.

The new two-speed capacitor motor is an extremely simple machine. It uses standard three-phase induction motor winding with suitable capacitors and requires only a simple switch for changing the speed from one value to the other. Only six terminals are required, the number being the same as in machines with star-delta starters.

RESULTS OF EXPERIMENTAL VERIFICATION.

Test results on two machines, one a standard three-phase machine

operated from single-phase supply and another with slightly modified winding arrangement, show satisfactory behaviour in operation at both the normal and the one-third speed. The present study includes a discussion on the design of such machines and of the switching arrangement.

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CONTENTS

(NOTE - Detailed contents are given at the beginning of every Section).

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CHAPTER-1

INTRODUCTION

1. INTRODUCTION

The squirrel-cage induction motor continues to be the most popular form of alternating current drives. The main reasons for its popularity are its essentially simple but rugged mechanical construction and its requirement of little or no maintenance. However all induction motor drives, whether polyphase or single-phase suffer from the basic defect of being constant speed drives, i.e., the speed of the drives is non-adjustable in operation. Several methods of speed control of poly-phase induction motors have been suggested from time-to-time and with a little modification they are also applicable to single-phase machines.

The suggested methods can be classified in two major categories (i) those giving continuous speed variation and (ii) those giving two or more discrete speeds. In the first category are included the well-established methods of using variable voltage source, variable frequency source and unbalanced voltage source and the recently developed phase-mixing and phase-spreading techniques. In the second category fall the following:

i) Use of windings with different pole-numbers on the stator for operation at different speeds.

ii) Use of the Alexanderson connection for 2:1 operation.

iii) Use of the zero-sequence connection for 3:1 operation.

iv) Use of the pole-amplitude modulation techniques.

The methods indicated in (i) and (ii) above have been in common use for a long period and require little comment, while those in (iii) and (iv) have gained only recent entry in the commercial field in the three-phase motor version and their modified single-phase versions have still to be developed. The scope of the investigation described in the present dissertation is limited to the development of a self-starting single-phase motor capable of operation at two discrete speeds in the ratio 3:1.

Brown and Butler[6] had discussed the zero-sequence operation of poly-phase induction motor and an extension of this work led to the development of a 3:1 pole-changing motor by Barton and Butler,[20] and Rawcliffe and Jayvant.[21] It is possible to operate satisfactorily a poly-phase motor from a single-phase supply[3,4,18] using a static phase convertor and it has been shown that the best form of the convertor is a pure capacitor and hence the capacitor motor proves in practice to be the most satisfactory single-phase induction motor. If a three-phase motor is used from a single-phase supply with a capacitor convertor, it is possible to obtain 3:1 speed operation by getting the higher speed through normal operation and the lower speed through zero-sequence arrangement of the phase-windings.

Jha[18] has shown in a recent paper that single-phase operation of two-phase motors with asymmetrical windings not in quadrature leads under certain conditions to the production of large third harmonic torques and consequent large dips in the torque-speed characteristics at one-third speed. This phenomenon could be exploited to make the machine run at two discrete speeds in the ratio 3:1.

The present dissertation examines in detail both the above methods of speed control i.e. the zero-sequence connection method and the asymmetrical non-quadrature stator winding connection method and discusses their relative merits. Test results show that the latter method is more satisfactory. A comprehensive theory of this type of two-speed capacitor motor is developed using the generalized rotating-field theory of Brown and Jha[16]. Basic considerations for the design of this type of machine have also been indicated. Test results obtained on two different types of motors show satisfactory behaviour in operation at both the speeds.

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CHAPTER-2

SINGLE-PHASE OPERATION OF POLY-PHASE SQUIRREL-CAGE INDUCTION MOTORS

2.1 OPERATION OF A THREE-PHASE INDUCTION MOTOR FROM SINGLE-PHASE SUPPLY WITH AN EXTERNAL STATIC PHASE CONVERTOR.

2.1.1 General

The most common form of the primary winding for single-phase motors in the lower horse-power ranges is the asymmetrical 90^{o} - winding but for ratings 3 to 10 H.P. range there appears to be an increasing tendency to use a standard three-phase winding. The three-phase voltages, not necessarily balanced, are derived from the single-phase supply with the help of a static phase convertor.

The problems in this aspect are those of selecting suitable components of the static phase convertor to give the best performance with respect to : 1. Locked-rotor torque and current; 2. break-down torque; 3. current balance in normal operation and 4. operating efficiency.

2.1.2 Analysis of Performance

2.1.2.1 General

Figs.2.11(a) and 2.11(b) represent, together with their inspection equations, the primary windings in star and delta connections of a three-phase induction motor connected to the single-phase supply with an external static phase-convertor of admittance Y, in circuit. These equations can be solved in terms of symmetrical components and the complete performance of a given machine with any of the possible values of Y can be synthesized[1]. Because of interchangability of the parameters from star to delta or delta to star connected circuits, only one connection can be considered. And here the star-connected winding will be considered.

2.1.2.2 Starting Performance

In reference (3) of bibliography a more complete analysis of the starting performance is derived. But in the present discussion the attention will be confined only to the most important factors relating to the starting performance.

It can be shown that the ratio of the starting torque, T, to the starting torque under balanced three-phase conditions, T_b, is given by the following expression:-

$$\frac{T}{T_b} = \frac{2\sqrt{3}y \operatorname{Sin}\alpha}{9 + 4y^2 + 12y \operatorname{Cos}\alpha} \qquad (2.1.1)$$

where $y = |Y_s/Y|$, Y_s is the admittance of the machine at stand still, $\alpha = \beta - \phi$, and β and ϕ are arguments of Y and Y_s respectively

It may be noted that this equation contains only the two dimensionless parameters y and , and it is therefore possible to deduce results which are applicable to any induction motor with any form of phase convertor. It can be shown that for a given value of α, the torque ratio is a maximum when $y = 3/2$ and for a given value of y the torque ratio is a maximum according to a value of $\alpha = \text{arc Cos}\left[-12y/(9 + 4y^2)\right]$; and further that when $y = 3/2$, the maximum torque ratio exceeds unity when $\alpha > 147.8^\circ$. The variations in the value of ratio T/T_b with the variations in the values of y and α are shown in Figs.2.12(a) and 2.12(b).

The unbalance factor, which is defined as the ratio of the negative-sequence current to the positive-sequence current, at stand-still is given by

$$U = \left[\frac{3 + y^2 + 2\ 3y \operatorname{Cos}(\alpha + 30)}{3 + y^2 + 2\ 3y \operatorname{Cos}(\alpha - 30)}\right]^{1/2} \qquad (2.1.2)$$

And for the fixed value of o the unbalance factor is a minimum when $y = \sqrt{3}$, and for a fixed value of y, when $\alpha = \arccos\left[-3y/(3+y^2)\right]$ with an absolute minimum of zero when $y = \sqrt{3}$ and $\alpha = 150^\circ$.

2.1.2.3 Run-up Performance.

In theory, torque/speed curves could be calculated for any form of phase convertor from the equivalent circuits for positive-and negative-sequence operation. A general procedure is to determine the torque/speed curves for positive- and negative-sequence operation for a fixed voltage and to use this as a basis for theoretical calculations

The torque/speed curves with different values of y are given in Fig.2.13.

In giving an operating rating to a motor, heating must be considered in addition to ratio of pull out torques. It was found that the total stator losses had not increased by a large amount; the large increase in losses appears in the rotor, as even a slight unbalance in voltage sets up a considerable negative-sequence field which generates double-frequency currents in the rotor, with high losses.

2.1.3 Conclusions.

The best performance is obtained when the starting and running conditions approach those of balanced three-phase operation. The study has also indicated that it is difficult to produce completely balanced terminal voltages with the help of a simple static phase convertor at all loads, so there must be a derating of the three-phase motor when operated in such a way.

2.2 THE ZERO-SEQUENCE OPERATION OF THREE-PHASE INDUCTION MOTORS.

2.2.1 General

It was generally accepted that zero-sequence operation of three-phase induction motor fails to produce a torque[7,8,9], till Kamon[10] and Brown and Butler[6] showed that this need not be so. Though, under the zero-sequence operation no starting torque is developed, but if the motor once comes to the speed, it will continue to run at a speed slightly less than one-third of the synchronous speed and can also take some load at this speed.

2.2.2 The Equivalent Circuit

Fig.2.21 represents the primary windings of a three-phase induction motor connected to the single-phase supply for zero-sequence operation. It may be shown (see section 7.1) that when a balanced three-phase winding carries, zero-sequence sinusoidal current, of frequency f, the n^{th} harmonic m.m.f. at a point x electrical degrees along the periphery of the armature from the axis of any phase winding, at any instant of time t, is

$$F_{nx} = K_n F_n' (1 + 2 \cos 2n\pi/3) \cos(nx + 2n\pi/3) \cos \omega t \quad (2.2.1)$$

where K_n = n^{th} harmonic winding factor of each phase, when each phase winding is distributed,

F_n' = Amplitude of the n^{th} harmonic m.m.f. of each phase when each phase winding is considered to be of the non-distributed and full pitch form,

$\omega = 2\pi f$, angular velocity.

It can be seen that F_{nx} is zero for all values of n, except n = 3 and multiples of 3. Thus, the m.m.f. waveform, due to the currents of zero-sequence, produces a magnetic field in space which has three times the number of poles for which the machine is actually wound. The resultant field is stationary in space and pulsates at the fundamental frequency f. The pulsating field may be resolved into two components which rotate in opposite directions at a synchronous speed equal to one-third of that for normal three-phase operation.

The equivalent circuit of the machine, for zero-sequence operation is as shown in Fig.2.22. The switch P is introduced to consider the effect of the physical arrangement of the primary winding.

If S be the fractional slip of the secondary winding with respect to the normal forward rotating field, rotating at the synchronous speed of the motor, then the slip of the secondary winding with respect to forward rotating field, rotating at one-third of normal synchronous speed, is given by,

$$S'' = \frac{N_s/3 - N}{N_s/3}$$

$$= -2 + 3S \qquad (2.2.2)$$

and the slip of secondary winding with respect to the backward rotating field, is given by

$$S''' = \frac{-N_s/3 - N}{-N_s/3}$$

$$= 4 - 3S \qquad (2.2.3a)$$

$$\text{also } S''' = 2 - S'' \qquad (2.2.3b)$$

2.2.3 Performance Characteristics

The variations of current, power and torque throughout the speed range may be predicted by determining the machine parameters, as discussed by Brown and Buttler[6], for known values of fractional slip S''.

If $R_o + jX_o$ is the impedance of the motor per phase then, the current per phase,

$$I_o = \frac{V_o}{\sqrt{R_o^2 + X_o^2}} \qquad (2.2.4)$$

Power per phase P_o will be given by

$$P_o = I_o^2 R_o \qquad (2.2.5)$$

The torque per phase in synchronous watts referred to the zero-sequence synchronous speed is given by

$$T_o = P_f - P_b \qquad (2.2.6)$$

$$= (R_{2f}/S'')\, I_f^2 - (R_{2b}/2 - S'')\, I_b^2 \qquad (2.2.7)$$

If the different parameters are known then the complete performance of the machine can be predicted on the basis of above equations.

On the basis of the tests made by Brown and Buttler[6] some useful results are summarised below.

On the assumption that saturation may be neglected, on the basis of the full line voltage applied to the terminals in two cases i.e. the zero-sequence operation and balanced three-phase operation, the line current was approximately the same for the same slip but the outputs in two cases were in ratio of 1:9. However, utilizing control of supply frequency to reduce the speed of the squirrel-cage motor to one-third of the synchronous speed with the same slip, with positive sequence operation, the ratio of the outputs reduces to 1:3.

It is possible that for those applications where a speed reduction of 67% is required occasionally the cost of a fairly simple switching arrangement for changing to zero-sequence operation is preferable to the expense and space requirement of a frequency convertor, despite the consequent reduction in available output to approximately 33%.

2.2.4 Conclusions

Zero-sequence operation of a three-phase squirrel-cage induction motor provides characteristics some what similar to those of a single-phase motor having three times the number of poles.

The torque/speed characteristic being of particular interest where a speed reduction of 67% is occasionally required. The zero-sequence effect can be eliminated, or accentuated, by special design.

2.3 SINGLE-PHASE OPERATION OF TWO-PHASE INDUCTION MOTORS HAVING STATOR WINDINGS NOT IN QUADRATURE.

2.3.1 General

In most two-phase induction motors the stator has a main and an auxiliary winding which are in space quadrature. In practice design limitations imposed by the number of slots and poles are such that often it is not possible to have the stator windings in exact quadrature. It has been shown[18] that all other relevant factors being equal, it is possible to obtain higher starting torques by non-quadrature windings.

Several attempts have been made to analyse the operation of the machine. All authors with the notable exception of Jha[18], have based their analysis on a consideration of only the fundamental components of the magnetic fields and have ignored the effects of space harmonics. Jha has included the effect of space harmonics by using his "Generalized rotating-field theory",[16] which is based on an extension of the counter-rotating field theory of the single - phase induction motors.

2.3.2 Analysis of Performance

2.3.2.1 General

Fig.2.31, represents, together with the inspection equations, a two-phase induction motor connected to a single-phase supply of voltage V with a static impedance Z in circuit. Where m and a represent respectively the main and the auxiliary stator windings. The auxiliary has k times as many turns as the main winding and is displaced by an electrical angle $\theta°$ from it. These equations can be solved in terms of generalized rotating field parameters[16], and the complete performance of a given machine can be synthesized.[18,16] The equivalent circuit of the induction motor is as shown in Fig.2.32, it is assumed here that the iron losses can be estimated separately and added to the other power requirements of the motor.

2.3.2.2 Calculation of Torque

The torque in synchronous watts can be obtained by finding the difference of the power inputs to the forward and backward fields. Remembering that the synchronous speed for the n^{th} harmonic field is $1/n^{th}$ that of the fundamental.

2.3.2.3 Starting Performance

For between 60° and 120°, it has been shown[18] that the ratio of the starting torque, T_θ , to the starting torque under balanced two-phase conditions, T_b, due to the n^{th} harmonic field is approximately given by

$$\left[\frac{T_\theta}{T_b}\right]_n = \frac{ky(\sin\alpha + kx\sin\overline{\gamma-\alpha})}{y^2 + k^4 + 2k^2 y\cos\alpha} \cdot \frac{\sin n\theta}{\sin(n\ \ /2)} \qquad (2.3.1)$$

where $y = \left|\frac{Z}{Z_s}\right|$

$$x = \left|\frac{2\Sigma\ Z_{ns}\cos n\theta}{Z_s}\right| \qquad (2.3.2)$$

$$\alpha = \beta - \phi,\ \gamma = \phi_x - \phi$$

and $(-\phi)$, $(-\phi_x)$ and $(-\beta)$ are the arguments of Z_s, $\Sigma Z_{ns}\cos n\theta$ and Z respectively and Z_s and Z_{ns} are the standstill values of Z_{11} and Z_{nf}.

It can be shown from this equation that for given values of k, x, and γ , the torque is maximum when $y = k^2$.

Also the approximate ratio of the main winding current $I_{m\theta}$ to its value when the windings are in quadrature is given by

$$\left|\frac{I_{m\theta}}{I_{m90^{o}}}\right| \simeq \left[1 - \frac{2kx\,(k^{2}\,\mathrm{Cos}\,\gamma + y\,\mathrm{Cos}\,\overline{\gamma-\alpha}\,)}{y^{2} + k^{4} + 2k^{2}y\,\mathrm{Cos}\,\alpha}\right]^{1/2} \qquad (2.3.3)$$

And the ratio of the auxiliary winding currents is given by

$$\left|\frac{I_{a\theta}}{I_{a90^{o}}}\right| \simeq (1 - 2kx\,\mathrm{Cos}\,\gamma\,)^{1/2} \qquad (2.3.4)$$

The above ratios have been obtained by neglecting the higher powers of x.

2.3.3 Harmonics in Squirrel - Cage Motors

2.3.3.1 General

A squirrel-cage winding reacts strongly to fields of all pole numbers. This makes all squirrel-cage induction motors very susceptible to the harmonics of the air gap field. Of all the harmonics present, the ones which have the most noticeable effect on the motor performance are the phase-belt harmonics of the order (2m ± 1) and the stator slot harmonics of the order (2s ± 1), where m and s are the number of phases and stator slots per pole respectively. The lower order harmonics affect the starting and the run-up performance of the motor, where as the slot harmonics are instrumental in the production of stray load losses.

In balanced poly-phase operation, the harmonic of the order (2m - 1) rotates backwards while that of the order (2m + 1) rotates forwards with respect to the fundamental. The backward rotating harmonic produces an almost uniform negative torque over the entire speed range of the motor and hence creates no run-up problem, provided that the fundamental torque is of the adequate magnitude. The forward rotating harmonics, however, develops a torque which changes sign at the synchronous speed of the harmonic thus creating a dip in the motor torque/speed curve. Since this dip is responsible for the 'crawling' of the motor, it is standard practice in the design of the stator winding either to eliminate the $(2m + 1)^{th}$ harmonic completely or to reduce its amplitude to as small a value as practicable.

One harmonic field which is rarely taken into consideration in the design of stator winding for poly-phase induction motors is the third. In three-phase machines, though the individual phases may produce large third harmonic components of m.m.f., the resultant air-gap field has no third harmonic component for all forms of balanced operation and those unbalanced forms in which the stator windings are connected in star with the star point remaining isolated In two-phase machines on the other hand, though the third harmonic is present in the resultant m.m.f. wave, it rotates backwards for all forms of balanced operation and hence does not affect the run-up performance of the motor to any significant degree.

When a poly-phase motor is operating under unbalanced condition, however, all the harmonic fields present in the air-gap have both forward and backward components. The third harmonic forward field, if present, assumes great importance in such modes of operation and may cause serious run-up trouble unless its amplitude is very small compared with that of the fundamental. In Fig.2.33 curves (a) and (b) show two torque/speed curves obtained by test[18] on the same squirrel-cage motor but with two different stator windings. In both cases the applied voltage was adjusted to give the same fundamental flux, but the amplitude of the third harmonic m.m.f. was about 20%

that of the fundamental in case (a) and zero in case (b). The two curves illustrate admirably the importance of keeping the third harmonic m.m.f. as low as possible in all cases of single phase operation.

2.3.3.2 Effect of Displacement Angle on Run-up Performance.

When both the main and auxiliary windings are carrying current, the amplitudes of the various harmonic fields in the resultant m.m.f. wave become functions of the displacement angle θ. Its effect on the run-up performance is not very easy to estimate quantitatively. It is, however, quite obvious that the dip in the torque/speed curve at $1/n^{th}$ synchronous speed caused by the reversal of torque due to the forward component of the n^{th} harmonic field can be eliminated if

$$|I_m| = k\,|I_a| \qquad (2.3.5)$$

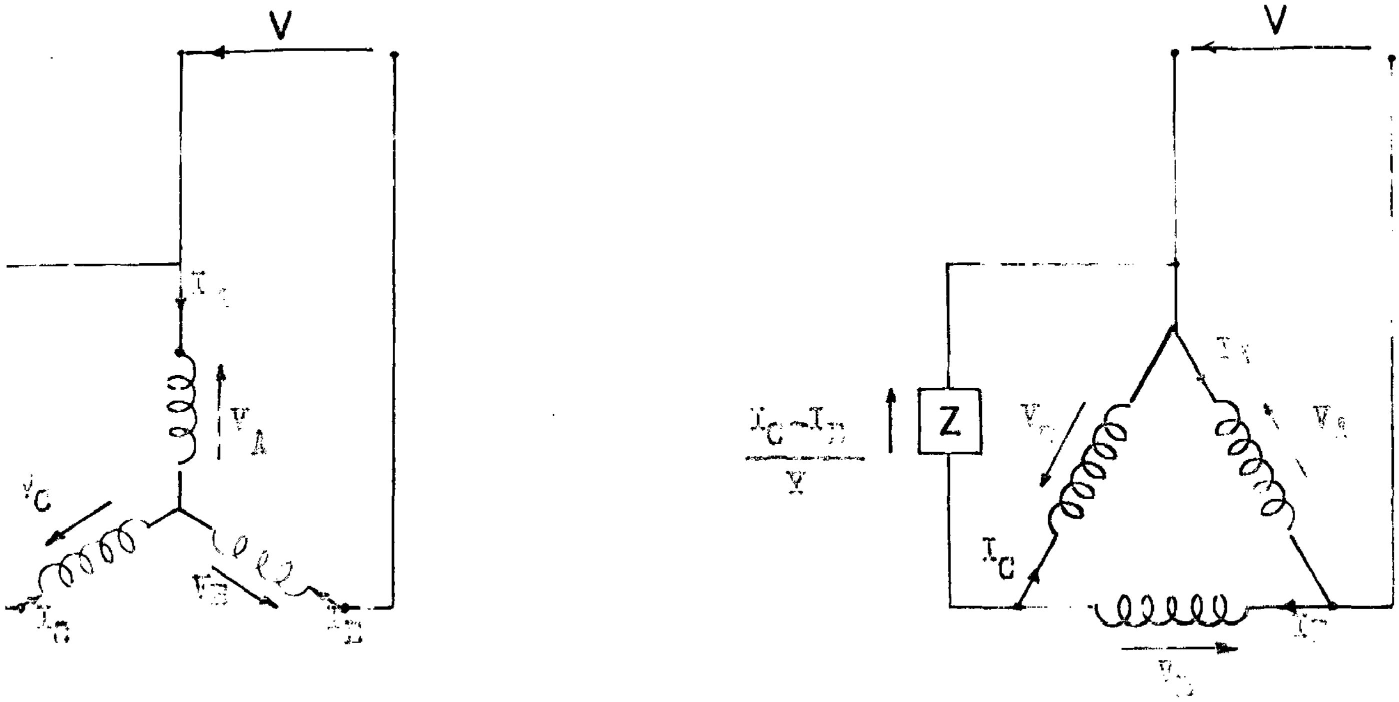
$$\text{and } \psi - n\theta = b\pi \qquad (2.3.6)$$

where b is any odd integer.

It was found[18] for a particular machine that a capacitance of 25 uf according to equation nos.(2.3.5 & 2.3.6), should show no third harmonic dip in the torque/speed curve when the θ was 100°. Curves for different values of capacitance are shown in Fig.2.34, with the same capacitor in circuit the torque/speed characteristics of the machine for four different values of displacement angle θ (60°, 80°, 100° and 120°) were obtained, these are shown in Fig.2.35

2.3.4 Conclusions

The use of the generalized rotating field theory has resulted in the satisfactory analysis of the two-phase motors. It has been shown[18] that, for normal squirrel-cage motors, about 20% more fundamental torque can be obtained by making the displacement angle other than 90°. If present, the most important harmonic field, from run-up point of view, is the forward component of the third.



[illegible] EQUATIONS

$I_A + I_B + I_C = 0$

$V_A + V_B = 0$

$V_A - V_C - I_C/Y = 0$

(a)

[illegible] EQUATIONS

$V_A + V_B + V_C = 0$

$V_A - V = 0$

$V_C + (I_C - I_D)/Y = 0$

(b)

.2·11: PRIMARY WINDINGS OF A THREE PHASE INDUCTION MOTOR CONNECT TO A SINGLE PHASE SUPPLY WITH AN EXTERNAL PHASE CONVENTER CIRCUIT.

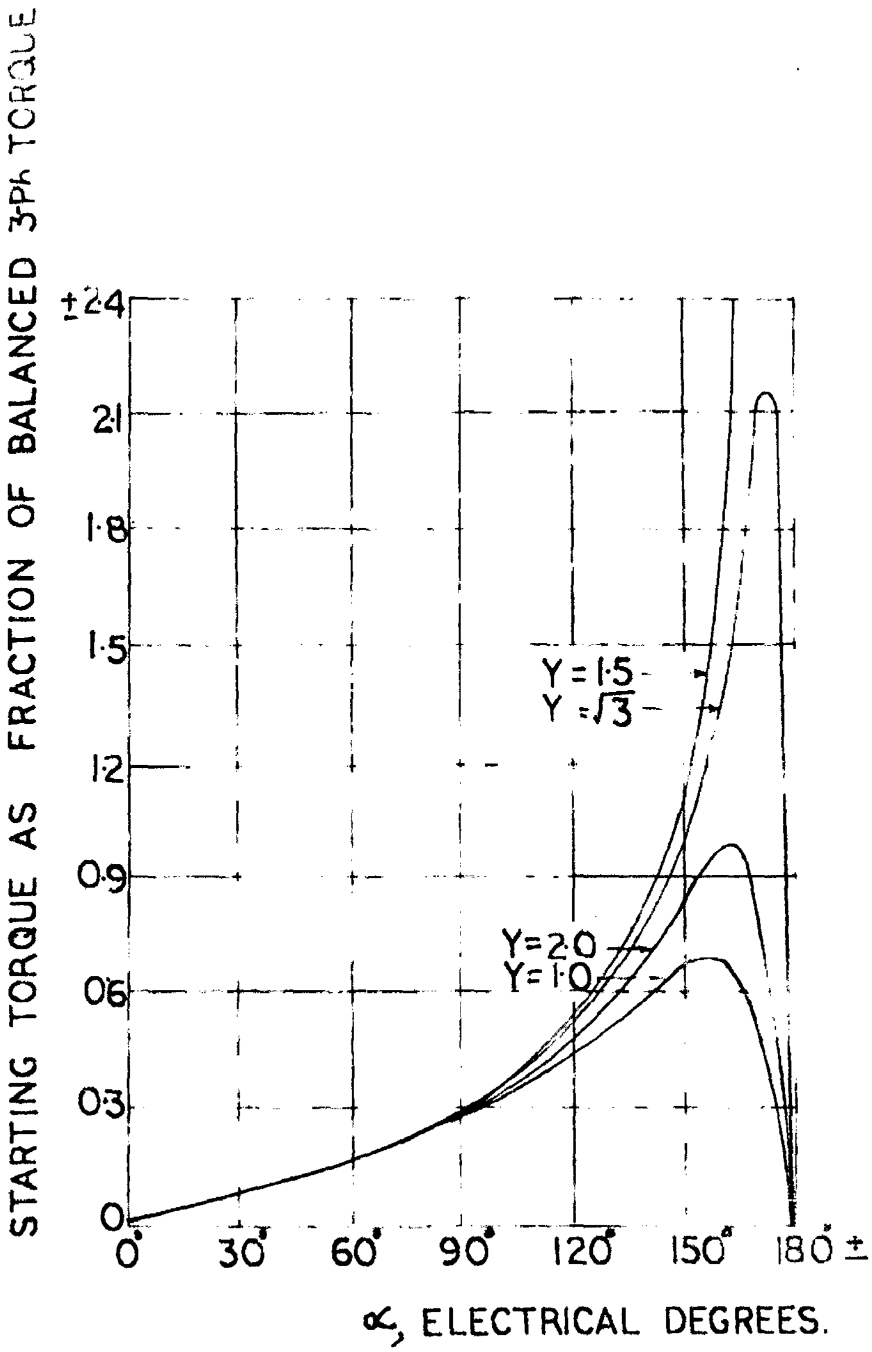


FIG. 2.12a VARIATION OF STARTING TORQUE WITH α.

(Negative torques are associated with negative values of α)

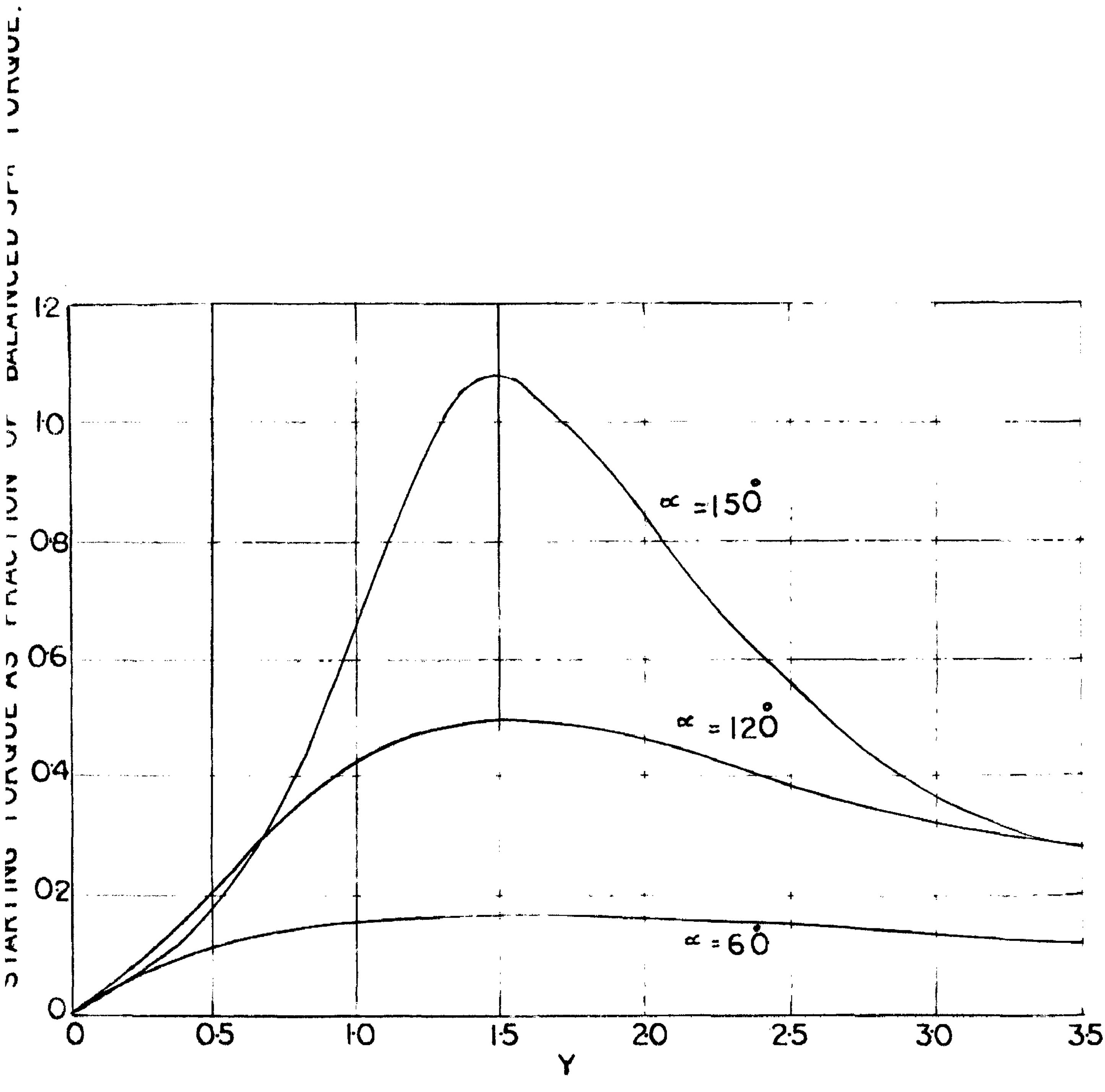


FIG. 2·12(b) VARIATION OF STARTING TORQUE WITH Y.

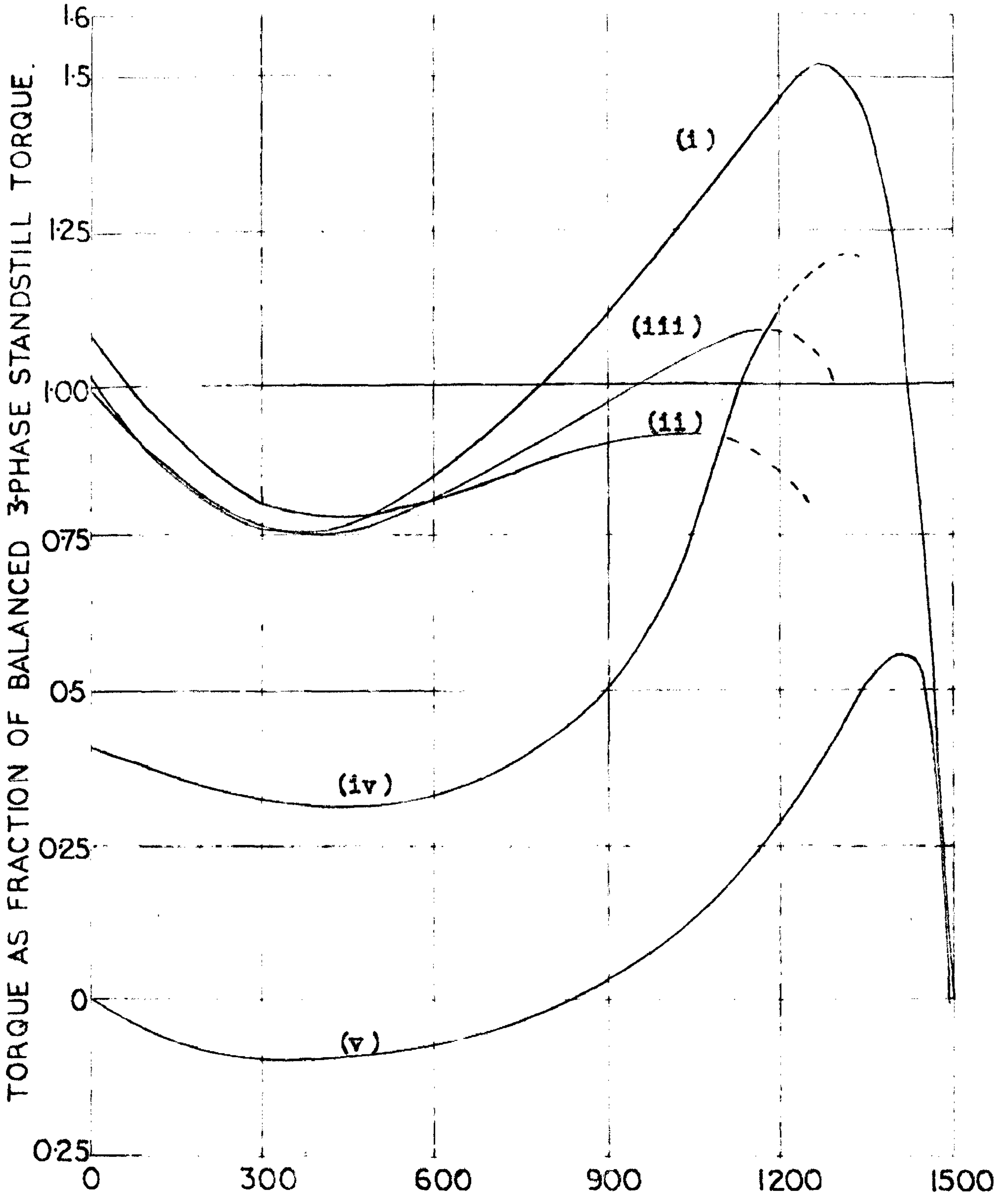


FIG. 213 VARIATION OF TORQUE WITH SPEED WITH DIFFERENT VALU OF Y.

Curve (i) Balanced 3-phase operation.

(ii) Single-phase operation with capacitor, y=1.5

(iii) Single-phase operation with capacitor, y= 3

(iv) Single-phase operation with capacitor, y=3.0

(v) Single-phase operation with capacitor, y= ∞

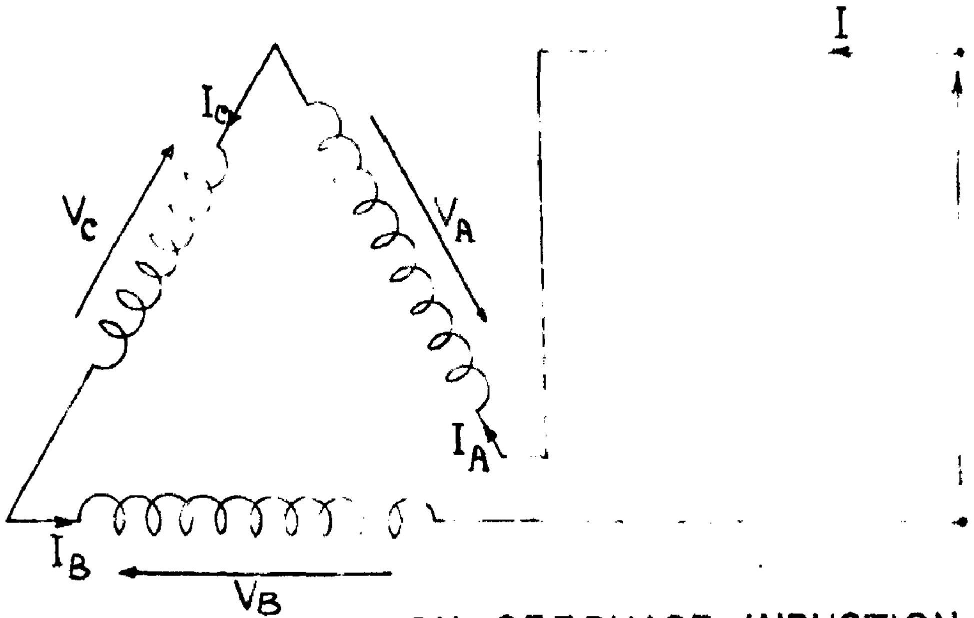


FIG. 2·21 ZERO-SEQUENCE OPERATION OF 3-PHASE INDUCTION MOTOI

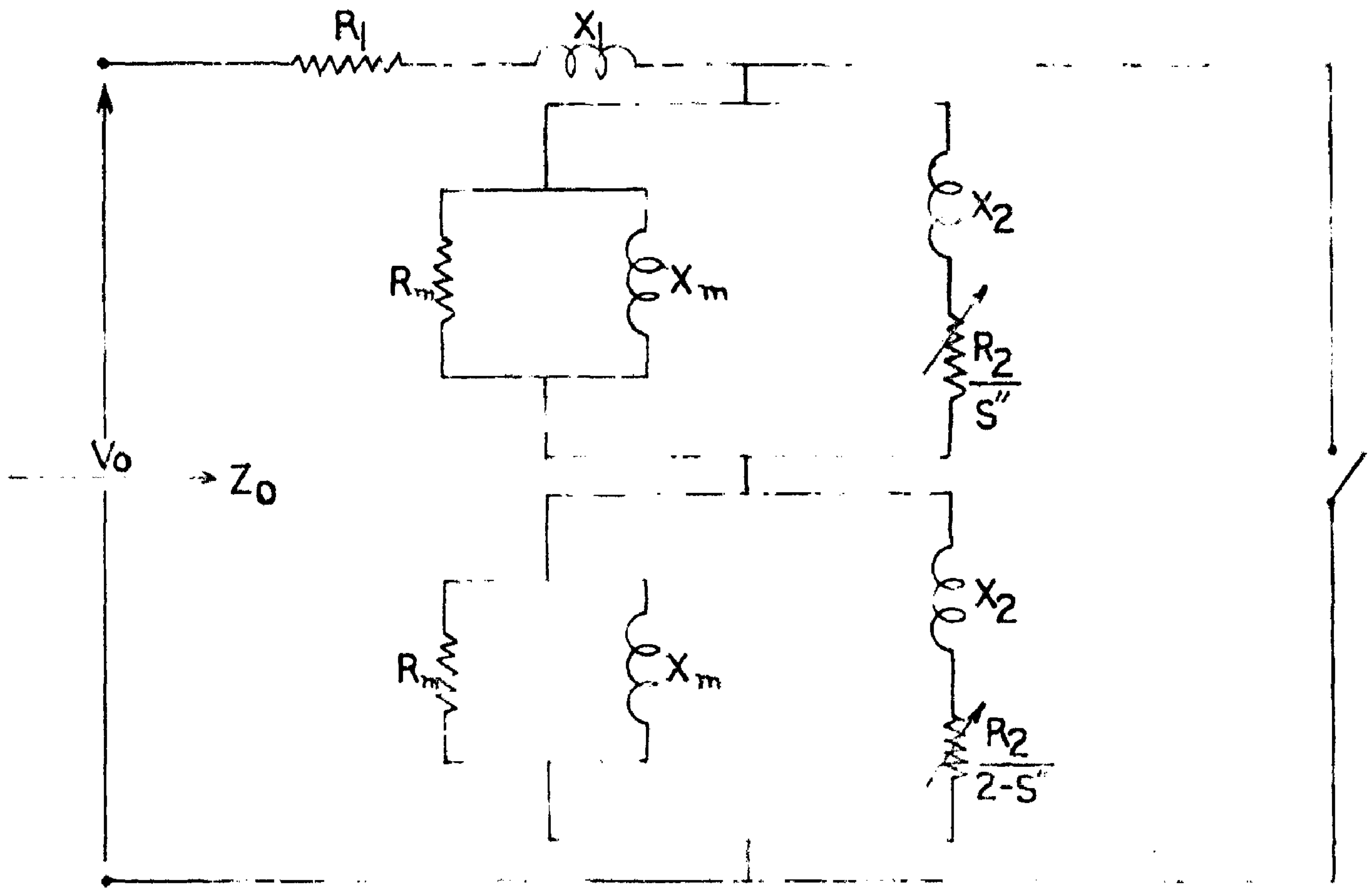
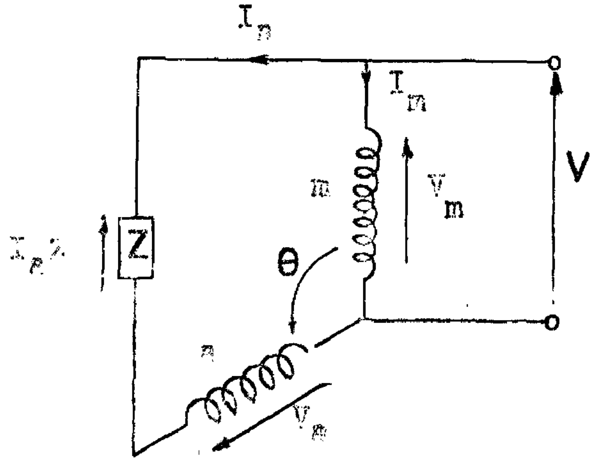


FIG. 2·22 EQUIVALENT CIRCUIT 3-PHASE INDUCTION MOTOR WITH ZERO-SEQUENCE OPERATION

(Switch P is closed when primary windings have coil span of 2/3 of a pole pitch)



INJECTION EQUATIONS

$$V - V_m = 0$$

$$V - V_a - I_a Z = 0$$

FIG. 2·31: STATOR WINDINGS OF A TWO-PHASE INDUCTION MOTOR CONNECTED TO A SINGLE-PHASE SPPLY WITH A STATIC IMPEDANCE Z IN CIRCUIT.

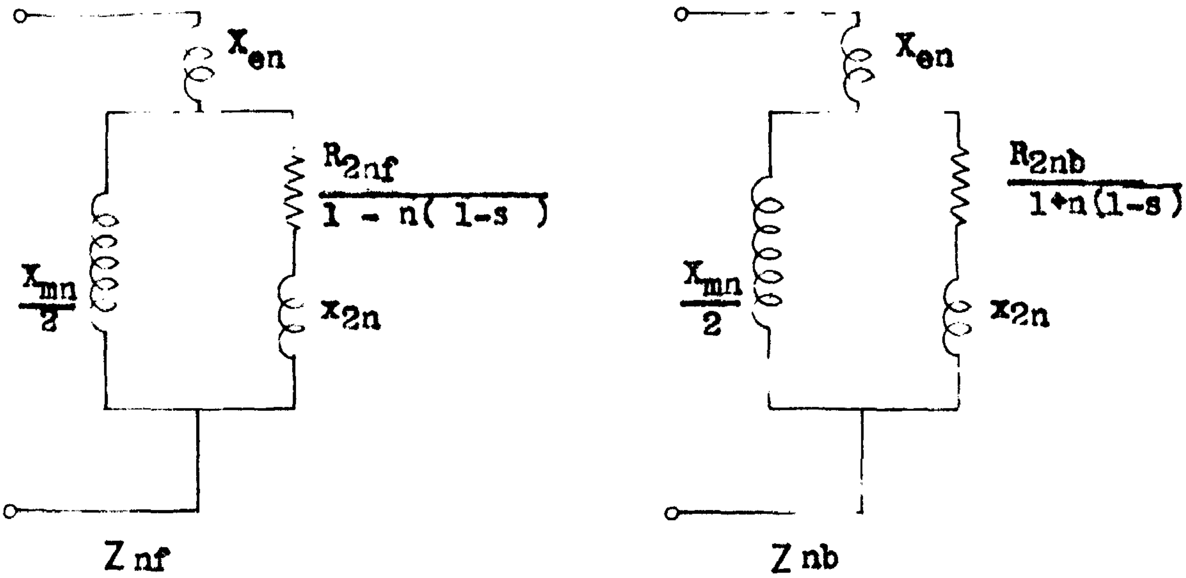


FIG. 2·32 CIRCUITS REPRESENTING THE IMPEDANCE OF THE MAIN WINDI[NG] TO THE n^{th} HARMONIC FORWARD & BACKWARD FIELDS.

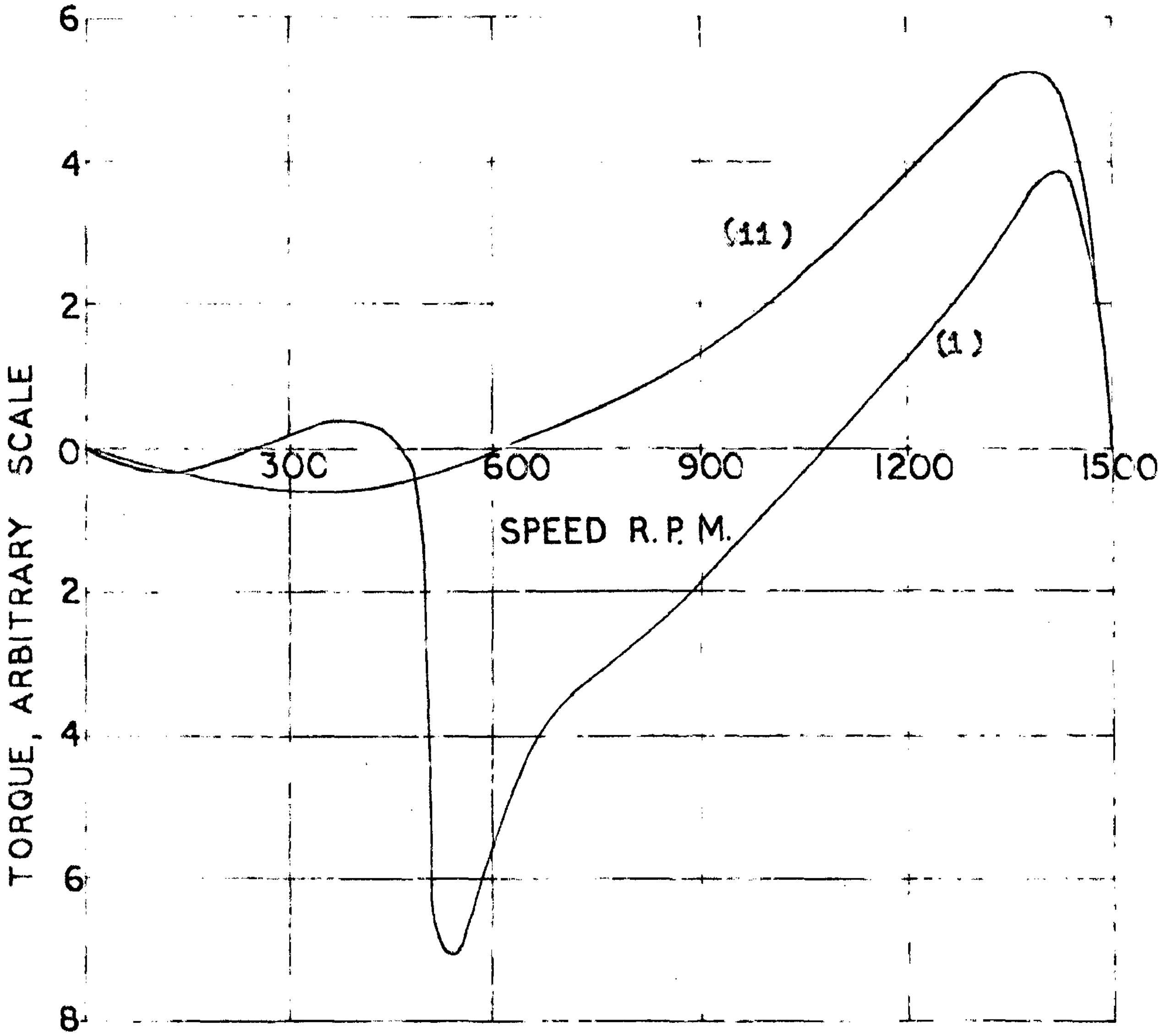


FIG. 2·33 TORQUE-SPEED CURVES FOR THE INDUCTION MOTOR.

Curve (i) For 60° spread, single-phase operation.

(ii) For 120° spread, single-phase operation.

(Two-phase squirrel-cage Induction motor).

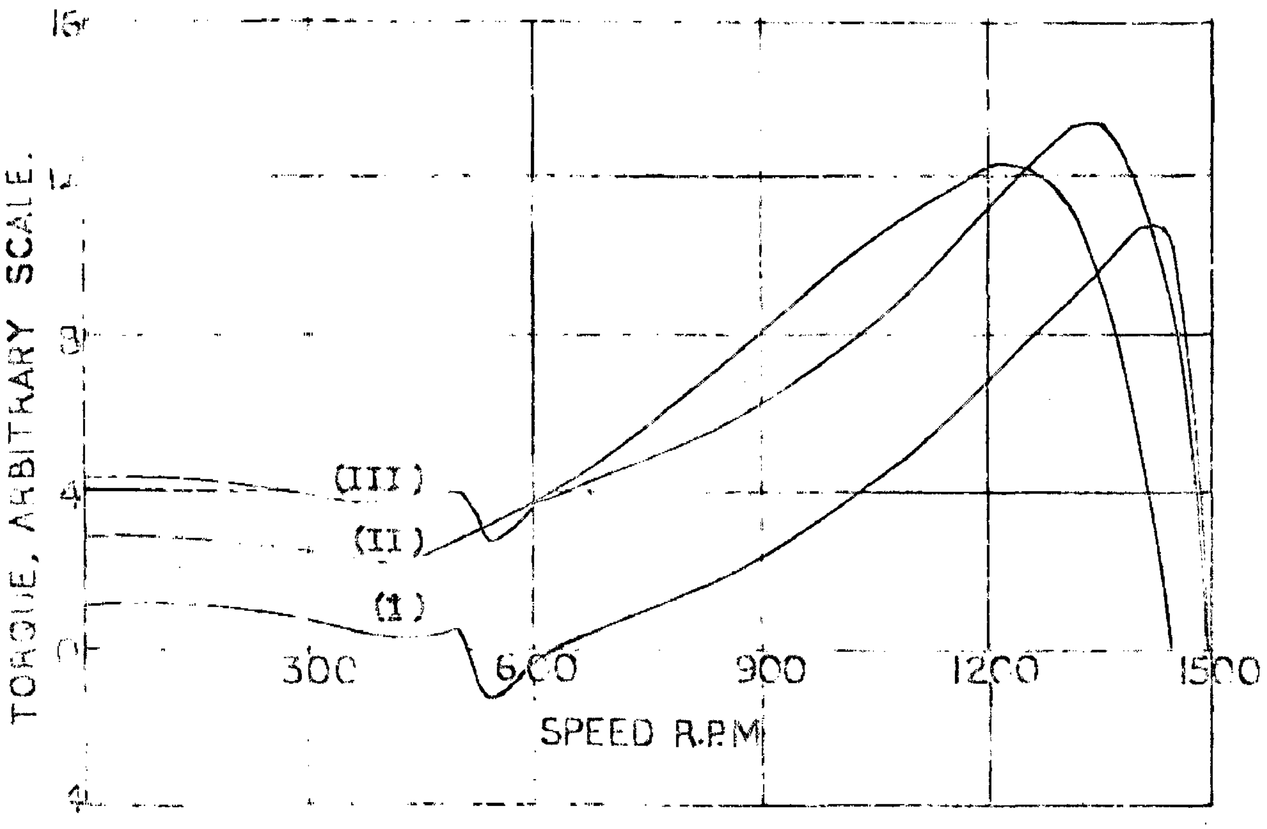


FIG. 2·34 TORQUE-SPEED CURVES FOR THE INDUCTION MOTOR WHEN THE DISPLACEMENT ANGLE $\theta = 100^{\circ}$.

Curve (I) With a 15 µf capacitor in circuit.

(II) With a 25 µf capacitor in circuit.

(III) With a 35 µf capacitor in circuit.

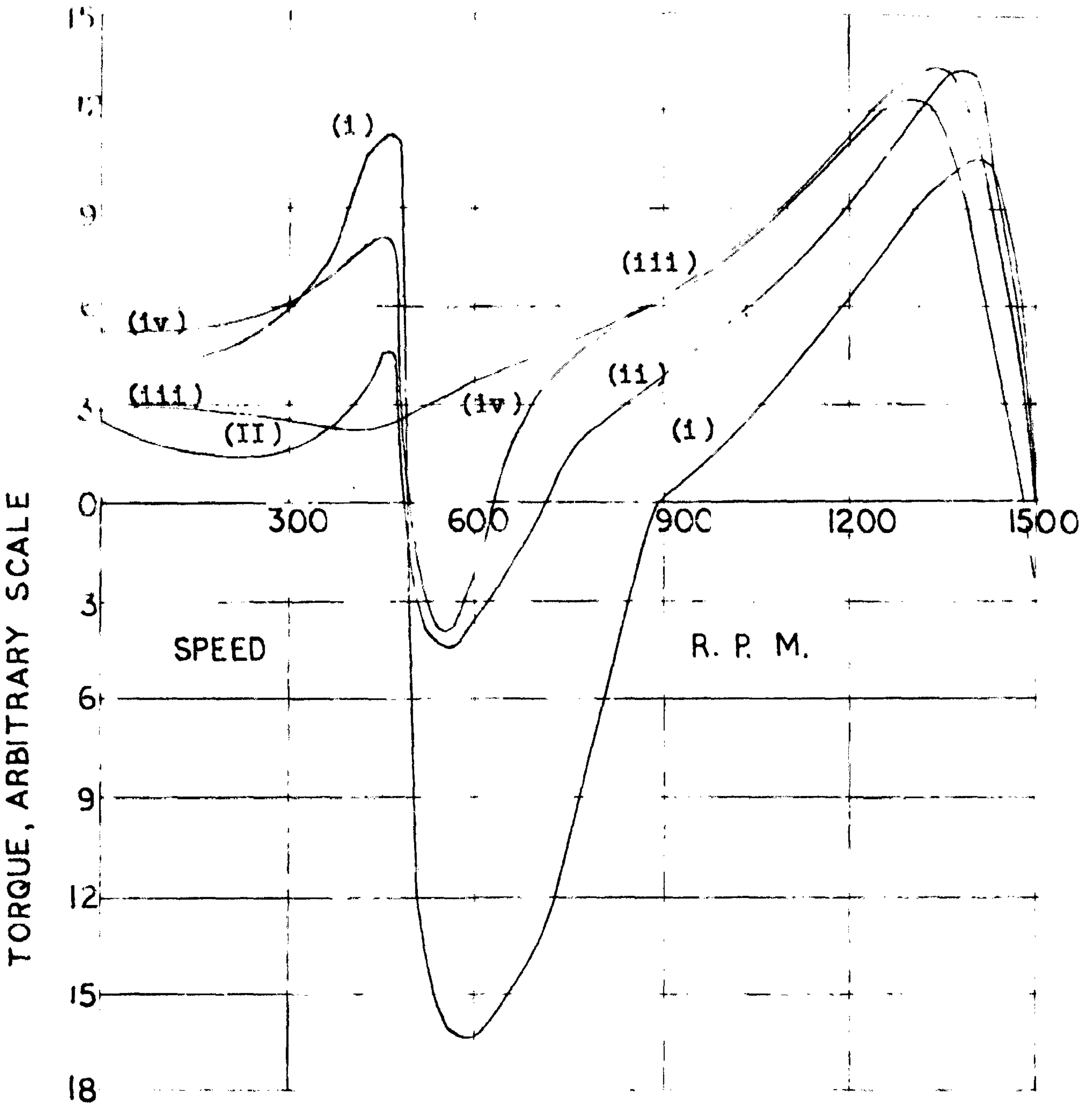


FIG. 2·35 TORQUE-SPEED CURVES FOR THE INDUCTION MOTOR OBTAINED WITH A 25 μF CAPACITOR.

Curve (i) for θ=60°, (ii) for θ=80°, (iii) for θ=100°, (iv) for θ=120°.

CHAPTER-3

THEORY OF A NEW TWO-SPEED CAPACITOR MOTOR

3. THEORY OF A NEW TWO-SPEED CAPACITOR MOTOR

3.1 General

It has been well established[3,4] (as discussed in detail in Section 2) that a three-phase induction motor can be operated satisfactorily from a single-phase supply. Several stator winding connections are possible for such operation and are shown in Figs.3.1 (a,b,c,d,e,f, and g). Out of these Figs.3.1 (a & b) represent respectively the star and delta connections, Figs.3.1 (c,d & e) represent respectively the 120°, 60° and equivalent 90° connections, and the Fig.3.1 (f) represents the single winding connection while the Fig.3.1 (g) represents the zero-sequence operation.

The operation of the motor with these connection arrangements has been discussed in previous sections. Some of the points of particular interest are summarised below:

(a) Operation with connections of Figs.3.1 (f & g) suffers from the disadvantage of non-availability of the starting torque and is inferior in this respect to that with other connections.

(b) The single winding connection has a small third harmonic torque and has maximum positive torque near the synchronous speed due to the fundamental component.

(c) The zero phase sequence has a torque/speed characteristic similar to a single-phase induction motor having three times the number of poles.

(d) When the windings are connected with winding axes either 60° or 120° (electrical) apart the higher starting torque can be achieved but the third harmonic components are sufficient to affect the running performance of the motor. And in certain cases the third harmonic torque is sufficient to hold the motor stable at one-third of the synchronous speed due to the fundamental component. The amplitude of the third harmonic torque can be increased or decreased by selecting suitable values of the external capacitor. (See Fig.2.34 and equation No.2.3.5 and 2.3.6).

From the foregoing discussion a very important conclusion can be drawn that when a three-phase motor, with different winding arrangements, is connected to single-phase supply the motor runs either at a speed corresponding to the fundamental component or at a speed corresponding to the third harmonic field. This leads to a possibility that the same three-phase motor can be used as a two-speed single-phase motor. One speed being the same as the normal operating speed of the motor and other the one-third of the normal speed.

For the operation of the motor at one-third of the normal speed the stator winding should not have a pitch of $(2/3)\pi$ electrical radians or a winding spread of $(2/3)\pi$ electrical radians. Because a pitch of $(2/3)\pi$ electrical radians gives a pitch factor of zero and a spread of $(2/3)\pi$ electrical radians gives a distribution factor of zero for third harmonic field. Further the single winding connection Fig.3.1(f) and zero-phase sequence Fig.3.1(g) connections cannot be used in practice due to the non-availability of starting torque in those connections. The single winding connection also suffers from poor running performance due to poor stator space utilization.

Out of the remaining three types of connections Figs.3.1(c,d,e) virtually anyone can be chosen for the one-third speed operation.

But the third harmonic torque is maximum when the displacement angle is 60°. Also the third harmonic component currents will be maximum if the stator winding spread is $\pi/3$ electrical radians.

For the normal or full speed operation the stator windings may be connected in any way except the zero-sequence operation connections Because at zero sequence operation the stable torque is obtained only at one-third speed. Out of the other connections all except star and delta will show a tendency of crawling at one-third speed. The third harmonic component in case of 60° & 120° displacement angle connections can be suppressed only at the expense of the starting torque[18], which is undesirable. Third harmonic component can also be suppressed in case of equivalent 90° connections, by selecting the proper external impedance[18]. But the same impedance may not be able to give sufficient starting torque and satisfactory full speed running characteristics. Thus necessitating atleast three values of external impedance and turning the operation of the motor into a complicated system. It may be noted that the maximum fundamental torque is obtained when the windings are connected in star or delta. It is therefore obvious that the best arrangement would be to use either a star or delta connected winding for the full speed operation which is free of third harmonic crawling, requiring only two capacitors, one for starting and other for running.

Hence one can conclude that proper winding connections would permit a satisfactory operation of a three-phase machine from single phase supply not only near synchronous speed but also near one-third synchronous speed.

3.2 Application of the Generalized Rotating Field Theory.

The generalized rotating field theory can be used to analyse the performance of the motor. Each of the forward and backward rotating components of the n^{th} harmonic stator m.m.f. wave of the single-phase winding induces its own component rotor currents and produces induction motor action with n times the fundamental number of poles. When the rotor windings are on open circuit, the forward and backward rotating fluxes due to any harmonic field must each be equal to half the corresponding alternating flux. The reaction of the short-circuited rotor to these counter rotating fluxes is well known from induction motor theory. The resulting equivalent circuit for a one-winding induction motor is as shown in Fig.3.2. The constituent circuits for all the forward and backward rotating fields in this figure have been connected in series since the m.m.f. responsible for their production is supplied in cases by the same stator phase current.

The circuit as drawn neglects the iron losses in the machine. The iron losses can be calculated separately and added to the other power requirements of the machine.

If Z_{fn} and Z_{bn} represent the self-impedance of the winding due respectively to the forward and the backward rotating components of the n^{th} harmonic field. ΣZ_{fn} and ΣZ_{bn} may then be written to represent the sum of the impedances due respectively to all the forward-rotating and all the backward-rotating harmonics fields. The total self-impedance of the stator phase winding is then given by

$$Z_{phase} = r + jx + \Sigma Z_{fn} + \Sigma Z_{bn} \qquad (3.1)$$

where r and x are respectively the resistance and leakage reactance of the stator winding. The voltage equations for the machine with three-phase stator windings are therefore

$$\begin{aligned} V_a = {} & I_a(z_a + \Sigma Z_{fn} + \Sigma Z_{bn}) + k_b\, I_b(\Sigma\alpha^{-2n} Z_{fn} + \Sigma\alpha^{+2n} Z_{bn}) \\ & + k_c\, I_c\, (\Sigma\alpha^{-n} Z_{fn} + \Sigma\alpha^{n} Z_{bn}) \\ V_b = {} & k_b\, I_a(\Sigma\alpha^{2n} Z_{fn} + \Sigma\alpha^{-2n} Z_{bn}) + I_b(z_b + \Sigma Z_{fn} + \Sigma Z_{bn}) \\ & + (k_b/k_c)\, I_c(\Sigma\alpha^{n} Z_{fn} + \Sigma\alpha^{-n} Z_{bn}) \\ V_c = {} & I_a\, k_c(\Sigma\alpha^{n} Z_{fn} + \Sigma\alpha^{-n} Z_{bn}) + (k_c/k_b)\, I_b\, (\Sigma\alpha^{-n} Z_{fn} + \Sigma\alpha^{n} Z_{bn}) \\ & + I_c(z_c + \Sigma Z_{fn} + \Sigma Z_{bn}) \end{aligned}$$ (3.

where $z_a = r_a + jx_a$, $z_b = r_b + jx_b$, $z_c = r_c + jx_c$

and $k_b = \dfrac{(\text{No. of turns in b winding})}{(\text{No. of turns in a winding})}$

$k_c = \dfrac{(\text{No. of turns in c winding})}{(\text{No. of turns in a winding})}$

The performance of the machine can be easily calculated if the parameters of the equivalent circuit of Fig.3.2 are known.

3.3 Analysis of Performance at Full Speed

3.3.1 General Equations

Figs.3.1(a and b) represent respectively the primary windings of a star and delta connected three-phase induction motor connected to a single-phase supply with an external static phase convertor of impedance Z, in circuit. Because there is a normal relationship[3] between a star and delta connected balanced system. So, for the present purpose, it is only necessary to consider one of the connections, and in what follows attention is confined to the star-connected system. Inspection equations[1] for this circuit obtained by the application of Kirchhoff's laws, are as follows:

$$I_A + I_B + I_C = 0 \qquad (3.3)$$

$$V - V_A + V_B = 0 \qquad (3.4)$$

$$V_A - V_C - I_C Z = 0 \qquad (3.5)$$

These equations can be solved in terms of generalized rotating field theory parameters. (See section 3.2). By utilising the substitutions

$$\left.\begin{aligned} V_A &= I_A Z_{11} + I_B Z_{12} + I_C Z_{13} \\ V_B &= I_A Z_{13} + I_B Z_{11} + I_C Z_{12} \\ V_C &= I_A Z_{12} + I_B Z_{13} + I_C Z_{11} \end{aligned}\right\} \qquad (3.6)$$

equation (3.6) is obtained from equation (3.2) by substituting

$$\left.\begin{aligned} z_a + \Sigma Z_{fn} + \Sigma Z_{bn} &= Z_{11} \\ \Sigma \alpha^{-2n} Z_{fn} + \Sigma \alpha^{2n} Z_{bn} &= Z_{12} \\ \Sigma \alpha^{-n} Z_{fn} + \Sigma \alpha^{n} Z_{bn} &= Z_{13} \end{aligned}\right\} \qquad (3.7)$$

As the stator has a symmetrical three-phase winding,

$$z_a = z_b = z_c$$

$$\text{and} \quad k_b = k_c = 1 \qquad (3.8)$$

$$\alpha = e^{j2\pi/3}$$

It can easily be shown that the solutions of the equations (3.3), (3.4) and (3.5) are given by the following:

$$I_A = V \frac{Z+Z_{11}+Z_{12}-2Z_{13}}{(Z_{11}+Z_{12}-2Z_{13})(Z+Z_{11}+Z_{12}-2Z_{13})+(Z+2Z_{11}-Z_{12}-Z_{13})(Z_{11}-2Z_{12}+Z_{13})} \qquad \ldots \quad \ldots \quad (3.9)$$

$$I_B = -V \frac{Z+2Z_{11}-Z_{12}-Z_{13}}{(Z_{11}+Z_{12}-2Z_{13})(Z+Z_{11}+Z_{12}-2Z_{13})+(Z+2Z_{11}-Z_{12}-Z_{13})(Z_{11}-2Z_{12}+Z_{13})} \qquad \ldots \quad \ldots \quad (3.10)$$

$$I_C = V \frac{Z_{11}-2Z_{12}+Z_{13}}{(Z_{11}+Z_{12}-2Z_{13})(Z+Z_{11}+Z_{12}-2Z_{13})+(Z+2Z_{11}-Z_{12}-Z_{13})(Z_{11}-2Z_{12}+Z_{13})}$$

... ... (3.11)

These equations give the generalised solutions for currents in the three windings of the symmetrical stator of a three-phase induction motor having a symmetrical rotor and connected to a single phase supply. These include the effect of space harmonics.

3.3.2 Calculation of Torque

The torque in synchronous watts can be obtained by finding the difference of the power inputs to the forward and backward fields. Remembering that the synchronous speed for the n^{th} harmonic field is $1/n^{th}$ that of the fundamental, the torque due to the n^{th} harmonic field is given in synchronous watts by

$$\begin{aligned} T_{fn} = \text{Re} \Big[& (I_A Z_{fn} + I_B \alpha^{n} Z_{fn} + I_C \alpha^{-n} Z_{fn}) I_A^{\circ} + \\ & (I_A \alpha^{-n} Z_{fn} + I_B Z_{fn} + I_C \alpha^{n} Z_{fn}) I_B^{\circ} + \\ & (I_A \alpha^{n} Z_{fn} + I_B \alpha^{-n} Z_{fn} + I_C Z_{fn}) I_C^{\circ} \Big] n \end{aligned} \quad (3.12)$$

where I_A°, I_B° and I_C° are the complex conjugates of I_A, I_B and I_C, and Re stands for "Real part of". If R_{fn} is the real part of the forward impedance Z_{fn}, the above equation reduces to

$$T_{fn} = n \left(\left| I_A + I_B \alpha^{n} + I_C \alpha^{-n} \right| \right)^2 R_{fn} \quad (3.13)$$

Similarly, the torque due to the n^{th} harmonic backward field is given by

$$T_{bn} = n \left(\left| I_A + I_B \alpha^{-n} + I_C \alpha^{n} \right| \right)^2 R_{bn} \quad (3.14)$$

where R_{bn} is the real part of the backward field impedance Z_{bn}. The net forward torque in synchronous watts is therefore,

$$T_n = n\left(\left|I_A + I_B\alpha^{n} + I_C\alpha^{-n}\right|\right)^2 R_{fn} - n\left(\left|I_A + I_B\alpha^{-n} + I_C\alpha^{n}\right|\right)^2 R_{bn} \qquad \ldots \quad \ldots \quad (3.15)$$

Equation (3.15) is generalised equation for the torque due to any harmonic field of order n.

3.3.3 Starting Performance

3.3.3.1 Performance Equations at Standstill

At starting the impedance to the forward and backward fields are equal, i.e. $Z_{fn} = Z_{bn}$. If Z_{so} and Z_{sn} represent the standstill values of Z_1 and Z_{fn}, the equations for starting performance reduce from equations (3.9), (3.10), & (3.11) to

$$I_A = V\frac{Z + Z_{so} - 2\Sigma Z_{sn}\cos n\theta}{(Z_{so} - 2\Sigma Z_{sn}\cos n\theta)(2Z + 3Z_{so} - 6\Sigma Z_{sn}\cos n\theta)} \qquad \ldots \quad \ldots \quad (3.16)$$

$$I_B = -V\frac{Z + 2Z_{so} - 4\Sigma Z_{sn}\cos n\theta}{(Z_{so} - 2\Sigma Z_{sn}\cos n\theta)(2Z + 3Z_{so} - 6\Sigma Z_{sn}\cos n\theta)} \qquad \ldots \quad \ldots \quad (3.17)$$

$$I_C = V\frac{Z_{so} - 2\Sigma Z_{sn}\cos n\theta}{(Z_{so} - 2\Sigma Z_{sn}\cos n\theta)(2Z + 3Z_{so} - 6\Sigma Z_{sn}\cos n\theta)} \qquad \ldots \quad \ldots \quad (3.18)$$

As the stator has a symmetrical three-phase winding, and is connected either in star or delta, so all the even harmonics will be absent together with the third and its multiple. So the value of

$$Z_{so} = z_a + 2Z_{s1} + 2Z_{s5} + 2Z_{s7} + \ldots \qquad (3.19)$$

also $$2\Sigma Z_{sn}\cos n\theta = -(Z_{s1} + Z_{s5} + Z_{s7} + \ldots) \qquad (3.20)$$

and hence $$Z_{so} - 2\Sigma Z_{sn}\cos n\theta = z_a + 3(Z_{s1} + Z_{s5} + \ldots) \qquad (3.21)$$

Equation (3.21) is the same as for Z_s for symmetrical component impedance[16] at standstill,

or $Z_{so} - 2\Sigma Z_{on} \cos n\theta = Z_s$ (3.21b)

Substituting the equation (3.21b) in equations (3.16), (3.17) and (3.18) and expressing the three phase currents in terms of corresponding balanced three-phase current, $|I_b| = |V| / \sqrt{3}\, |Z_s|$. Thus

$$\left|\frac{I_A}{I_b}\right| = \left[\frac{3 + 3y^2 + 6y \cos \alpha}{9 + 4y^2 + 12y \cos \alpha}\right]^{1/2} \qquad (3.22)$$

$$\left|\frac{I_B}{I_b}\right| = \left[\frac{12 + 3y^2 + 12y \cos \alpha}{9 + 4y^2 + 12y \cos \alpha}\right]^{1/2} \qquad (3.23)$$

and

$$\left|\frac{I_C}{I_b}\right| = \left[\frac{3}{9 + 4y^2 + 12y \cos \alpha}\right]^{1/2} \qquad (3.24)$$

where $y = |Z/Z_s|$, $\alpha = \beta - \phi$ and $(-\beta)$ and $(-\phi)$ are the arguments of Z and Z_s. All the three equations are equal to unity for a value of $y = \sqrt{3}$ and $\alpha = 150^\circ$.

3.3.3.2 Starting Torque

From equation (3.15) the starting torque follows by substituting $R_{fn} = R_{bn}$,

$$T = 4(|I_A|\,|I_B| \sin \psi_1 + |I_B|\,|I_C| \sin \psi_2 + |I_C|\,|I_A| \sin \psi_3) \times (\Sigma n \sin n\theta \; R_{fn}) \qquad (3.25)$$

where $\psi_1 = \phi_A - \phi_B$, $\psi_2 = \phi_B - \phi_C$ and $\psi_3 = \phi_C - \phi_A$ and ϕ_A, ϕ_B and ϕ_C are the arguments of I_A, I_B and I_C.

It can be shown that the ratio of the starting torque, T, to the starting torque under balanced three-phase conditions, T_b, is given by the equation

$$\frac{T}{T_b} = \frac{2\sqrt{3}y \sin \alpha}{9 + 4y^2 + 12y \cos \alpha} \qquad (3.26)$$

3.3.3.3 Unbalance Factor

Unbalance factor is the ratio of the backward current (negative-sequence current) to the forward current (positive-sequence current). Thus the unbalance factor U is given by

$$U = \frac{\left| I_A + I_B\alpha^{n} + I_C\alpha^{-n} \right|}{\left| I_A + I_B\alpha^{-n} + I_C\alpha^{n} \right|} \qquad (3.27)$$

Substituting the values of I_A, I_B and I_C from equations (3.16),(3.17) and (3.18) and expressing U in terms of parameters y and α,

$$U = \left[\frac{3 + y^2 + 2\sqrt{3}y \operatorname{Cos}(\alpha + 30^\circ)}{3 + y^2 + 2\sqrt{3}y \operatorname{Cos}(\alpha - 30^\circ)} \right]^{1/2} \qquad (3.28)$$

3.3.3.4 Measures of Starting Quality

The accepted measures of the "starting-quality" are starting torque per amper of supply current, and starting torque per amper squared of supply current. A better criterion, which takes account of the heating effect due to all three phase currents, is the starting torque per watt of stator copper loss. The ratio of the starting torque per watt of stator copper loss under unbalanced and balanced conditions is given by

$$Q = \frac{T/(\,|I_A|^2 + |I_B|^2 + |I_C|^2\,)\,R}{T_b/(3\,|I_H|^2\,)\,R}$$

$$= \frac{\sqrt{3}y \operatorname{Sin}\alpha}{3 + y^2 + 3y \operatorname{Cos}\alpha} \qquad (3.29)$$

It can be shown that Q is maximum when $y = \sqrt{3}$ and $\alpha = \text{arc Cos}\left[- 3y/(3 + y^2)\right]$ for fixed values of α and y respectively. It may be noted that the conditions for the proposed quality to be a maximum are same as those for perfect balance.

3.3.3.5 Voltage Across the Phase Convertor

The voltage across the phase convertor will be

$$V_Z = I_C Z \tag{3.30}$$

substituting the value of I_C from equation (3.18) and taking the ratio of this voltage to supply voltage

$$\left|\frac{V_Z}{V}\right| = \frac{y}{(9 + 4y^2 + 12y \cos\alpha)^{\frac{1}{2}}} \tag{3.31}$$

The ratio is maximum when $y = \left[-3/(2 \cos\alpha)\right]$. At the condition of perfect balance i.e. $y = \sqrt{3}$ and $\alpha = 150^\circ$ the ratio is equal to unity. And thus the voltage for the phase convertor is same as the supply voltage. For other values of y and α the voltage can be calculated from equation (3.31).

3.3.4 Run-up Performance

In theory, torque/speed and other characteristic curves for the machine can be calculated from the equivalent circuits. The generalized equivalent circuit is as given in Fig.3.2. As the machine is symmetrical and connected either in star or delta so all the even and triplan harmonics will be absent.

If the circuit of Fig.3.2 is splited into two circuits, one for all the positively rotating fields and other for all the negativel rotating fields. Then the two circuits will be as shown in Fig.3.3. It is assumed that the synchronous and rotor speeds of the machine are N_s and N r.p.m., respectively, and the direction of rotation of the rotor is always regarded as being positive.

3.3.4.1 Performance Equations

If the total impedances of positively rotating fields, and negatively rotating fields are Z_1 and Z_2 respectively then

$$\left.\begin{aligned} Z_1 &= z + 3\,(Z_{1f} + Z_{5b} + Z_{7f} + \ldots\ldots) \\ Z_2 &= z + 3\,(Z_{1b} + Z_{5f} + Z_{7b} + \ldots\ldots) \end{aligned}\right\} \qquad (3.32)$$

with these values of Z_1 and Z_2 the equations (3.9), (3.10) and (3.11) for three-phase currents reduce to

$$I_A = V \frac{Z + Z_1 e^{j\pi/3} + Z_2 e^{-j\pi/3}}{3Z_1Z_2 + Z_1Z + Z_2Z} \qquad (3.33)$$

$$I_B = -V \frac{Z + Z_1 + Z_2}{3Z_1Z_2 + Z_1Z + Z_2Z} \qquad (3.34)$$

$$I_C = V \frac{Z_1 e^{-j\pi/3} + Z_2 e^{j\pi/3}}{3Z_1Z_2 + Z_1Z + Z_2Z} \qquad (3.35)$$

Also it can be very easily shown that the positive-sequence and negative-sequence currents, I_1 and I_2 are given by the following:

$$I_1 = \frac{Ve^{-j\pi/6}}{\sqrt{3}} \left(\frac{Z + 3Z_2 e^{-j\pi/6}}{3Z_1Z_2 + Z_1Z + Z_2Z} \right) \qquad (3.36)$$

$$\text{and} \quad I_2 = \frac{Ve^{j\pi/6}}{\sqrt{3}} \left(\frac{Z + 3Z_1 e^{j\pi/6}}{3Z_1Z_2 + Z_1Z + Z_2Z} \right) \qquad (3.37)$$

3.3.4.2 Torque Equation

The torque developed by the machine can be calculated at any speed for any value of the external impedance with the help of the equations given from (3.12) to (3.15).

When expressed in terms of the starting torque under balanced three-phase conditions, T_{bs}, the torque ratio for the net forward torque is given by

$$\frac{T}{T_{bs}} = \frac{\{y_1^2+3+2\sqrt{3}y_1 \cos(\alpha_1-30)\} R_f/R_b - \{y_1^2+3y_2^2+2\sqrt{3}y_1y_2 \cos(\alpha_2-\alpha_1-30\ldots}{y_1^2+9y_2^2+y_1^2y_2^2+6y_1y_2^2 \cos\alpha_1+6y_1y_2 \cos(\alpha_1-\alpha_2)+2y_1^2y_2 \cos\alpha\ldots}$$

... ... (3.38)

$$\left.\begin{array}{ll} \text{where } y_1 = |Z/Z_2| , & y_2 = |Z_1/Z_2| \\ \alpha_1 = \beta - \phi_2 , & \alpha_2 = \phi_1 - \phi_2 \end{array}\right\} \quad (3.39)$$

and $(-\beta)$, $(-\phi_1)$, and $(-\phi_2)$ are respectively the arguments of Z, Z_1 and Z_2.

The above equation for the torque ratio is in terms of dimensionless parameters. For most of the induction motors the value of Z_2 at any speed differs very little from the standstill value Z_s (see Fig.3.4). It is therefore justifiable to assume that $y_1 = y$ and $\alpha_1 = \alpha$. And the equation (3.38) for the torque ratio can accordingly be modified.

The performance of the machine can be calculated from the equivalent circuit and the torque equation. In practice, the effects of harmonics and stray load losses are such that values of torque calculated on this basis differ considerably from those actually developed by the machine. A compromise procedure is to determine the torque/speed curves for positive and negative-sequence operation for a fixed voltage and use this as a basis for theoretical calculations[1].

3.3.4.3 Unbalance Factor

The unbalance factor, which is defined as the ratio of the negative-sequence current to the positive-sequence current is given b

$$U_r = \frac{y_1^2 + 3y_2^2 + 2\sqrt{3}y_1y_2 \cos(\alpha_2 - \alpha_1 - 30)}{y_1^2 + 3 + 2\sqrt{3}y_1 \cos(\alpha_1 - 30)} \quad (3.40)$$

In practice the effect of variation of the various parameters can be calculated by the above equation.

3.3.4.4 Voltage Across the Phase Convertor

The voltage across the phase convertor is given by the equation (3.30) as $V_Z = I_C Z$.

Substitute the value of I_C from equation (3.35) and taking the ratio of the voltage across the convertor to the supply voltage,

$$\frac{V_Z}{V} = \frac{Z_1 Z e^{-j\pi/3} + Z Z_2 e^{j\pi/3}}{3 Z_1 Z_2 + Z_1 Z + Z_2 Z} \qquad (3.41)$$

It can be shown that

$$\left|\frac{V_Z}{V}\right| = \frac{y_1^2 + y_1^2 y_2^2 + 2 y_1^2 y_2 \cos(\alpha_2 + 120)}{y_1^2 + 9 y_2^2 + y_1^2 y_2^2 + 6 y_1 y_2^2 \cos\alpha_1 + 6 y_1 y_2 \cos(\alpha_1 - \alpha_2) + 2 y_1^2 y_2 \cos\alpha_2} \qquad \ldots\ \ldots\ (3.42)$$

As the value of Z_2 at any speed differs very little from the standstill value Z_s. It is therefore justifiable to assume $y_1 = y$ and $\alpha_1 = \alpha$. Also if the value of y recommended for perfect balance at standstill i.e. $y = \sqrt{3}$ and $\alpha = 150^0$, this expression reduces to

$$\left|\frac{V_Z}{V}\right| \simeq \frac{1 + y_2^2 - y_2 \cos\alpha_2 - \sqrt{3} y_2 \sin\alpha_2}{1 + y_2^2 - y_2 \cos\alpha_2 + \sqrt{3} y_2 \sin\alpha_2} \qquad (3.43)$$

This ratio is unity when $\alpha_2 = 0$, which occurs at standstill and at a speed close to the running light speed. Between these values $90^0 > \alpha_2 > 0$ the ratio is less than unity. Hence if the starting capacitor is selected for perfect balance at standstill, there is no liklihood of over voltage on the capacitor during the run-up period.

3.4 Analysis of Performance at One-Third of Full Speed

3.4.1 General Equations

As discussed previously (sec.3.1) that the stator windings in 60° connections will be used for the machine to operate at one-third speed. So the analysis here will be done for such a machine. In Fig.3.1(d), A,B and C represent respectively the three windings of the three-phase induction motor. The A and B windings of this motor are connected to single-phase supply through a external impedance Z. Though for a balance motor the turns ratio of the three windings is unity. But for the analysis of the performance a more general case will be taken i.e. when the winding B (which is auxiliary for this operation) has k times as many turns as A winding (which is main winding for this operation). Inspection equations for this circuit obtained by the application of Kirchhoff's law are

$$V - V_A = 0 \qquad (3.44)$$

$$V + V_B + I_B Z = 0 \qquad (3.45)$$

As the rotor has a symmetrical winding, generalized rotating field theory can be used. Then the

$$V_A = I_A\,(z_a + \Sigma Z_{fn} + \Sigma Z_{bn}) - kI_B\,(\Sigma \alpha_o^{-n} Z_{fn} + \Sigma \alpha_o^{n} Z_{bn}) \qquad (3.46)$$

$$V_B = -kI_A\,(\Sigma \alpha_o^{n} Z_{fn} + \Sigma \alpha_o^{-n} Z_{bn}) + I_B\,(z_b + k^2 \Sigma Z_{fn} + k^2 \Sigma Z_{bn}) \qquad (3.47)$$

where $\alpha_o = e^{j\pi/3}$, z_a and z_b are the leakage impedances of windings A and B, Z_{fn} and Z_{bn} represent the impedances of the A winding due to n^{th} harmonic forward field and the n^{th} harmonic backward field.

Equations (3.46) and (3.47) can also be written in terms of four-terminals network parameters as

$$V_A = I_A Z_{11} - I_B Z_{12} \qquad (3.48)$$

$$V_B = -I_A Z_{21} + I_B Z_{22} \qquad (3.49)$$

$$\left.\begin{aligned} \text{where}\quad Z_{11} &= (z_a + \Sigma Z_{fn} + \Sigma Z_{bn}) \\ Z_{12} &= k(\Sigma \alpha_o^{-n} Z_{fn} + \Sigma \alpha_o^{n} Z_{bn}) \\ Z_{21} &= k(\Sigma \alpha_o^{n} Z_{fn} + \Sigma \alpha_o^{-n} Z_{bn}) \\ Z_{22} &= (z_b + k^2 \Sigma Z_{fn} + k^2 \Sigma Z_{bn}) \end{aligned}\right\} \qquad (3.50)$$

The impedance parameters Z_{11}, Z_{12}, Z_{21} and Z_{22} are all functions of the speed of the rotor.

Substituting the values of V_A and V_B from equations (3.48) and (3.49) in equations (3.44) and (3.45) the currents in both the windings can be calculated. Since the B winding has k times as many turns as the A winding, it would ideally have k^2 times as much leakage impedance ($z_b = k^2 z_a$). Then Z_{22} becomes equal to $k^2 Z_{11}$, and the currents in the windings are given by:

$$I_A = V\,(Z + k^2 Z_{11} - Z_{12}) \,/\, \left[(Z + k^2 Z_{11})\, Z_{11} - Z_{12} Z_{21}\right] \qquad (3.51)$$

$$I_B = -V\,(Z_{11} - Z_{21}) \,/\, \left[(Z + k^2 Z_{11})\, Z_{11} - Z_{12} Z_{21}\right] \qquad (3.52)$$

The above equations give the generalized solutions for currents in the A and B windings of the stator. They include the effect of harmonics.

3.4.2 Calculation of Torque

The torque in synchronous watts can be obtained by finding the difference of the power inputs to the forward and the backward fields. The torque due to the n^{th} harmonic field is given in synchronous watts by

$$T_{fn} = \mathrm{Re}\left[(I_A Z_{fn} - k I_B \alpha_o^{-n} Z_{fn}) I_A^{\circ} + (-k I_A \alpha_o^{n} Z_{fn} + k^2 I_B Z_{fn}) I_B^{\circ}\right] n \qquad (3.53)$$

where I_A° and I_B° are the complex conjugates of I_A and I_B and Re stands for the "real part". If R_{fn} is the real part of the forward field impedance Z_{fn}, the above equation reduces to

$$T_{fn} = n(|I_A - kI_B\alpha_o^{-n}|)^2 R_{fn} \qquad (3.54a)$$

$$= n\left[|I_A|^2 + k^2 |I_B|^2 + 2k |I_A| |I_B| \cos(\psi - n\pi/3)\right] R_{fn} \qquad (3.54b)$$

where $\psi = \phi_B - \phi_A$, and ϕ_B and ϕ_A are the arguments of I_B and I_A. Similarly, the torque due to n^{th} harmonic backward field is given by

$$T_{bn} = n(|I_A - kI_B\alpha_o^{n}|)^2 R_{bn} \qquad (3.55a)$$

$$= n\left[|I_A|^2 + k^2 |I_B|^2 + 2k |I_A| |I_B| \cos(\psi + n\pi/3)\right] R_{bn} \qquad (3.55b)$$

where R_{bn} is the real part of the backward field impedance Z_{bn}. The net forward torque is therefore

$$T_n = n(|I_A - kI_B\alpha_o^{-n}|)^2 R_{fn} - n(|I_A - kI_B\alpha_o^{n}|)^2 R_{bn} \qquad (3.56)$$

3.4.3 Starting Performance

3.4.3.1 Performance Equations at Standstill

At starting, the impedances to the forward and backward fields are equal, i.e. $Z_{fn} = Z_{bn}$. If Z_{so} and Z_{sn} represent the standstill values of Z_{11} and Z_{fn}, the equations for starting performance reduces from equations (3.51) and (3.52) to

$$I_A = \frac{V(Z + k^2 Z_{so} - 2k\sum Z_{sn} \cos n\pi/3)}{Z_{so}(Z + k^2 Z_{so}) - 4k^2(\sum Z_{sn} \cos n\pi/3)^2} \qquad (3.57)$$

$$I_B = -\frac{V(Z_{so} - 2k\sum Z_{sn} \cos n\pi/3)}{Z_{so}(Z + k^2 Z_{so}) - 4k^2(\sum Z_{sn} \cos n\pi/3)^2} \qquad (3.58)$$

3.4.3.2 Starting Torque

At starting the equation (3.56) reduces to

$$T = 4k \, |I_A| \, |I_B| \, \sin \psi \, \Sigma R_{fn} \sin n\pi/3 \qquad (3.59)$$

where the summation is to be carried out for all the orders of harmonics present in the air gap flux wave.

It may be noted that the starting torque due to the third harmonic field is zero. When expressed in terms of the starting torque under balanced two-phase condition, T_b, the torque ratio for the torque due to the n^{th} harmonic field is given by

$$\left[\frac{T}{T_b}\right]_n = \frac{k\left[y \sin \alpha + (k^3-k)\, x \sin \gamma + kxy \sin (\gamma-\alpha)\right] \sin n\pi/3}{\left[y^2+k^4+2k^2 y \cos \alpha + k^4x^4 - 2k^2x^2 y \cos(\alpha-2\gamma) - 2k^4x^2 \cos 2\gamma\right] \sin n\pi/3} \qquad \ldots \quad \ldots \quad (3.60)$$

where

$$\left.\begin{aligned} y &= |Z/Z_{so}| \\ x &= \left|(2\Sigma Z_{sn} \cos n\pi/3)/Z_{so}\right| \\ \alpha &= \beta - \phi, \quad \gamma = \phi_x - \phi \end{aligned}\right\} \qquad (3.61)$$

and $(-\phi)$, $(-\phi_x)$ and $(-\beta)$ are the arguments of Z_{so}, $\Sigma Z_{sn} \cos n\pi/3$ and Z.

The above equation for the torque ratio is in terms of dimensionless parameters. The two parameters x and γ take account of the coupling of the magnetic fields of the two windings. The dimensionless parameter x is the effective "co-efficient of coupling" between the stator windings. Whereas the parameter γ is the lagging phase shift introduced by the coupling field. When the angle between the axes of the two stator windings is $\pi/2$ the two parameters reduce to zero. Also for the angle to be $\pi/3$ the value of x never exceeds 0.3 and is usually much less. The terms containing x^2 and x^4 in equation (3.60) can therefore be neglected without much affecting the torque ratio. Also for normal values of k,x,y, α and γ the term $(k^3-k)\ x\ \text{Sin}\ \gamma$ is much smaller compared with $[y\ \text{Sin}\ \alpha + kxy\ \text{Sin}(\gamma-\alpha)]$ and hence equation (3.60) can be reduced to

$$\left|\frac{T}{T_b}\right|_m \simeq \frac{ky\left[\text{Sin}\ \alpha + kx\ \text{Sin}\ (\gamma-\alpha)\right]}{y^2 + k^4 + 2k^2 y\ \text{Cos}\ \alpha} \cdot \frac{\text{Sin}\ n\ \pi/3}{\text{Sin}\ n\ \pi/2} \qquad (3.62)$$

It can be shown that for given values of k,x,α and γ the torque ratio is maximum when $y = k^2$.

3.4.3.3 Starting Currents

The starting currents are given by equations (3.57) and (3.58). On simplification in terms of dimensionless parameters given by equation (3.61) and neglecting the higher powers of x the equations for starting currents reduce to

$$|I_A| \simeq \left|\frac{V}{Z_{so}}\right| \left[1 - \frac{2kx(k^2\ \text{Cos}\ \gamma + y\ \text{Cos}\ \overline{\gamma-\alpha})}{y^2+k^4+2k^2 y\ \text{Cos}\ \alpha}\right]^{1/2} \qquad (3.63)$$

and $$|I_B| \simeq \left|\frac{V}{Z_{so}}\right| \left[\frac{1-2kx\ \text{Cos}\ \gamma}{y^2+k^4+2k^2 y\ \text{Cos}\ \alpha}\right]^{1/2} \qquad (3.64)$$

3.4.3.4 Voltage Across the Phase Convertor

Voltage across the phase convertor is given by the equation

$$V_Z = I_B\ Z \qquad (3.65)$$

where the current I_B is given by equation (3.58) and its approximate modulus by equation (3.64). Hence

$$|V_Z| \simeq \left|\frac{V}{Z_{so}}\right| \left(\frac{1-2kx\ \text{Cos}\ \gamma}{y^2+k^4+2k^2 y\ \text{Cos}\ \alpha}\right)^{\frac{1}{2}} |Z| \qquad (3.66)$$

The ratio of the voltage across the convertor to the supply voltage is given by

$$\left|\frac{V_c}{V}\right| \simeq y \left[\frac{1 - 2kx \cos \gamma}{y^2 + k^4 + 2k^2 y \cos \alpha}\right]^{1/2} \qquad (3.67)$$

it can be shown that the above ratio is maximum when $y = (-k^2/\cos\alpha)$ for the fixed values of k, x, α and γ.

3.4.4 Run-up Performance

The performance of the machine at any speed can be calculated with the help of the equivalent circuit given in Fig.3.2. As explained earlier that when the two stator windings are connected 60° apart it has a large proportion of third harmonic field flux. And due to this flux the machine runs at one-third of synchronous speed due to the fundamental field. The characteristic curves can be calculated for third harmonic field with the help of the same generalised equivalent circuit.

3.4.4.1 Torque

The torque developed by the machine is given by the equations (3.56). But the dip at one-third of the synchronous speed is due to the forward component of the third harmonic field. And the forward torque is given by the equations (3.54a) and (3.54b). For the third harmonic field the forward torque will be

$$T_{f3} = 3\left[|I_A|^2 + k^2 |I_B|^2 + 2k |I_A| |I_B| \cos(\psi - \pi)\right] R_{f3} \qquad (3.68)$$

and for the fixed values of I_A, I_B and k the above equation will be maximum when $\psi = \pi$. Also it can be seen from the equation (3.56) that the net torque will be maximum when $\psi = \pi/2$.

For the balanced operation

$$|I_A| = k |I_B| \qquad (3.69)$$

Then the forward torque due to the fundamental component when

$$|I_A| = k\ |I_B| \quad ,$$

$$T_{f1} = |I_A|^2\ (2 + 2\ \mathrm{Cos}\ \overline{\psi - \pi/3}\ )\ R_{f1} \qquad (3.70)$$

and forward torque due to the third harmonic field when

$$|I_A| = k\ |I_B| \quad ,$$

$$T_{f3} = 3\ |I_A|^2\ (2 + 2\ \mathrm{Cos}\ \overline{\psi - \pi})\ R_{f3} \qquad (3.71)$$

The ratio of the two torques is

$$\frac{T_{f3}}{T_{f1}} = 3\ \frac{(1 + \mathrm{Cos}\ \overline{\psi - \pi}\ )}{(1 + \mathrm{Cos}\ \overline{\psi - \pi/3}\ )} \cdot \frac{R_{f3}}{R_{f1}} \qquad (3.72)$$

If $\psi = \pi$ the condition for maximum third harmonic forward field torque then the ratio of torque reduces to

$$\left[\frac{T_{f3}}{T_{f1}}\right]_{\psi=\pi} = 12\ (R_{f3}/R_{f1}) \qquad (3.73)$$

as for normal squirrel-cage induction motors (R_{f3}/R_{f1}) is not less than 1/12 the torque ratio for normal induction motors will be higher than unity.

If $\psi = \pi/2$, the condition for maximum forward torque the ratio of equation (3.72) reduces to

$$\left[\frac{T_{f3}}{T_{f1}}\right]_{\psi=\pi/2} = 1.6\ (R_{f3}/R_{f1}) \qquad (3.74)$$

Even for the above condition the third harmonic torque is comparable to the forward torque due to fundamental component. And for all other values of ψ between $\pi/2$ and π , the torque ratio will increase from what shown by equation (3.74).

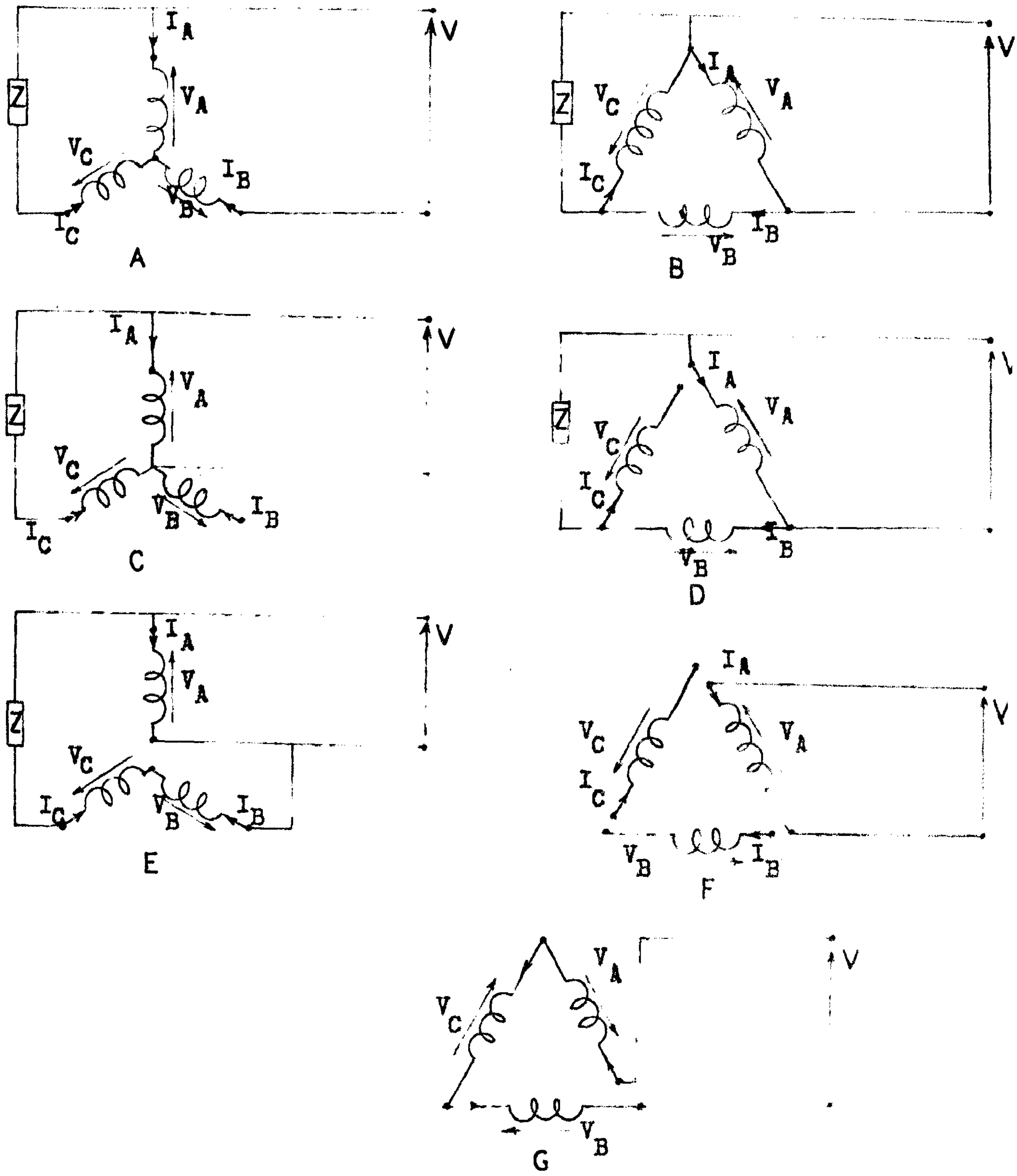
3.5 Conclusions

The use of generalized rotating-field theory has resulted in establishing a satisfactory theory for the analysis of the "New two-speed capacitor motor". The theory is applicable at any speed and for any type of connections possible.

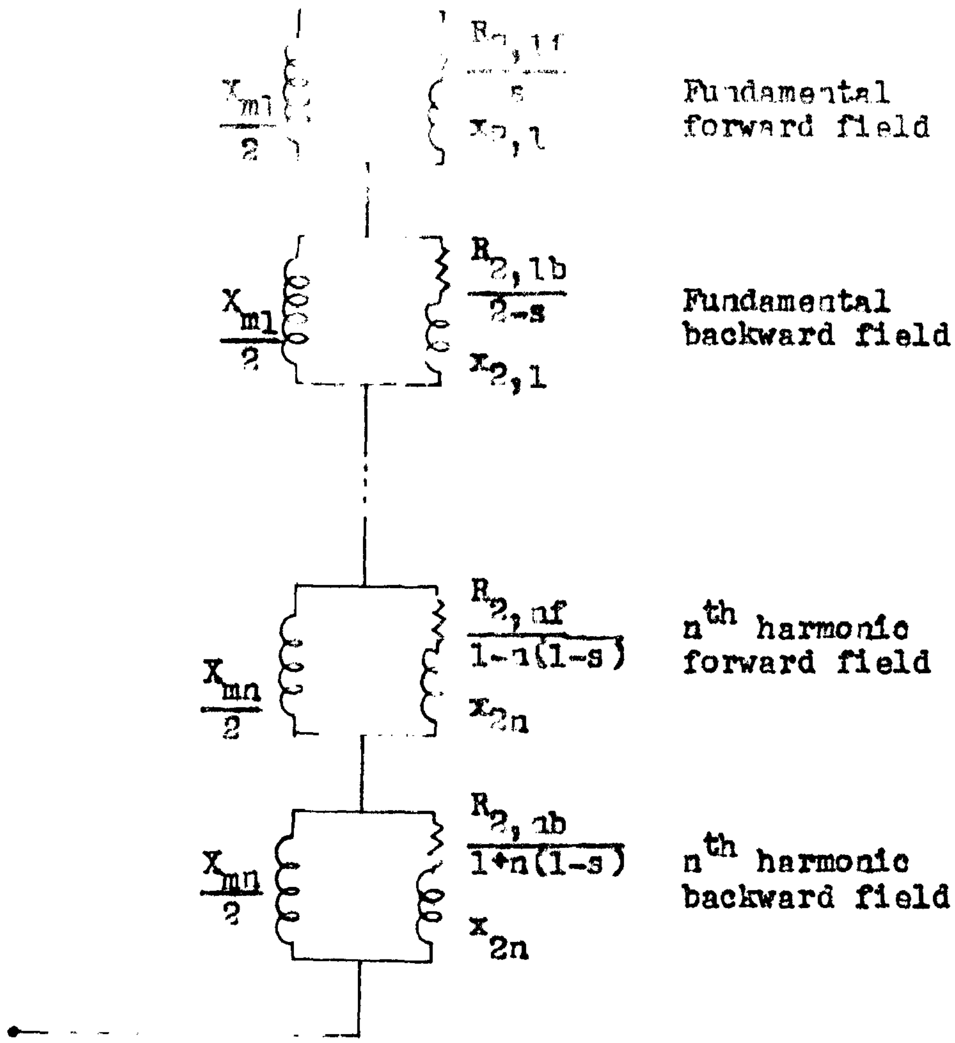
It has been shown that the third harmonic forward torque is comparable to the torque due to the fundamental component for certain winding arrangements. And hence the torque can be used as a motoring torque and a speed as low as one-third of synchronous speed due to fundamental field can be achieved successfully.

The safe output of the three-phase induction motor when connecte to a single-phase supply is about 67%. As the pull out torque at one-third speed is about the same as for normal speed than the output at one-third speed will be reduced only to about 22%. But the advantages of the arrangement discussed are in its simplicity and availability of the starting torque, which was absent in case of zero-sequence operation.

* * *



.31 OPERATION OF A 3-PHASE INDUCTION MOTOR FROM SINGLE-PHASE SUP WITH DIFFERENT STATOR WINDINGS ARRANGEMENTS.



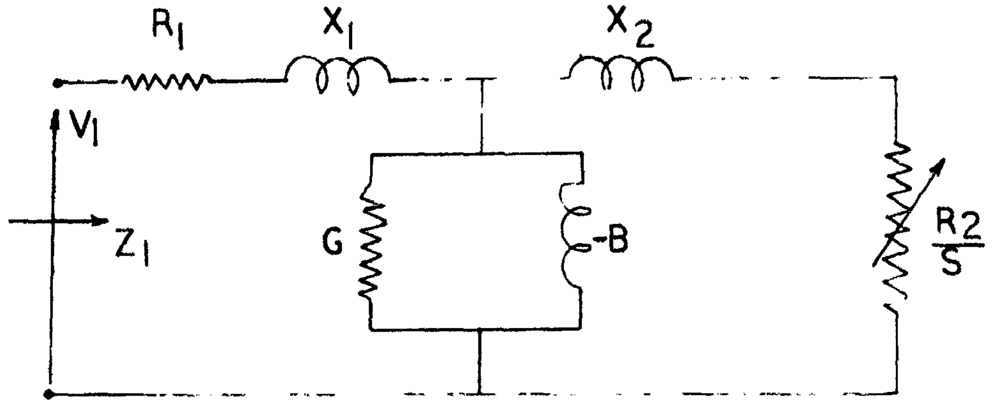
IG.3·2 GENERALISED EQUIVALENT CIRCUIT OF A SINGLE-PHASE INDUCTIC MOTOR HAVING A SYMMETRICAL ROTOR.

r , x – Resistance and leakage reactance of the stator winding respectively.

X_{mn} – Magnetising reactance of the stator winding due to the n^{th} harmonic field.

x_{2n} – Leakage reactance of the rotor due to the n^{th} harmonic field, referred to the stator winding.

R_{2nf}, R_{2nb} – Respective resistances of the rotor due to the forward and backward components of the n^{th} harmonic field, referred to the stator winding



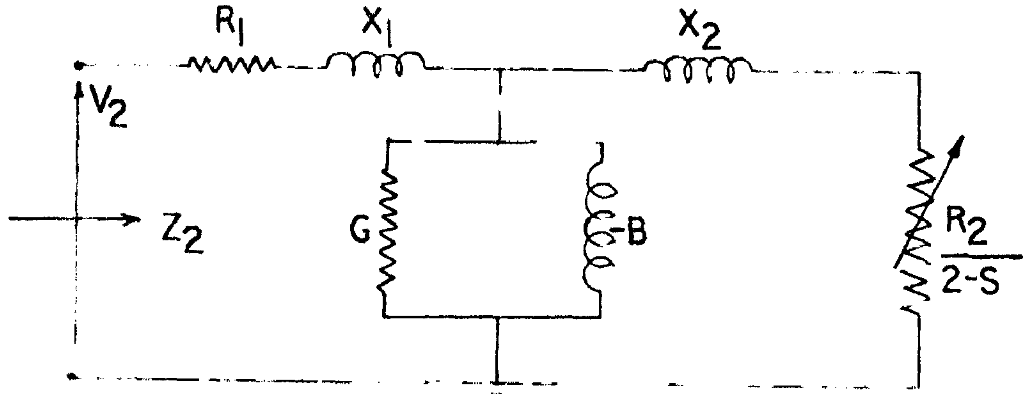


FIG.3·3 EQUIVALENT CIRCUITS

A. POSITIVE-SEQUENCE OPERATION

B. NEGATIVE-SEQUENCE OPERATION

CHAPTER-4

EXPERIMENTAL WORK

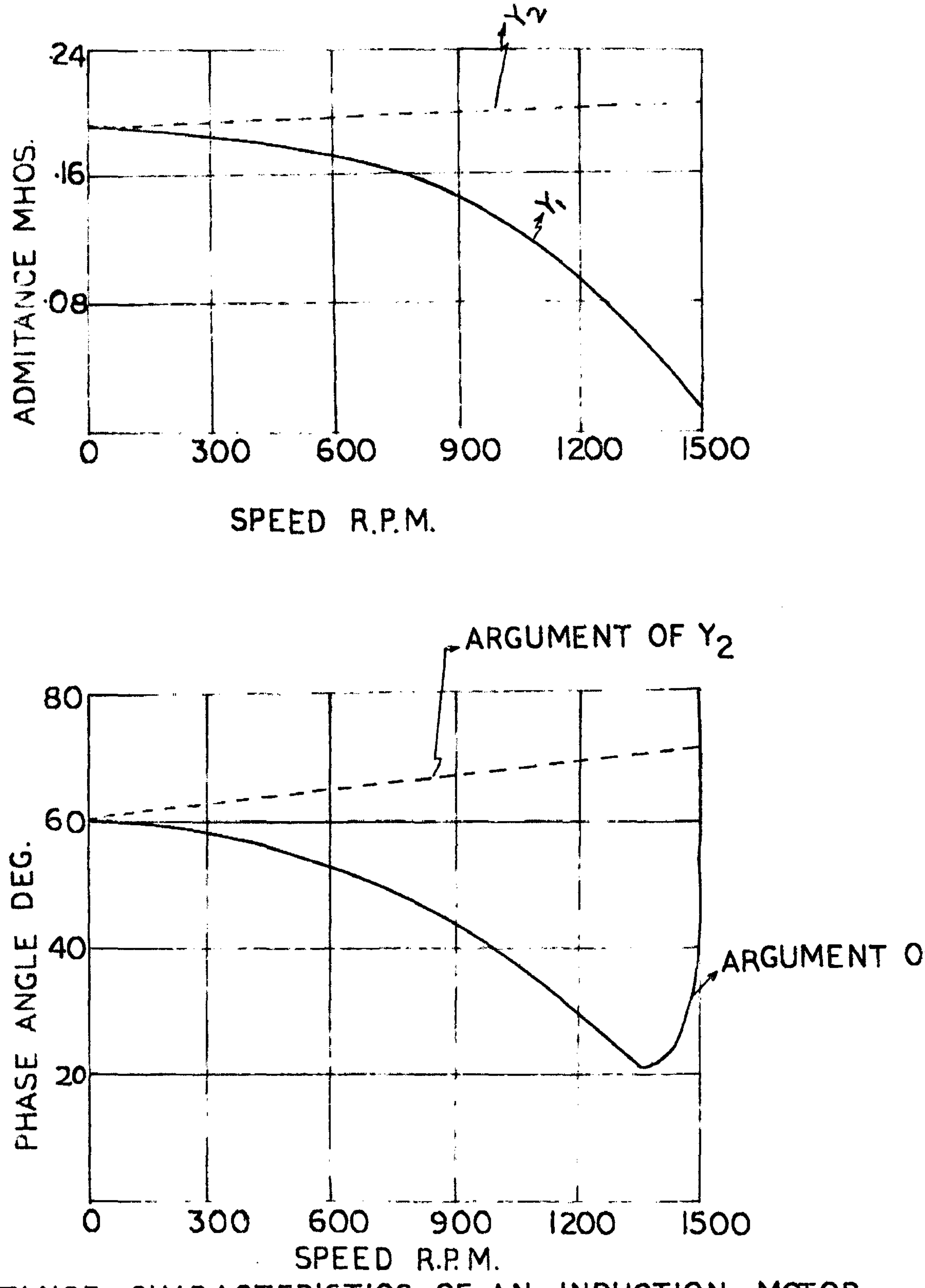


FIG. 3·4 ADMITANCE CHARACTERISTICS OF AN INDUCTION MOTOR.

4. EXPERIMENTAL WORK

4.1 General

To verify the theory set-out in the previous section tests were carried out on two induction motors. One of them was a standard three-phase squirrel-cage rotor motor having the following name-plate ratings:-

5 H.P., 400 volts, 8.5 amps, 50 c.p.s, 4 pole,delta connected.

The other motor was a specially wound squirrel-cage induction motor, which was designed and assembled for the present work (see Appendix 7.2), having the following tappings:

i) 57.7% tap in the main winding.

ii) 4:13 distribution of the third winding.

The proposed ratings of the specially wound motor were as follows:

5 H.P., 400 volts, 50 c.p.s, 4 pole, star-connected.

For test purposes each of the two test motors were coupled to a d.c. machine, the speed of which was controlled by means of ward-Ward-Leonard arrangement. A variable capacitor bank was used as a phase-convertor.

As the measurements on a stationary induction motor are affected by the position of the rotor and to avoid discrepancies due to this factor the standstill results were extrapolated from the graphs of readings taken over a range of low speeds in both directions. The test voltage was lower than the rated voltage to ensure that saturati effects were minimised.

Particular care was exercised to maintain the alternating supply voltage and temperature of the test machine constant throughout the tests. Sufficient time was allowed to reach the final temperature before taking the final readings for each set.

For the measurement of the electro-magnetic torque, the field current of the d.c. dynamo coupled to the test motor was maintained constant throughout the tests. And as the electro-magnetic torque developed by a d.c. machine is proportional to the product of field and armature currents, the armature current will give the torque at suitable scale if the field is kept constant. Hence the armature current of the d.c. machine was noted for the torque developed by the test machine after correcting for the frictional losses.

To avoid the fluctuations of the d.c. supply voltage provided in the laboratory a separate motor-generator set was used for the d.c. supply required for both the fields of the d.c. machines. Fig.4.1 shows the scheme of the testing.

4.2 Tests on Standard Three-Phase Induction Motor.

The various torque/speed and current/speed characteristics of the standard motor were studied with particular reference to

(a) Balanced three-phase operation with windings in (i) star and (ii) delta.

(b) Zero-sequence operation.

(c) Single-phase operation, with only one winding excited.

(d) Single-phase operation with a capacitor convertor in circuit and the windings connected in (i) star, (ii) delta, (iii) equivalent 90^{o}, (iv) 120^{o} and (v) at 60^{o}.

While obtaining the above characteristics, the effect of the magnitude of the capacitor on torque and currents was also studied. The braking characteristics of the machine were also recorded, when the windings were connected at 120^{o} and 60^{o}.

The value of capacitors, which gave the maximum starting torque were predicted and the characteristics, if possible, were obtained for these values. As the capacitor bank available were limited so the characteristics could not be taken for higher values of capacitor.

The open-circuit, short-circuit and zero-sequence standstill impedances of the machine are as follows:-

Open-circuit impedance	=	(2670 + j487) ohms
Short-circuit impedance	=	(21.5 + j38) ohms
Zero-sequence standstill impedance	=	(13 + j33.5) ohms

4.2.1 Starting Performance

From the short-circuit impedance the value of the capacitor which will give the maximum torque can be calculated, which is 49 μf when the stator windings are in star.

Similarly when the windings are connected in delta the capacitor which will give maximum starting torque will be 49 x 3 = 147 μf.

Also when the windings are connected in 60° or 120° connections the value of y is proportional to k^2 for maximum torque at starting. As for a symmetrical three-phase motor k is unity so y is also unity. Hence the value of capacitor which will give the maximum torque at starting is 49 x 1.5 = 74 μf.

For equivalent 90° connections the value of k is $\sqrt{3}$ so the value of y for maximum starting torque will be proportion to 3 or the value of the capacitor will be 25 μf.

Since the starting current in most induction motors is from four to six times the full load current, prolonged standstill tests can be carried out only at a lower voltage than the rated voltage. So it was decided to maintain the voltage for all the tests at 220^{V}

Fig.4.14 Torque/speed curves - single-phase operation with windings at 60° and a capacitor (with braking characteristics).

Fig.4.15 Current/speed curves - single-phase operation with windings at 60° and a capacitor (with braking characteristics).

Referring to above figures it may be noted that in all the cases curves have been recorded for the values of capacitors would gi maximum starting torque. Also to study the effect of capacitor on the magnitude of the torque, curves have been recorded for the various values of the capacitors. The capacitor which would give minimum third harmonic torque while the windings are at 120° was predicted and the torque-speed curve for this value was recorded in curve (iv) Fig.(4.12). Also for the comparision the balanced three-phase characteristics are given on each graph.

To record the variation of y giving the maximum torque with speed, tests were performed by holding the motor constant at one speed and the value of y noted for the maximum torque at that speed. The results are recorded in Fig.4.30.

4.3 Tests on the Specially Wound Motor

The open-circuit, short-circuit and zero-sequence standstill impedances of the machine are as follows:

Open-circuit impedance = (1875 + j221) ohms

Short-circuit impedance = (6.8 + j9.8) ohms

Zero-sequence standstill impedance= (7.6 + j5.5) ohms

The various characteristics of the machine were studied with particular reference to

(a) Balanced three-phase operation

(b) Single-phase operation with a capacitor convertor in circuit, and the windings connected in

(i) star, (ii) delta, (iii) at 120° and (iv) at 60°.

per phase.

4.2.2 Running Performance

The run-up performance for different winding arrangements was investigated with the following views:

1. To ensure that the convertor selected for starting would give satisfactory run-up performance.
2. To study the effects of the different values of the capacitors on the variation of the torque and current with the speed.

The results of the tests have been recorded in the usual form of torque/speed and current/speed curves in the figures listed below:

While obtaining the characteristics, the effect of the magnitude of the capacitor was also studied. The braking characterist of the machine were also studied when the windings were connected at 120° and 60°.

4.3.1 Starting Performance

The capacitor for the maximum starting torque when the windings are connected in star is 178 µf.

Similarly when the windings are connected in delta the capacitor which would give maximum starting torque will be $178 \times 3 = 534$ µf.

Also when the windings are connected in the 60° or 120° connections the value of capacitor for maximum starting torque is given as follows:

When the turn ratio is unity ($y=1$), $C = 178 \times 1.5 = 267$ µf.

As the maximum capacitor value available was only 186 µf, so it was not possible to record the characteristic curves for the maximum starting torque except in star connected windings.

To reduce the current at high slip values the voltage per phase was reduced to 150 volts per phase for all the tests.

4.3.2 Running Performance

The run-up performance of the machine was studied similarly as for the standard three-phase machine described in the section 4.2.

As for this machine it was possible to use whole of the periphe when the windings are at 60° or 120°, with a changed value of the turn ratio k, so special attention was given to these connections. The torque/speed and current/speed characteristics were studied for quite a number of capacitor values. And those of particular interes were recorded.

The results of the tests have been recorded in the usual forms of torque/speed and current/speed curves in the figures listed below:

Fig.4.16 Torque/speed curves - balanced three-phase operation with windings in (i) star and (ii) delta.

Fig.4.17 Current/speed curves - balanced three-phase operation with windings in (i) star and (ii) delta.

Fig.4.18 Torque/speed curves - single-phase operation windings in star and capacitor in circuit.

Fig.4.19 Current/speed curves - single-phase operation windings in star and capacitor in circuit.

Fig.4.20 Torque/speed curves - single-phase operation windings in delta and capacitor in circuit.

Fig.4.21 Current/speed curves - single-phase operation windings in delta and capacitor in circuit.

Fig.4.22 Torque/speed curves - single-phase operation with windings at 120° and a capacitor (with braking characteristics), when $k = 1$.

Fig.4.23 Current/speed curves - single-phase operation with windings at 120° and a capacitor (with braking characteristics), when $k = 1$.

Fig.4.24 Torque/speed curves - single-phase operation with windings at 120° and a capacitor (with braking characteristics), when $k \neq 1$.

Fig.4.25 Current/speed curves - single-phase operation with windings at 120° and a capacitor (with braking characteritics), when $k \neq 1$.

Fig.4.26 Torque/speed curves - single-phase operation with windings at 60° and a capacitor (with braking characteristics), when $k = 1$.

Fig.4.27 Current/speed curves - single-phase operation with windings at 60° and a capacitor (with braking characteristics), when $k = 1$.

Fig.4.28 Torque/speed curves - single-phase operation with windings at 60° and a capacitor (with braking characteristics), when $k \neq 1$.

Fig.4.29 Current/speed curves - single-phase operation with windings at 60° and a capacitor (with braking characteristics), when $k \neq 1$.

4.4 Discussion of the Results.

4.4.1 Discussion of the Results at Normal Speed.

The stator windings will be connected either in star or in delta with a capacitor in circuit for normal speed operation. It may be noted from Fig.4.2 and 4.16 that even with the same voltage per phase the torque developed by the motor when connected in delta is lower than when connected in star. This specially is true for lower speeds. However the torque is same in the operating range of the motor. This discrepancy may be due to the small unbalance in the supply voltage and hence resulting the third-harmonic current, which flows in the closed delta, but cannot in the star windings.

It has been mentioned in section 2.1 that the starting torque under single-phase operation exceeds the balanced three-phase provided, $\alpha > 147.8^{\circ}$. Of the two motors tested, one had a standstill impedance angle of 60°, and the other of 50°. It is obvious that whatever type of convertor could be used, $\alpha > 147.8^{\circ}$ is not possible in case of the second motor. However in case of the first machine, proper choice of convertor would give $\alpha > 147.8^{\circ}$, and hence it should be possible to experimentally obtain starting torque higher than balanced three-phase torque. These deductions bear out and are substantiated by experiments curves plotted in Figs.4.4 and 4.6 for the first machine, Fig.4.18 for the second machine.

As the values of Z_1 and Z_2 change with the speed, the value of external impedance Z which gives the maximum torque varies with the speed. Referring to the Fig.3.4, it is evident that the value of Y_2 remains practically constant throughout the operating range and the value of Y_1 varies slowly upto about two-third of synchronous speed, and decreases rapidly afterwards. The effect of this on the variation of y for the maximum torque with the speed is that y vary slowly in the beginning and upto about two-third of synchronous speed and increases rapidly after this speed. The variation of y for maximum torque with speed for the standard machine is plotted in Fig.4.30.

Referring to Figs.4.4,4.6,4.18 and 4.20 the break-down torque varies with the value of y and it occurs at different speeds for different values of y. The highest break-down torque in case of first motor is about 87% of the normal three-phase torque and for second motor is only 67%. This seems to be due to the rotor resistance, which is higher for the second motor.

In giving an operating rating to a motor, heating must be considered in addition to ratio of pull-out torques. A conservative way to evaluate this is to assume the winding temperature as a function of the highest phase current. From the stand point of local stator temperature rise, the delta connected motor appears better in the running range. The total electrical losses, however, are same in both star and delta connected stators.

Considering both the break-down torque and the heating of the stator the safe rating of the motor when operating from single-phase supply is only about 66%.

4.4.2 Discussion of the Results at One-Third Speed.

Characteristics of the machine when operating at one-third speed are plotted in Figs.4.12, 4.13, 4.14 and 4.15. A critical assessment of these curves show that the machine works satisfactorily both at $\theta = 120^{\circ}$ and $\theta = 60^{\circ}$, the main points of comparison between the use of these two displacement angles are given below:

(i) The maximum torque (pull-out) at one-third speed is approximately the same in either case.

(ii) The starting torque when $\theta = 120^\circ$ is higher than when $\theta = 6$

(iii) The currents in the windings when $\theta = 120^\circ$ are higher than when $\theta = 60^\circ$.

(iv) The net torque of the machine remains positive throughout the speed range when $\theta = 120^\circ$, but becomes negative in part of the range immediate after one-third speed with $\theta = 6C$

It is obvious from (iv) above therefore, that if the machine is to be started on one-third connection at no-load, the machine will definitely stabilize at one-third speed when $\theta = 60^\circ$, but may run up to full speed if the $\theta = 120^\circ$. This fact together with the point that currents are smaller when $\theta = 60^\circ$, indicate that this connection should be preferred for one-third speed operation.

Special connections were used to obtain 60° or 120° displacement (see Fig.7.1(a & b) in order to utilize all the winding space in the machine. Tests results with such equivalent 60° or 120° angle are shown in Figs.4.24, 4.26, 4.28 and 4.29. An evaluation of these curves in comparison with those of the normal machine with standard windings shows:

(a) The overall characteristics are better in the equivalent case as could have been expected.

(b) The comparative differences between 120° and 60° connectio which were apparent in the earlier case are also true for this case.

Another interesting point that can be noted is the variation of torque and the current with different values of capacitance, as shown in Figs.4.28 and 4.29. For $C = 180\ \mu f$, the maximum pull-out torque at one-third speed when $\theta = 60^{\circ}$ and $k = 1.6$ is about 61.4% of the pull-out torque under balanced three-phase conditions, with current of 9.2 amps in main winding. For C = 70 μf, the maximum torque falls to about 54% while the current drops to 4 amps. It is therefore obvious that a small sacrifice in torque could be very beneficial in reducing the current and hence the heating of the machine. It is possible to obtain satisfactory torque at low current values by a proper selection of the capacitor. For example at C = 70 μf, the performance of the motor is better and comparable with that of at the normal speed operation.

No theoretical calculation has been attempted to predetermine the magnitude of the optimum capacitor for one-third speed operation. The difficulties are that the variations of Z_1 and Z_2 of machines over the speed range is not necessarily similar and hence measurements of Z_1 and Z_2 at one-third speed would be necessary before the optimum value of capacitor could be predetermined. It is proposed to investigate in future the possibility of expressing the value of optimum capacitor as a function of Z_1 and Z_2 at one-third speed.

4.5 Study of Switching Circuits for Low-High and High-Low Switching

Depending upon the applications it will be required that the motor should be able to switch from one speed to other. It may be noted that when windings are connected in star or delta third harmonic torque is absent and if the motor is switched on it will run at full speed. The operation of the motor will not be affected either the windings are in star or in delta. But as the windings will be at 60° for the operation of the motor at one-third speed the switching will be simplified if the windings are in delta for full-speed operation. Had the windings been at 120° for one-third speed operatio then the star connection would have been favoured.

As far as the winding connections for high-low and low-high switching are concerned only a off-on switch is required for a normal induction motor (see Fig.4.51). Only by switching off the C winding out of the circuit, the motor will be switched to one-third speed operation. But the complicacy arises due to the fact that even when the windings are at 60° motor develops positive torque at full speed and hence the above switching will be effective only in one direction i.e. from low to high. Because when the motor is running at one-third speed and speed-selector switch is put on for the full-speed operation the motor will run at full speed. But if the reverse is the case i.e. if the motor is running at full speed and the speed-selector switch is put on for one-third speed, the motor will remain running at full speed due to the above said reason. To make the switching effective in both directions, some device depending upon speed will have to be used. The possible arrangement using centrifugal switch is given in Fig.4.52. The centrifugal switch remains close upto say 35% - 40% of normal speed and open afterwards. A double pole switch is used as a speed-selector switch. Total number of points used are thus four alongwith a centrifugal switch.

If the C-winding has 4:13 tappings, the C-winding can be used alongwith A and B phase windings to give the resultant angle of 60° between the two axes. But here also the motor develops positive torq at full speed. The centrifugal switch is again required for high-low switching. The possible switching circuit is shown in Fig.4.53. Tot number of tappings required from the motor windings are six and numbe of terminals on the switch are nine.

...

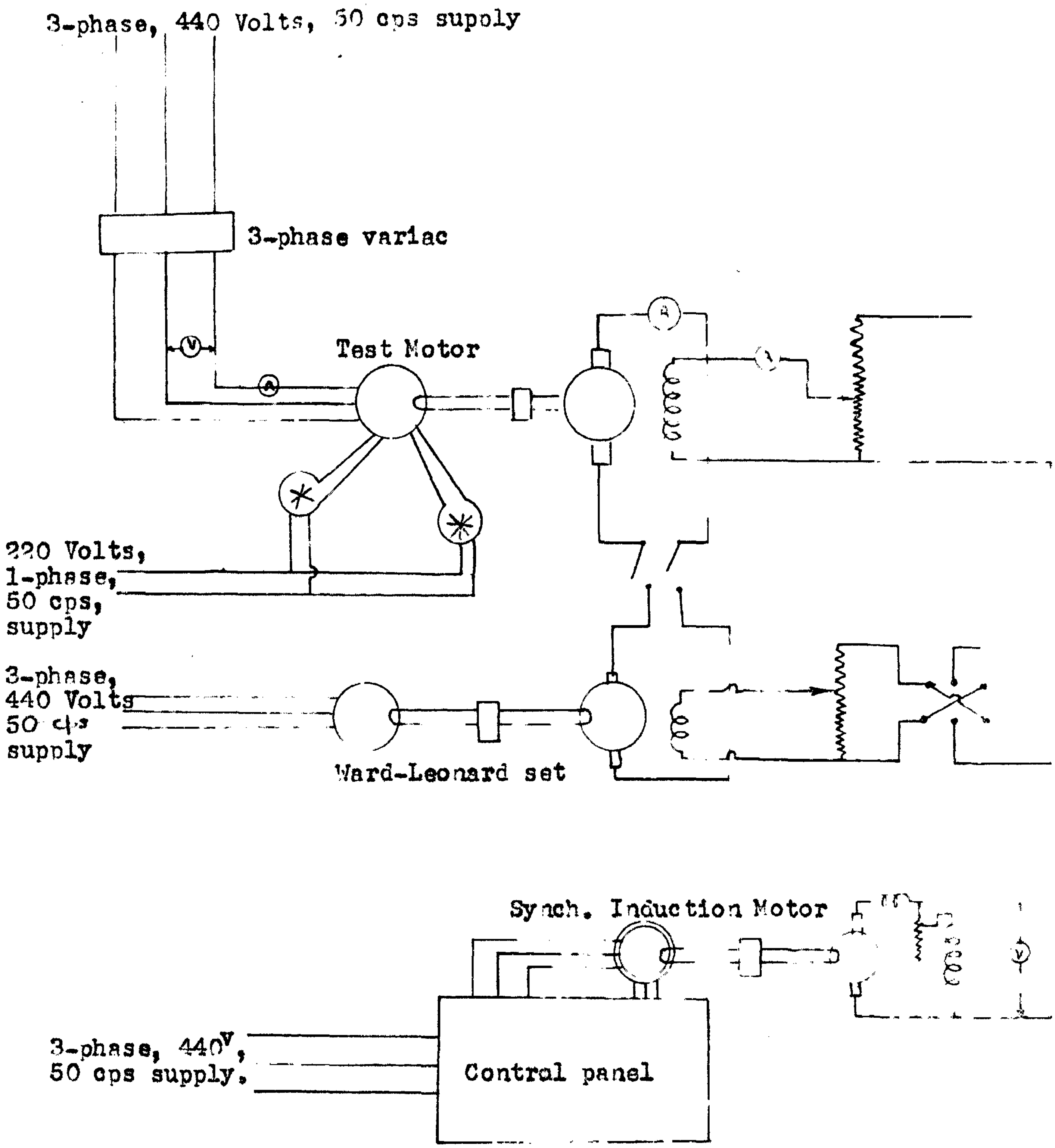


FIG. 4·1 SCHEME OF TESTING

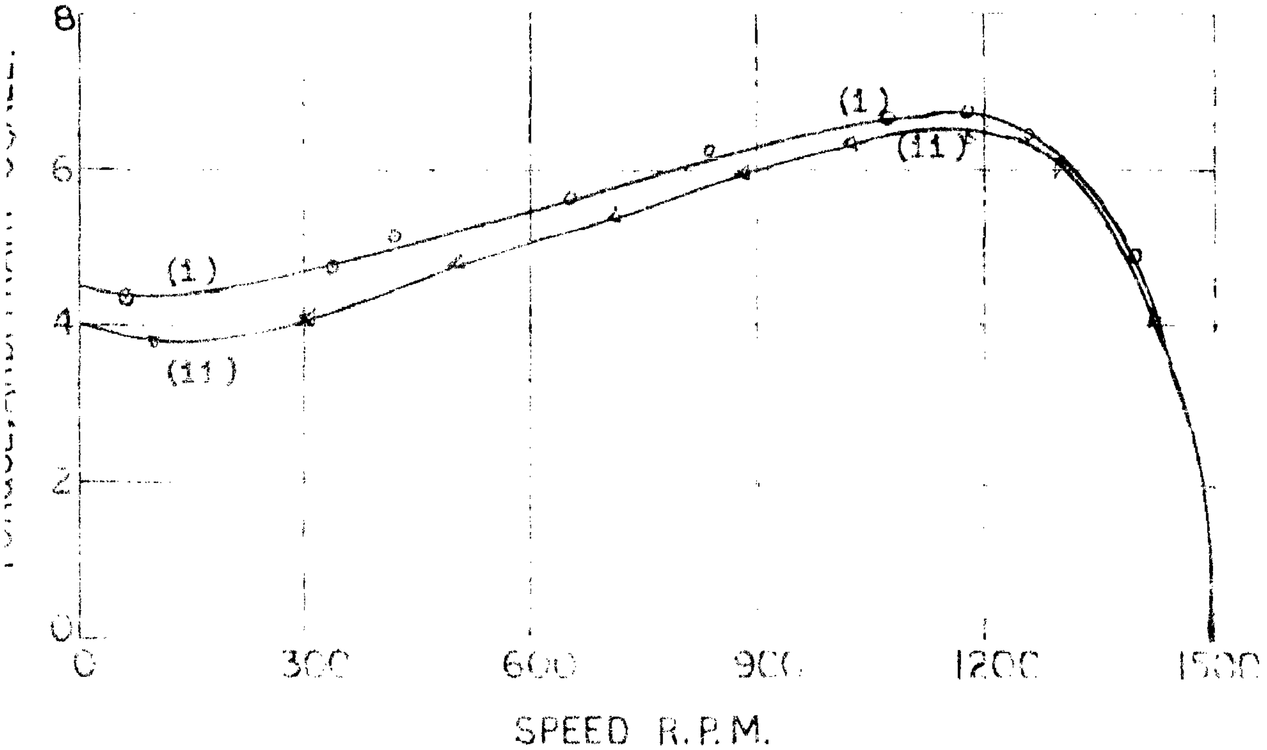


FIG 42 TORQUE-SPEED CURVES FOR TEST MACHINE No 1
STATOR WINDINGS IN STAR
STATOR WINDINGS IN DELTA.

Curve (i) Balanced 3-phase operation, Windings in star.

(ii) Balanced 3-phase operation, Windings in delta.

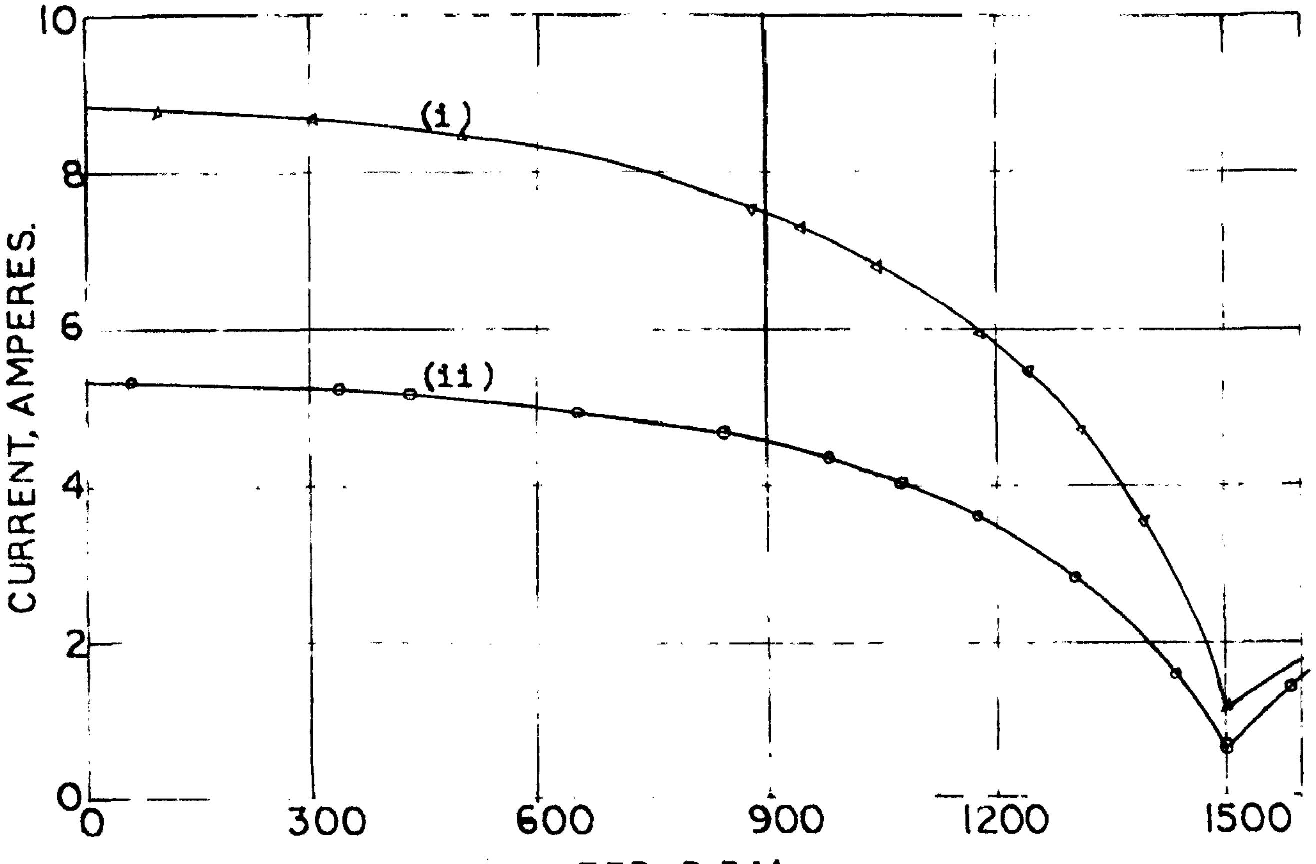


FIG. 4·3 CURRENT-SPEED CURVES FOR TEST MACHINE Nº 1

Curve (i) Balanced 3-phase operation stator windings in del

(ii) Balanced 3-phase operation stator windings in sta

(Line Currents)

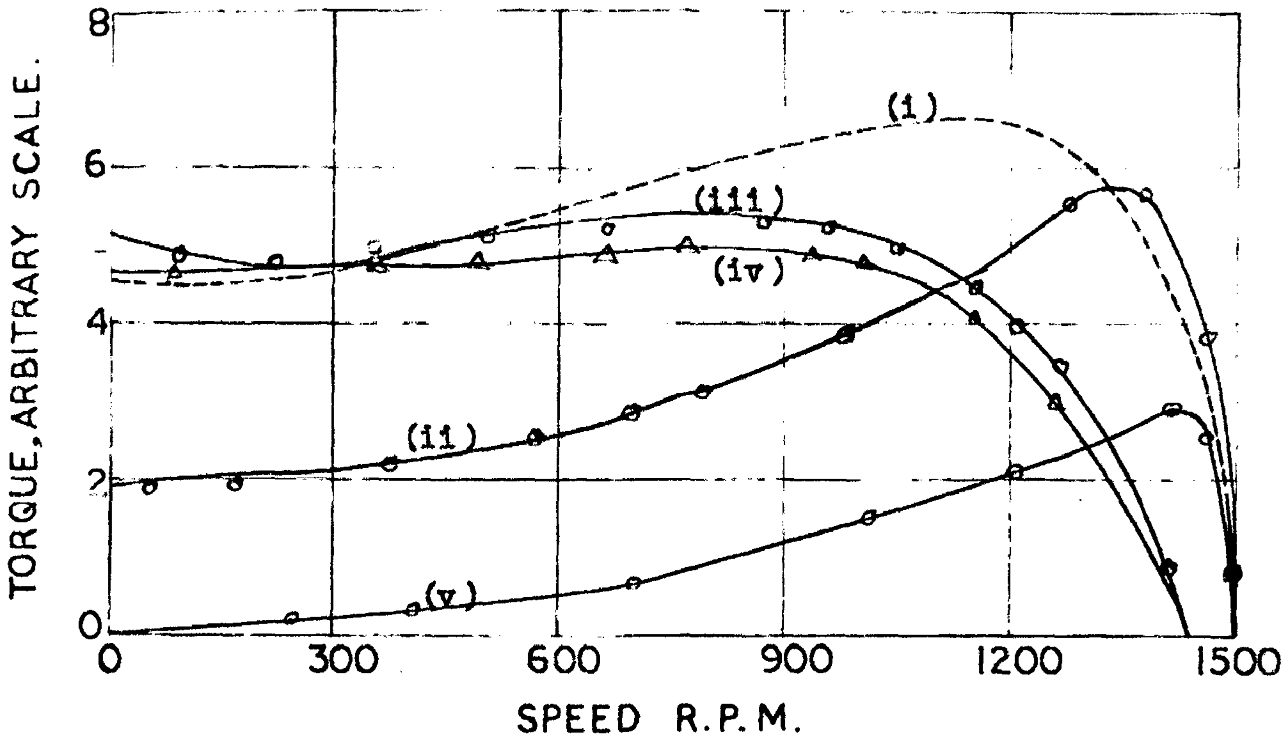


FIG. 4·4 TORQUE-SPEED CURVES FOR TEST MACHINE №1 STATOR WINDINGS IN STAR.

Curve (i) Balanced 3-phase operation.

(ii) Single-phase operation with 25 μf capacitor.

(iii) Single-phase operation with 49 μf capacitor.

(iv) Single-phase operation with 60 μf capacitor.

(v) Single-phase operation with zero capacitor.

(Third curve is for maximum starting torque).

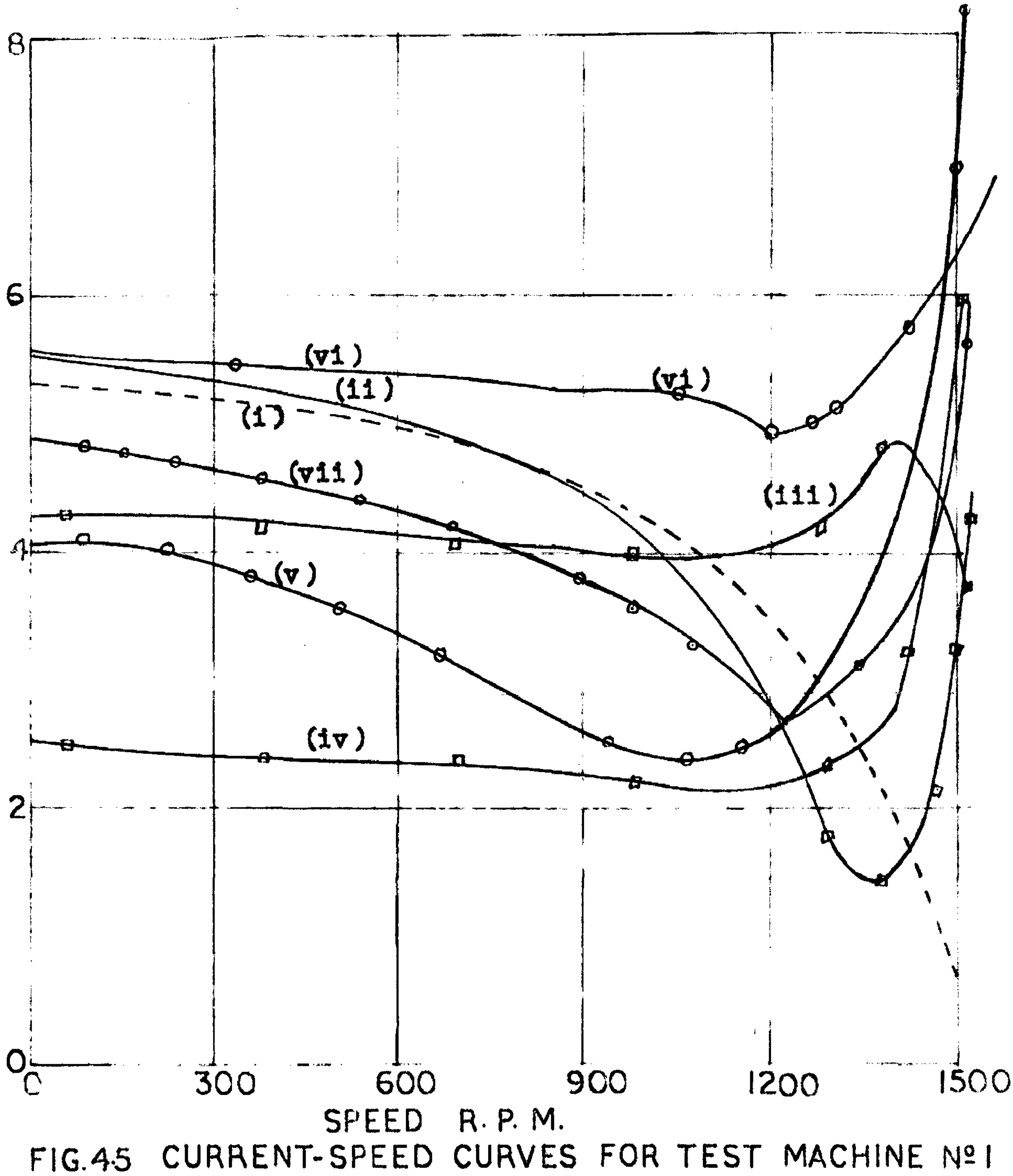


FIG.4.5 CURRENT-SPEED CURVES FOR TEST MACHINE No 1 STATOR WINDINGS IN STAR.

Curve (i) Balanced 3-phase operation.

Single-phase operation with capacitor

(ii) A, (iii) B and (iv) C_phase currents with 25 μf capaci

(v) A, (vi) B and (vii) C-phase currents with 49 μf capacit

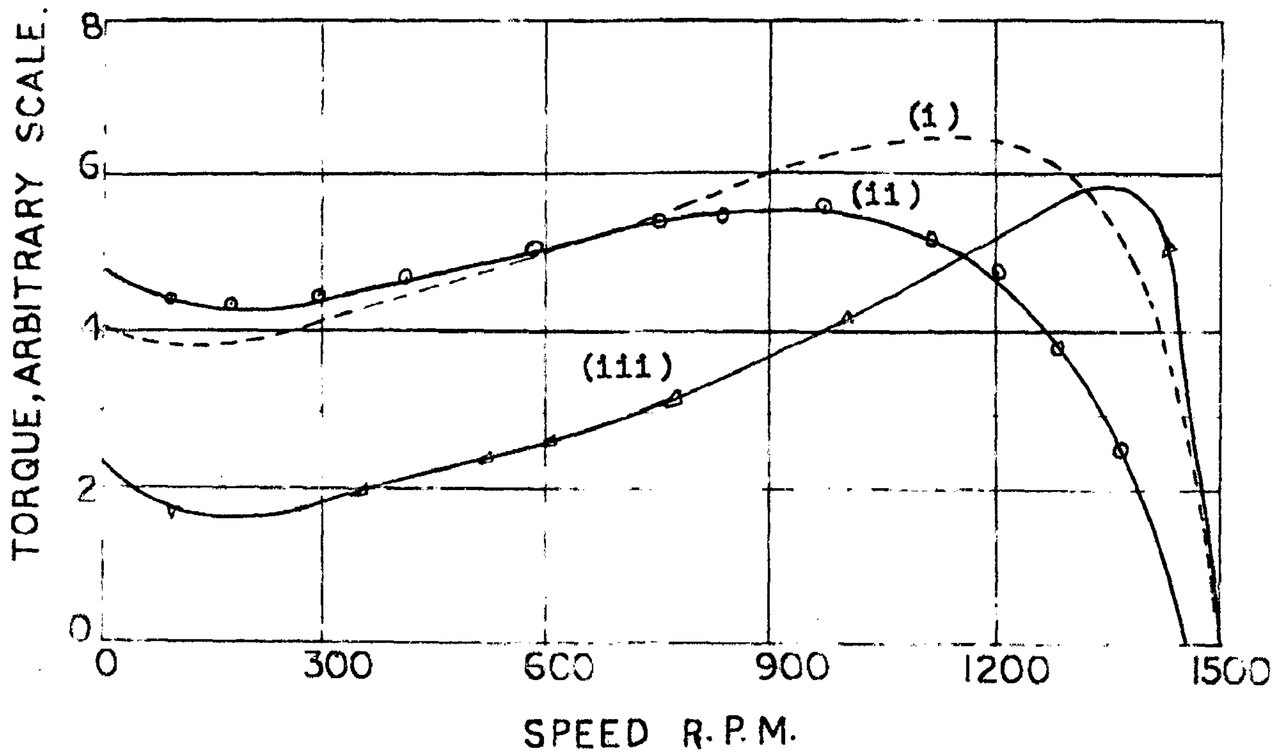


FIG. 4.6 TORQUE-SPEED CURVES FOR TEST MACHINE No. 1
STATOR WINDINGS IN DELTA.

Curve (i) Balanced 3-phase operation.

(ii) Single-phase operation with 147 μf capacitor.

(iii) Single-phase operation with 80 μf capacitor.

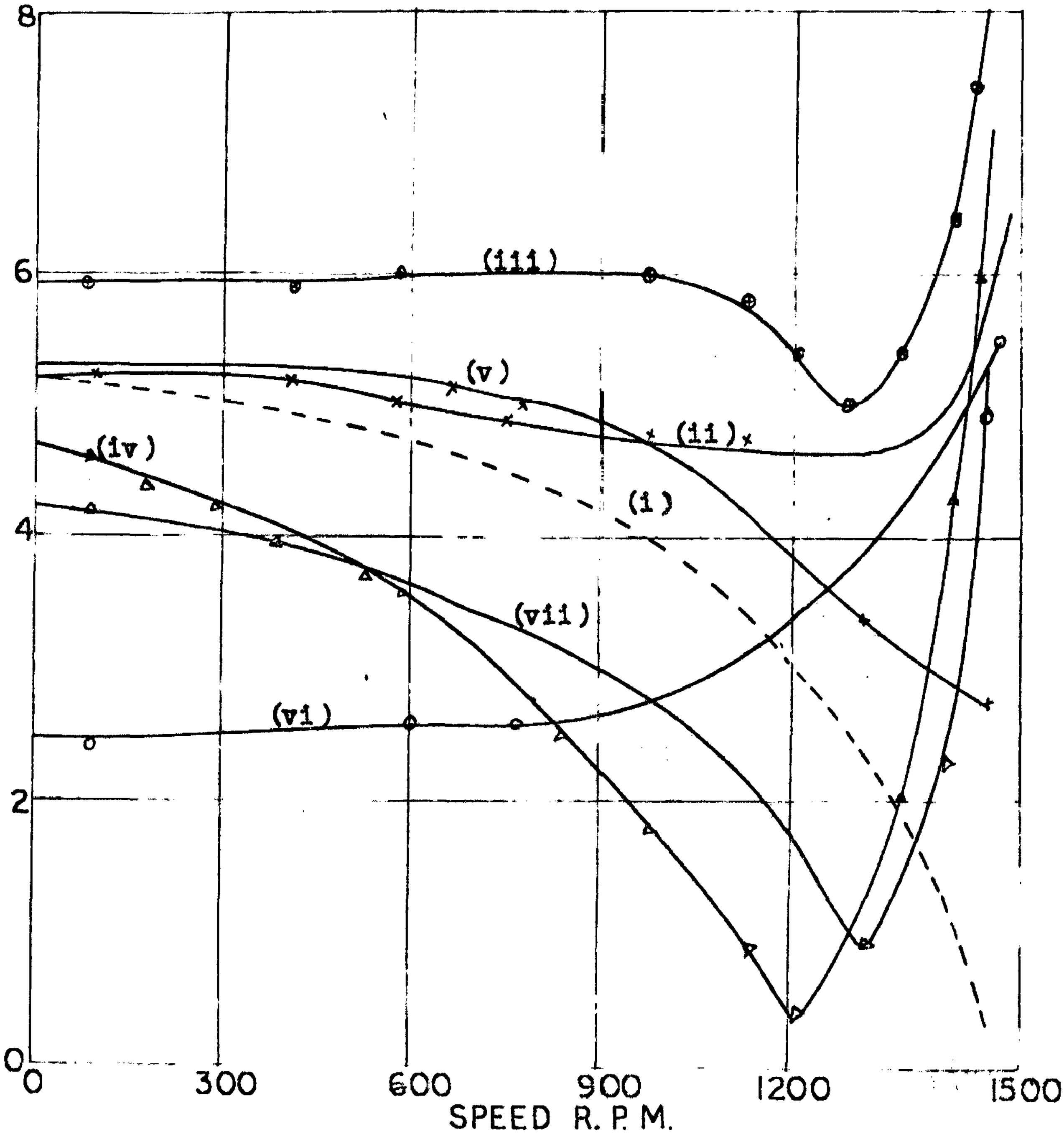


FIG. 4.7 CURRENT-SPEED CURVES FOR TEST MACHINE No 1
STATOR WINDINGS IN DELTA

Curve (i) Balanced 3-phase operation, phase current.
Single-phase operation (ii) A, (iii) B, (iv) C, phase currents with 147 μf capacit
(v) A, (vi) B and (vii) C phase currents with 80 μf capaci

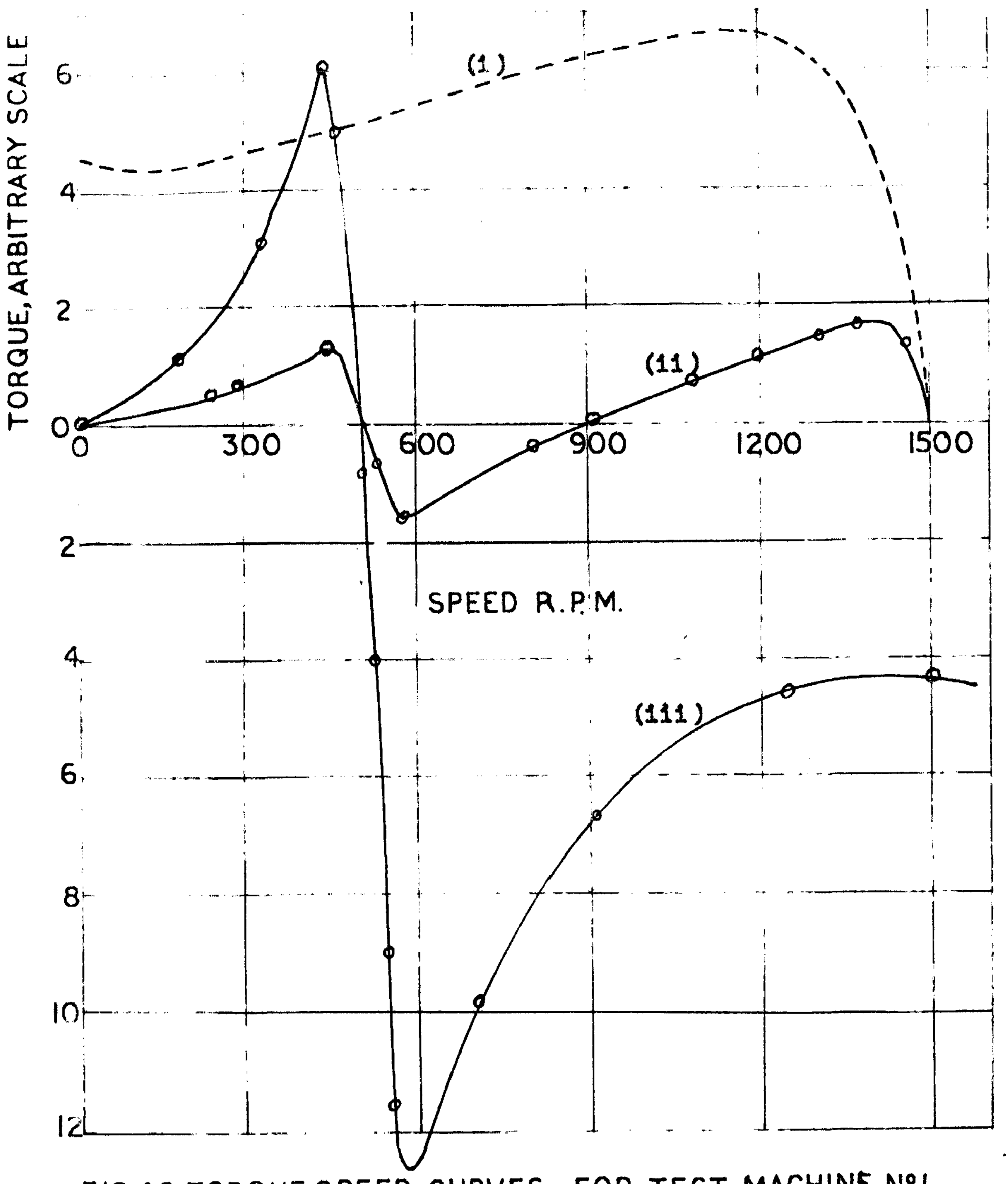


FIG.4·8 TORQUE-SPEED CURVES FOR TEST MACHINE Nº I

Curve (i) Balanced 3-phase operation.

(ii) Single-phase operation, only one phase winding exci

(iii) Zero-sequence operation.

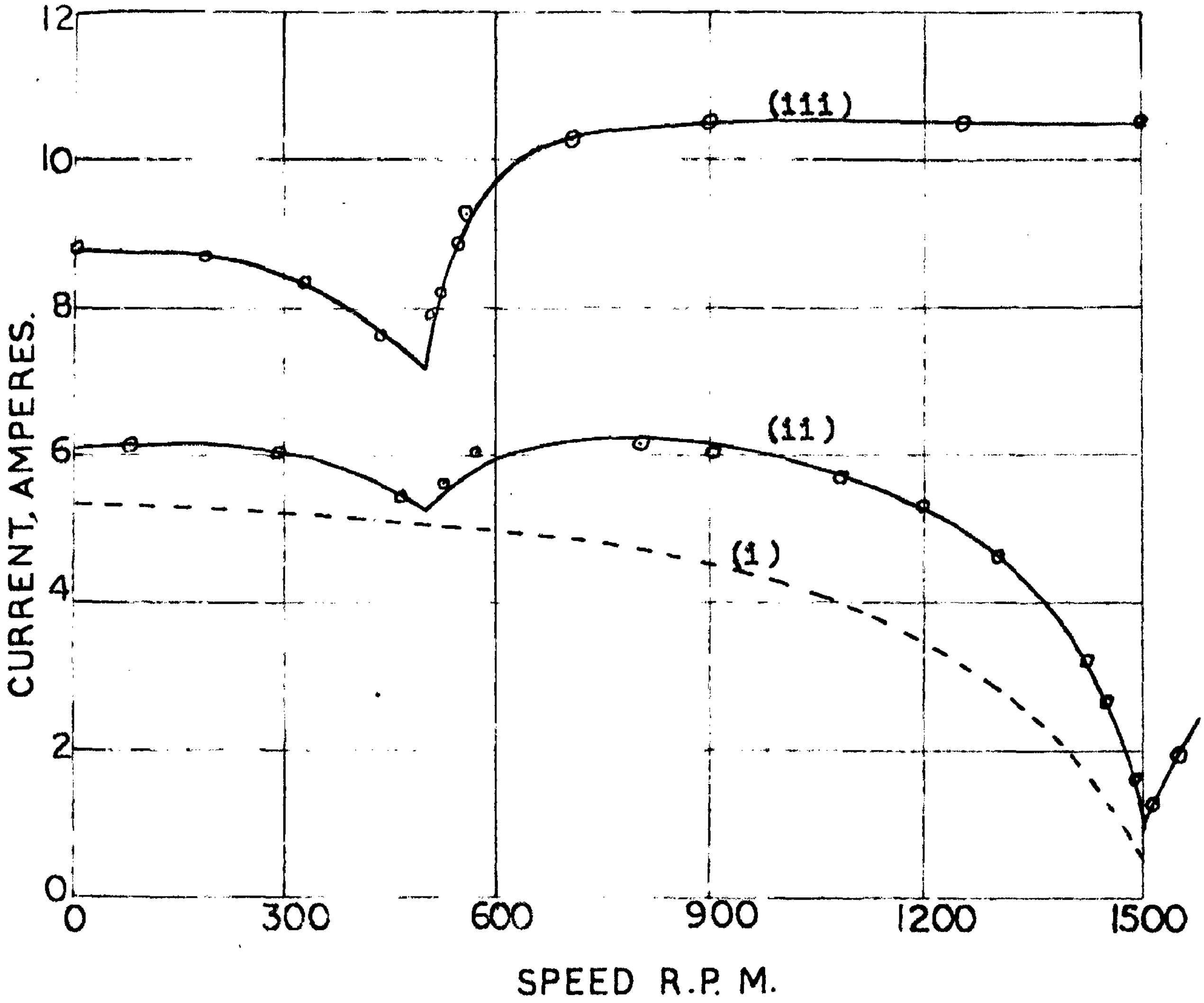


FIG. 4·9 CURRENT–SPEED CURVES FOR TEST MACHINE Nº1

Curve (i) Balanced 3-phase operation.

(ii) Single-phase operation, only one winding exc

(iii) Zero-sequence operation.

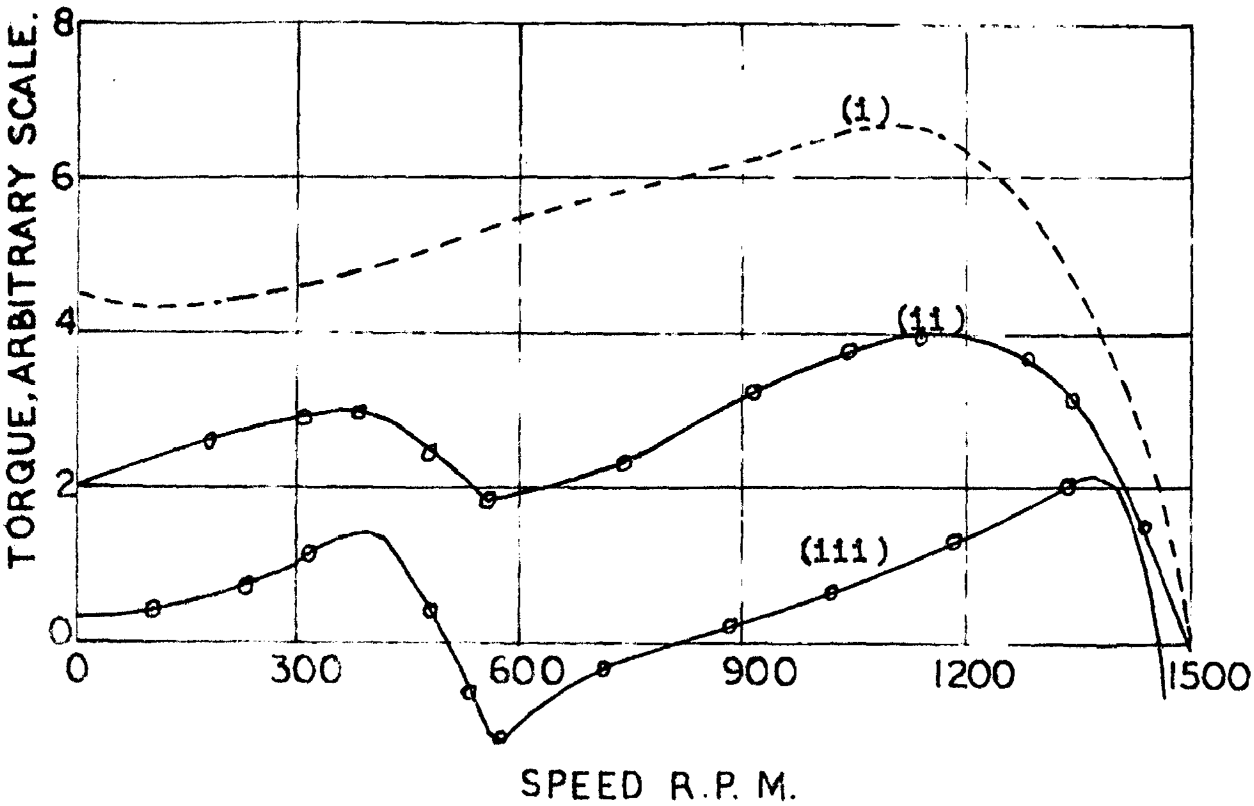


FIG. 4·10 TORQUE-SPEED CURVES FOR TEST MACHINE No. 1 STATOR WINDINGS IN EQUIVALENT 90° CONNECTIONS

Curve (i) Balanced 3-phase operation.

(ii) Single-phase operation with 25 μf capacitor.

(iii) Single-phase operation with 5 μf capacitor.

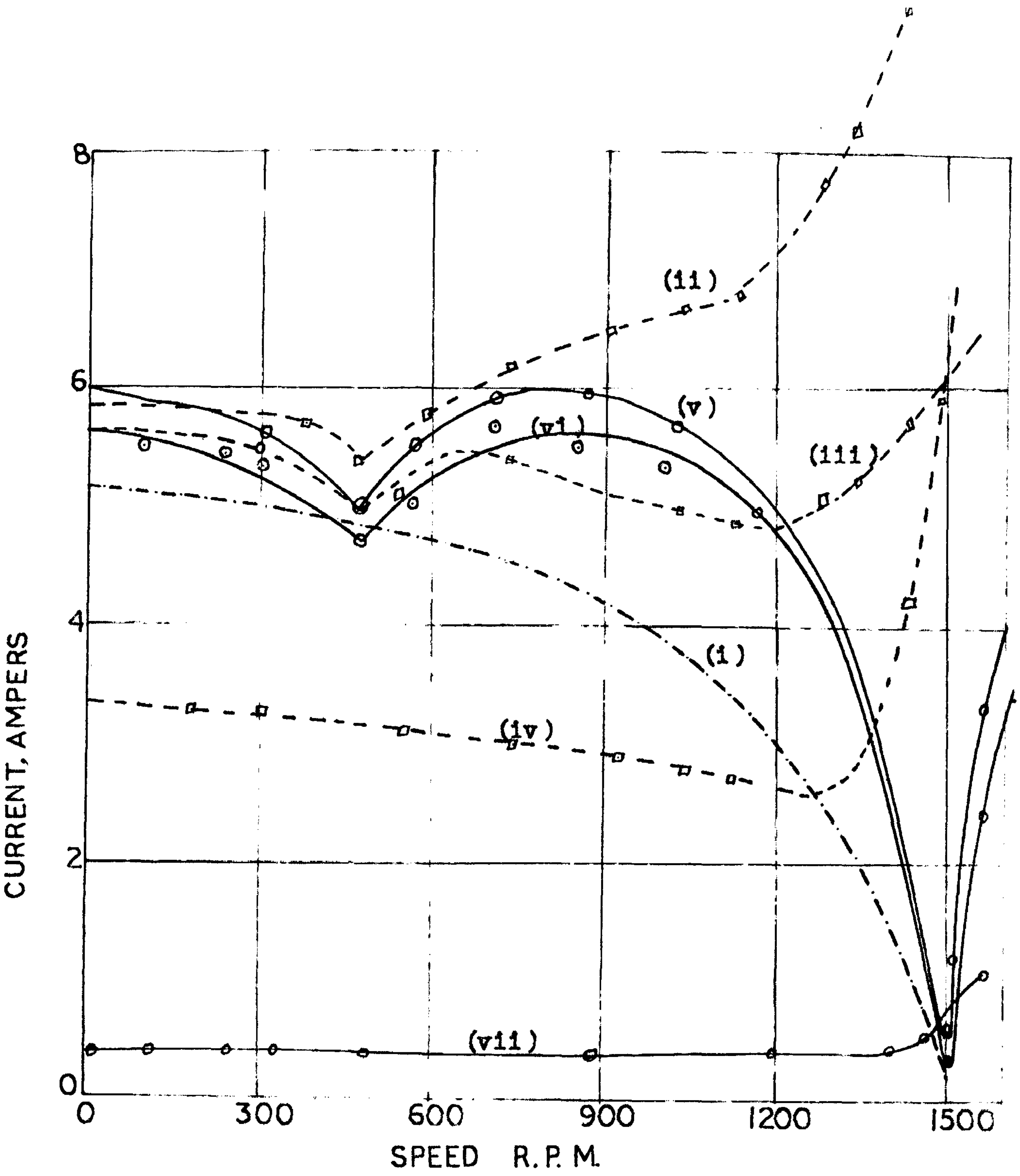


FIG. 4·11 CURRENT-SPEED CURVES FOR TEST MACHINE No. 1

STATOR WINDINGS IN EQUIVALENT 90° CONNECTIONS.

Curve (i) Balanced 3-phase operation, phase current.

Single-phase operation

(ii)	Line current	(v)	Line current
(iii)	A-phase current	(vi)	A-phase current
(iv)	Capacitor current with 25 µf.	(vii)	Capacitor curre[nt] with µ.

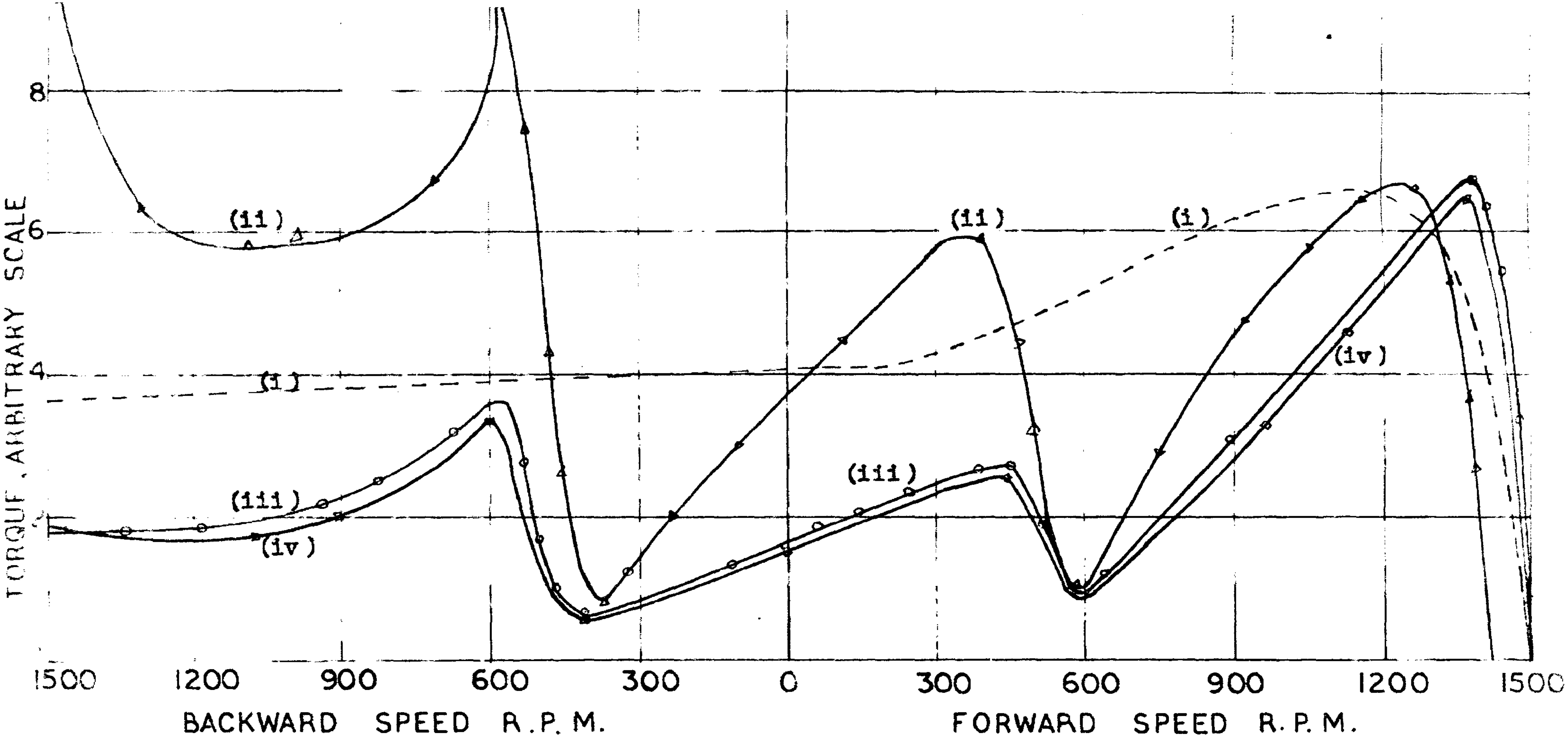


FIG.4·12 TORQUE-SPEED CURVES FOR TEST MOTOR Nº1
SINGLE-PHASE OPERATION WINDINGS AT 120° WITH A CAPACITOR.

Curve (i) Balanced 3-phase operation.

(ii) with 74 μf capacitor. (iii) with 47 μf capacitor.) k=1.

(iv) with 45½ μf capacitor. (Minimum third harmonic torque)

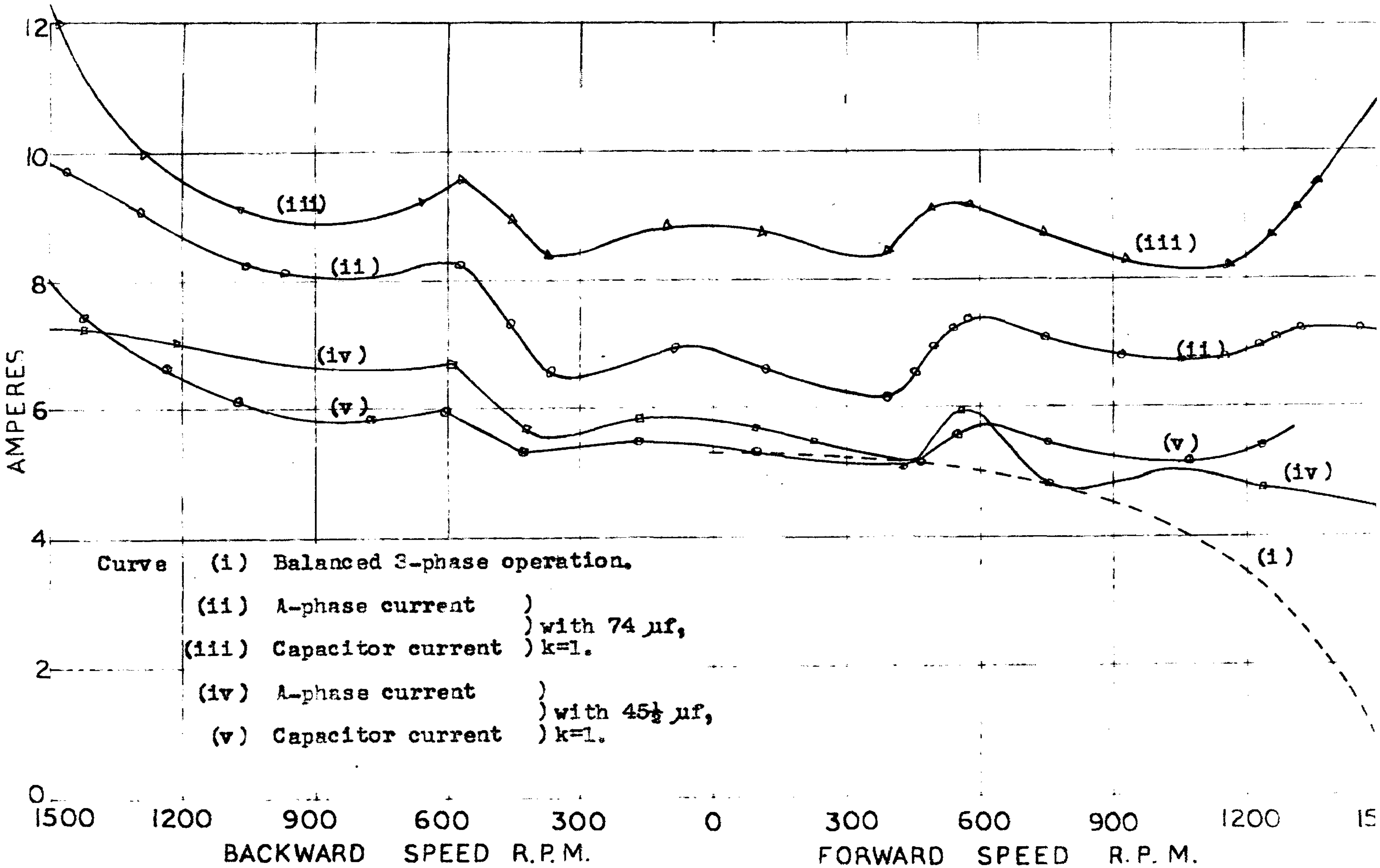


FIG. 4.13 CURRENT-SPEED CURVES FOR TEST MOTOR No. 1
SINGLE-PHASE OPERATION WINDINGS AT 120° WITH A CAPACITOR

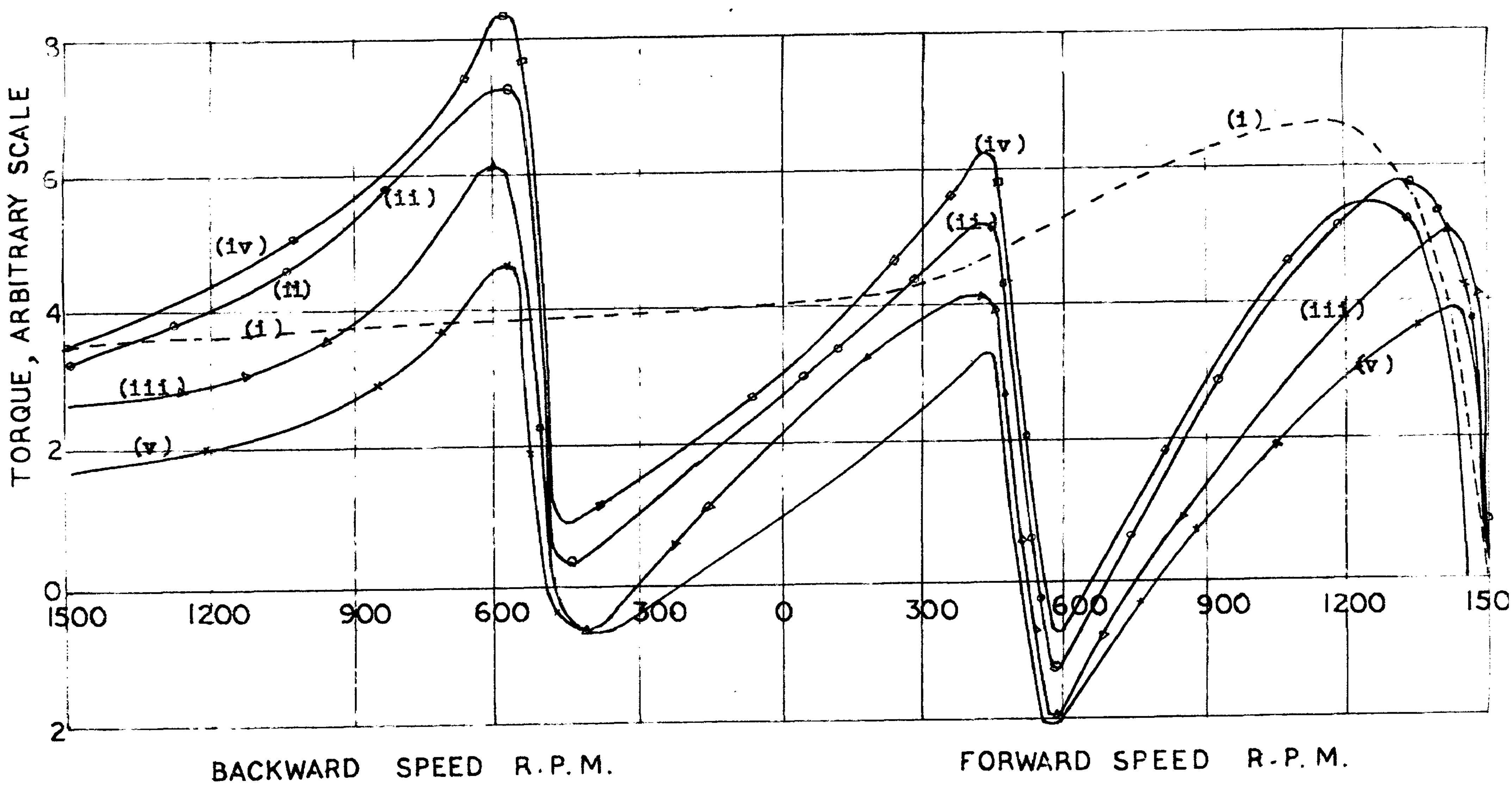


FIG. 4.14 TORQUE - SPEED CURVES FOR TEST MOTOR Nº 1
SINGLE-PHASE OPERATION WINDINGS AT 60° WITH A CAPACITOR.

Curve (i) Balanced 3-phase operation.

(ii) with 70 μf capacitor. (iii) with 50 μf capacitor.) k=1

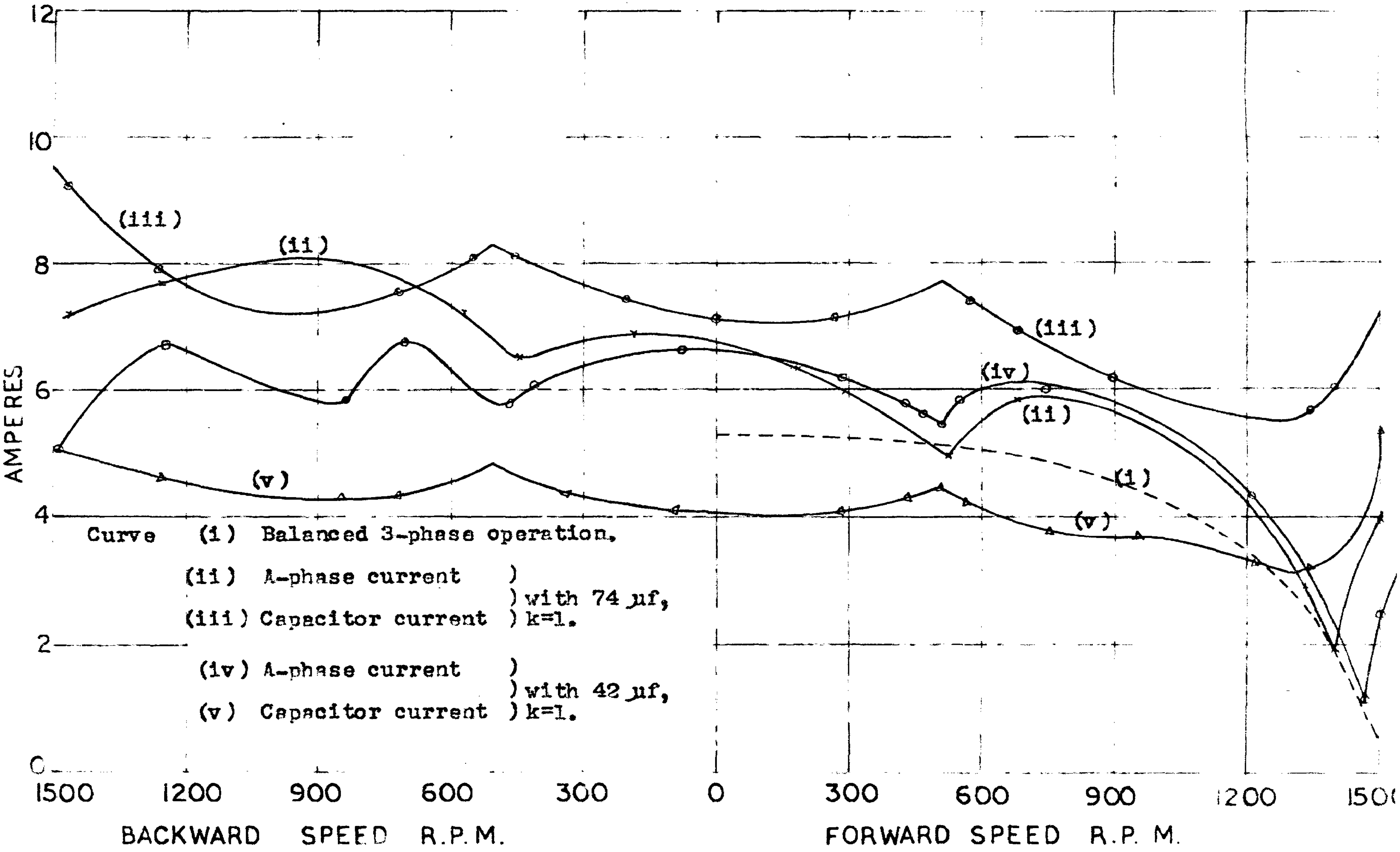


FIG. 4.15 CURRENT-SPEED CURVES FOR TEST MOTOR No 1

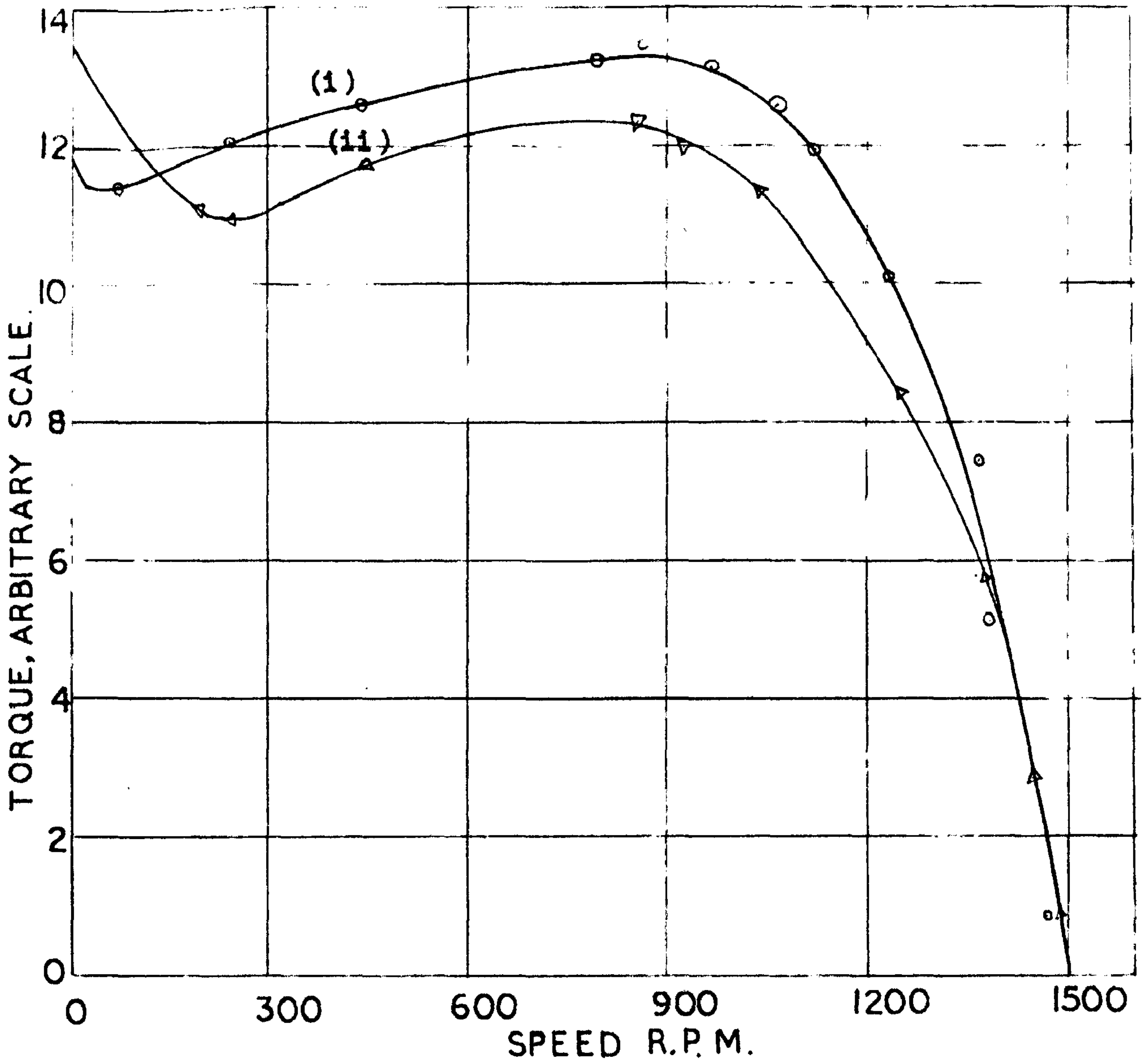


FIG. 4·16 TORQUE-SPEED CURVES FOR TEST MACHINE № 2

Curve (i) Balanced 3-phase operation, stator windings in st

(ii) Balanced 3-phase operation, stator windings in de

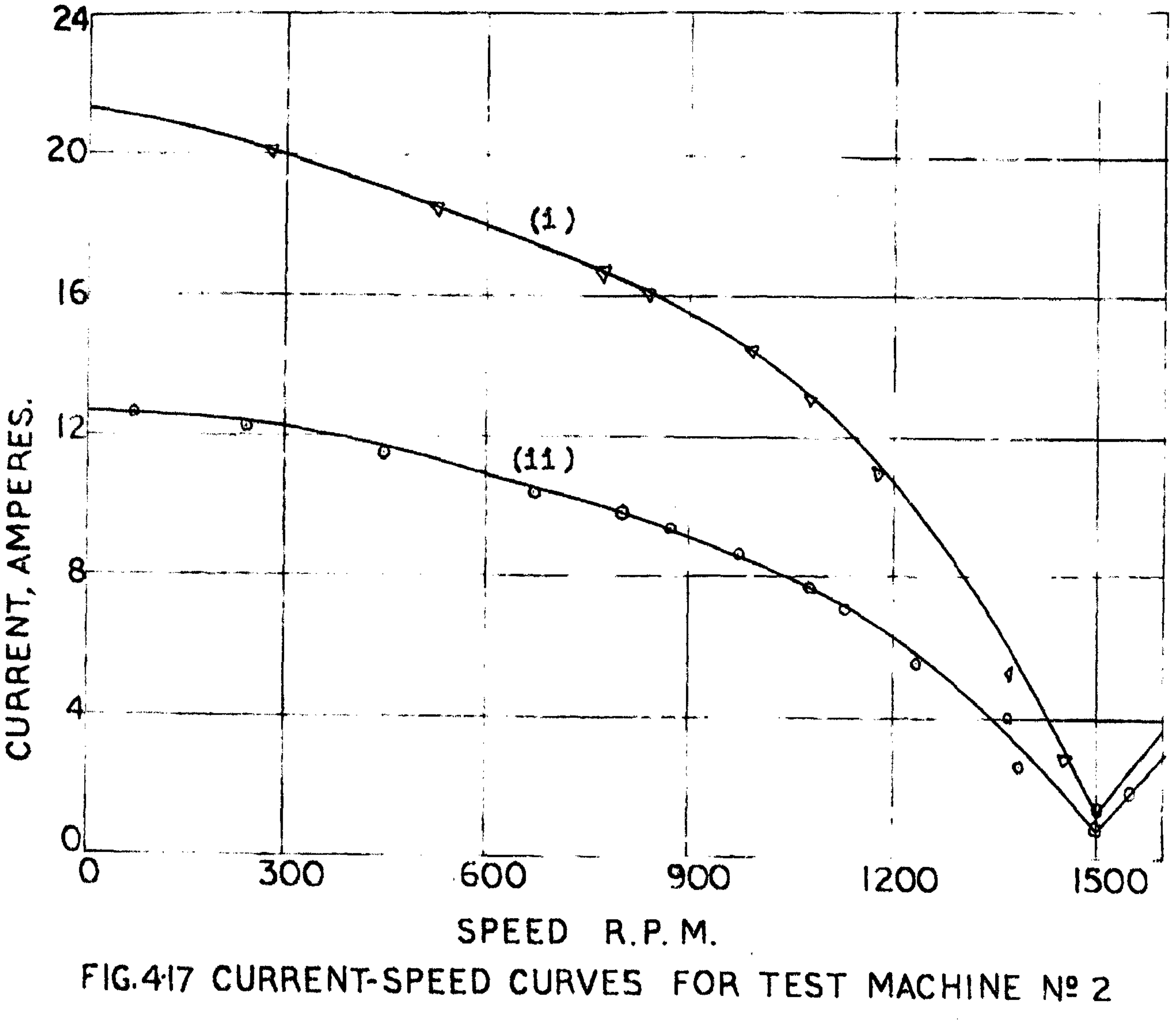


FIG. 4·17 CURRENT-SPEED CURVES FOR TEST MACHINE Nº 2

Curve (i) Balanced 3-phase operation, stator windings in de

(ii) Balanced 3-phase operation, stator windings in st

(Line currents)

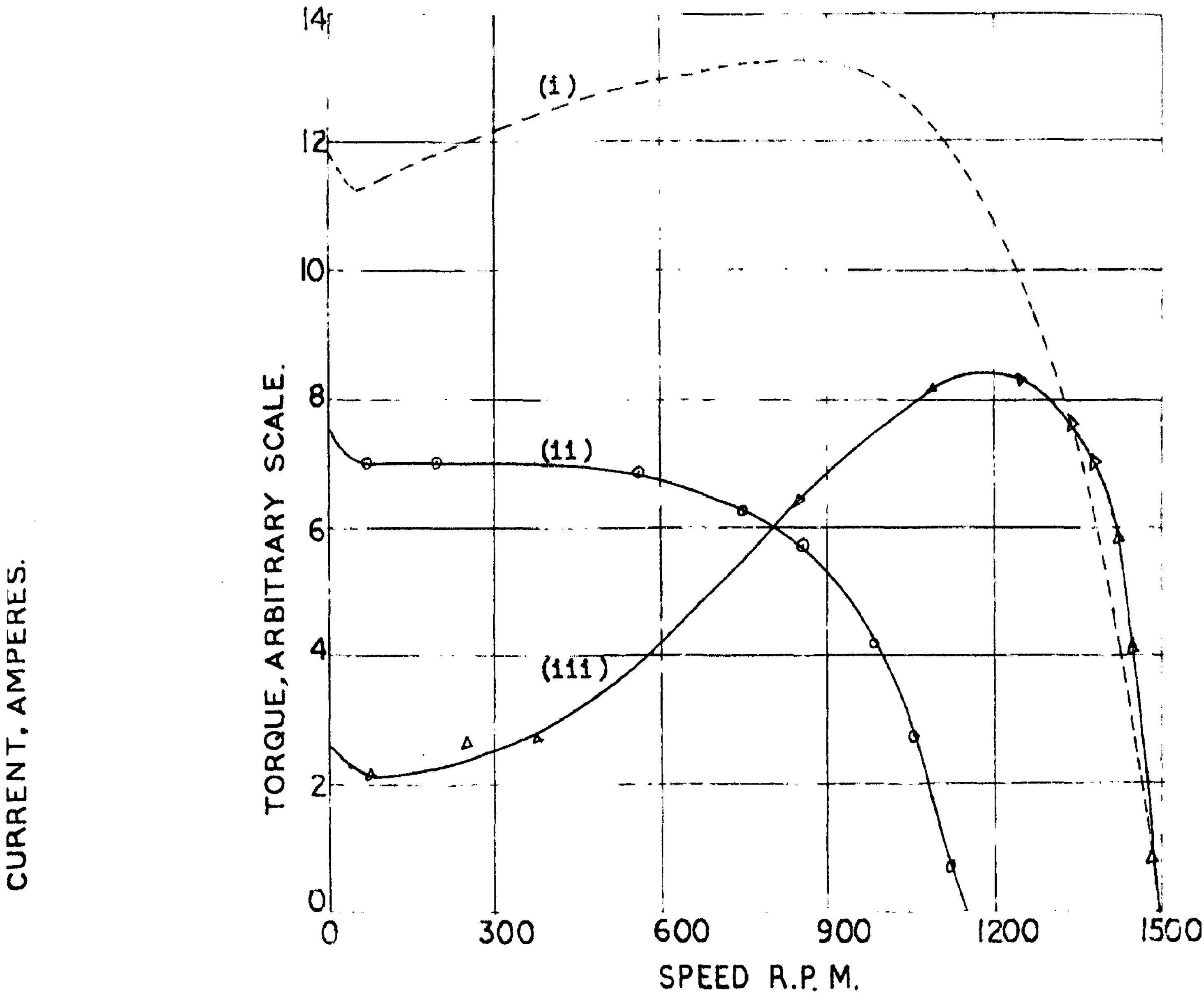


FIG. 4·18 TORQUE-SPEED CURVES FOR TEST MACHINE № 2
STATOR WINDINGS IN STAR

Curve (i) Balanced 3-phase operation.

(ii) Single-phase operation with 178 µf capacito

(iii) Single-phase operation with 50 µf capacitor

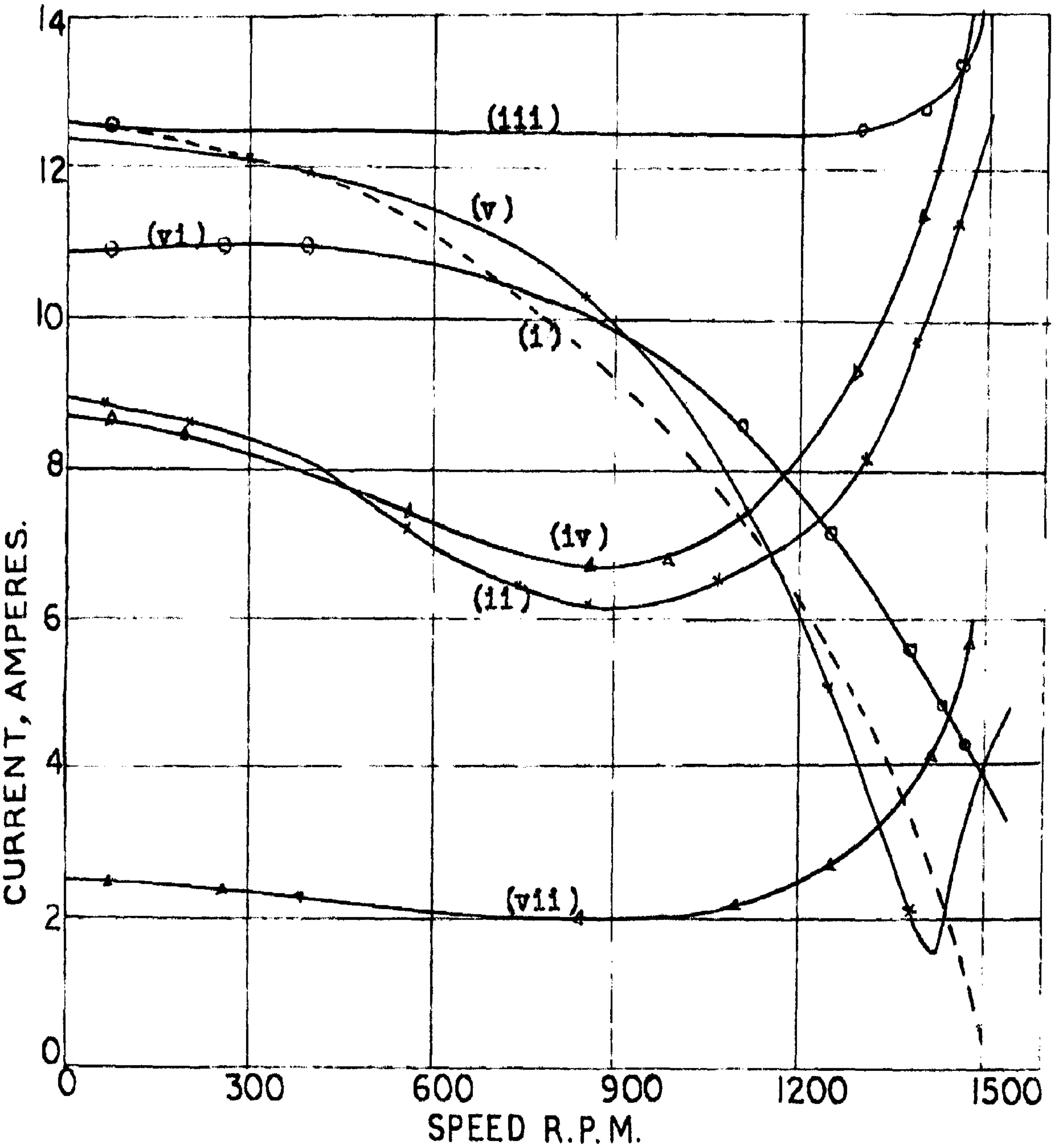


FIG. 4.19 CURRENT-SPEED CURVES FOR TEST MACHINE № 2 STATOR WINDINGS IN STAR.

Curve (i) Balanced 3-phase operation.

(ii) A, (iii) B and (iv) C-phase currents with 178 μf capacit...

(v) A, (vi) B and (vii) C-Phase currents with 50 μf capacit...

Single phase operation with a capacitor in circuit.

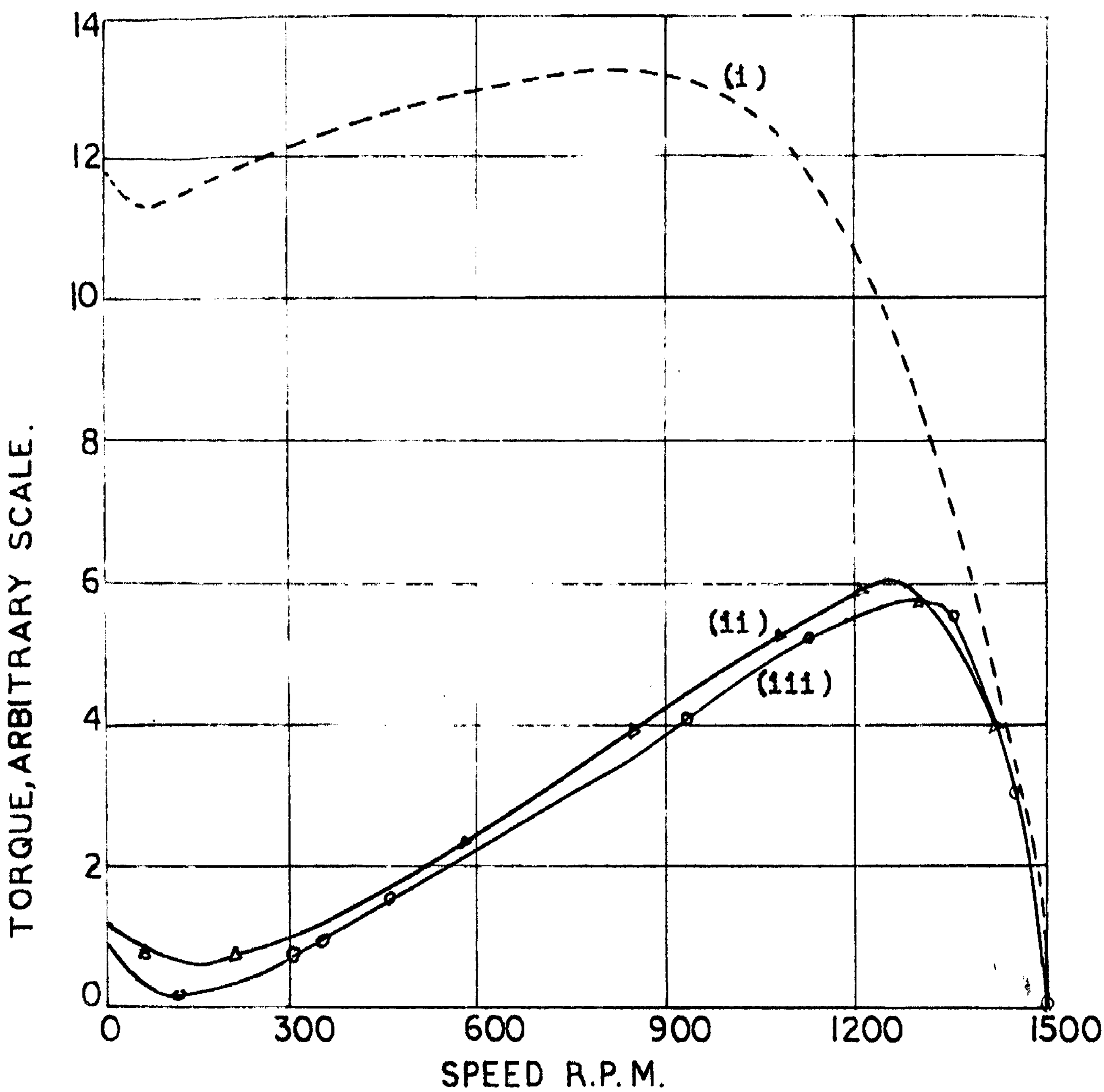


FIG. 4.20 TORQUE-SPEED CURVES FOR TEST MACHINE No. 2
STATOR WINDINGS IN DELTA.

Curve (i) Balanced 3-phase operation.

(ii) Single-phase operation with 186 μf capacitor.

(iii) Single-phase operation with 140 μf capacitor.

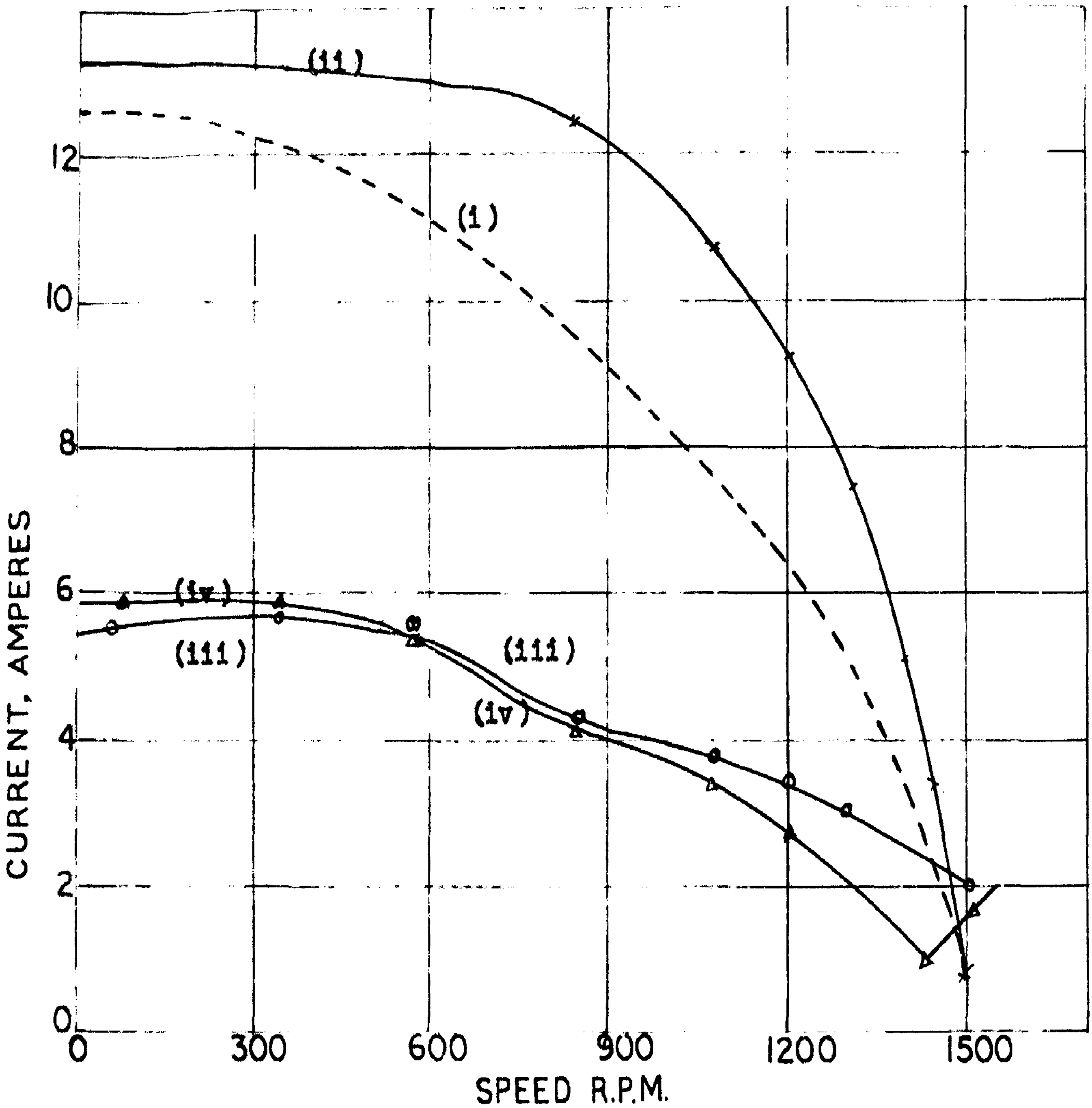


FIG. 4·21 CURRENT-SPEED CURVES FOR TEST MACHINE Nº 2
STATOR WINDINGS IN DELTA

Curve (i) Balanced 3-phase operation.

(ii) A, (iii) B and (iv) C-phase currents. Single-phase operation with 136 μf capacitor.

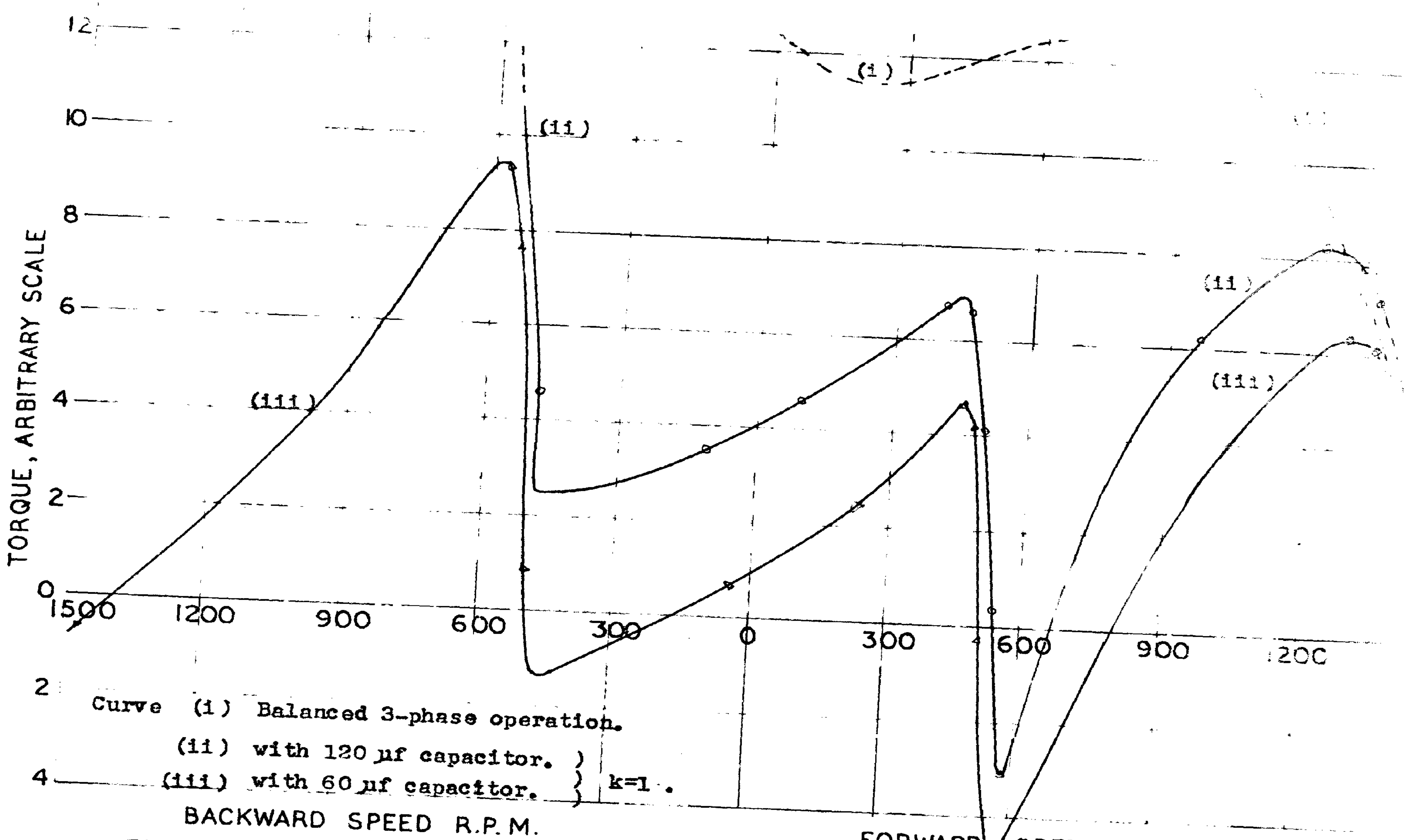


FIG. 4·22 TORQUE - SPEED CURVES FOR TEST MOTOR № 2
SINGLE-PHASE OPERATION WINDINGS AT 120° WITH A CAPACITOR.

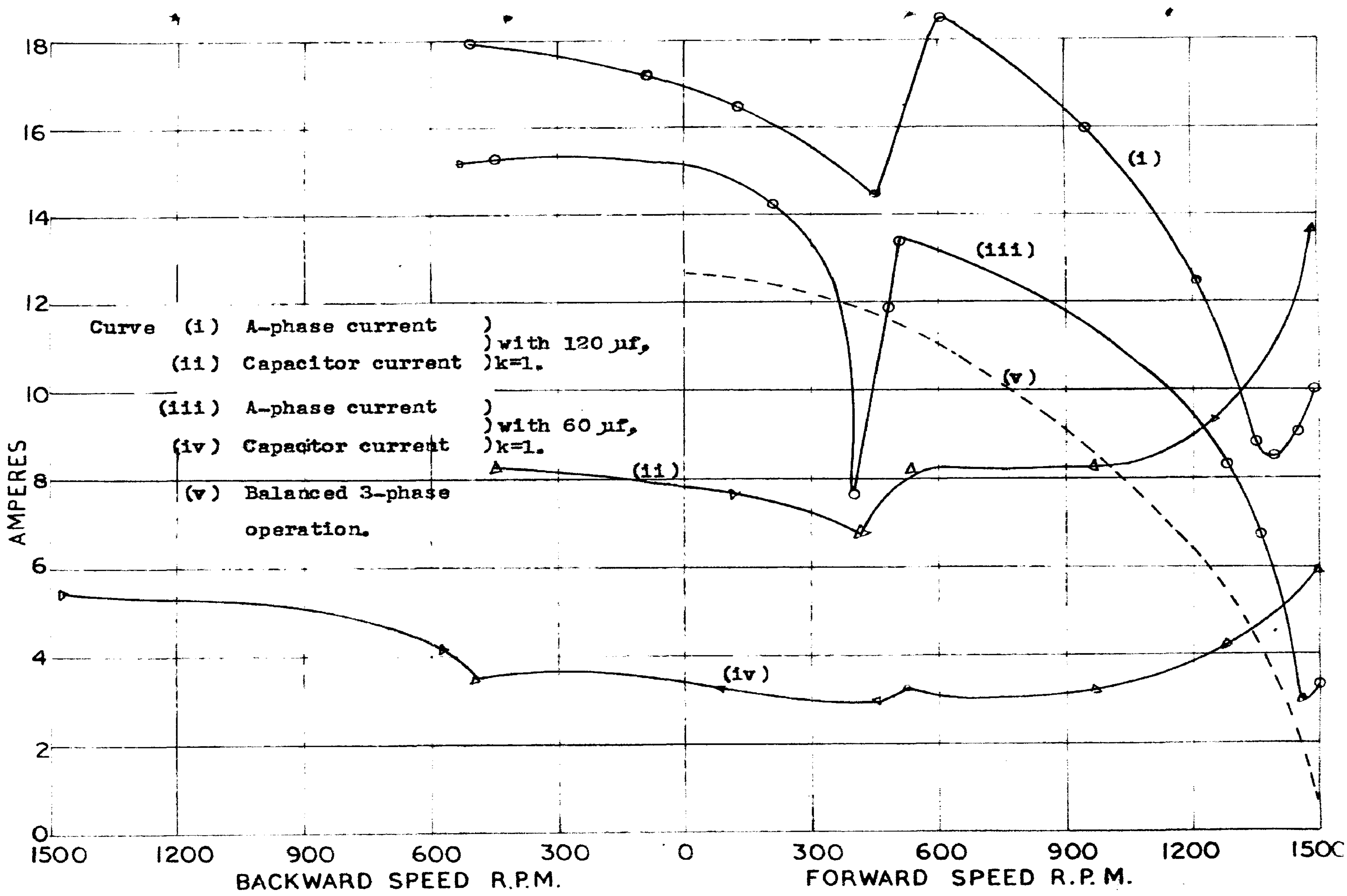


FIG. 4.23 CURRENT-SPEED CURVES FOR TEST MOTOR № 2
SINGLE-PHASE OPERATION WINDINGS AT 120° WITH A CAPACITOR.

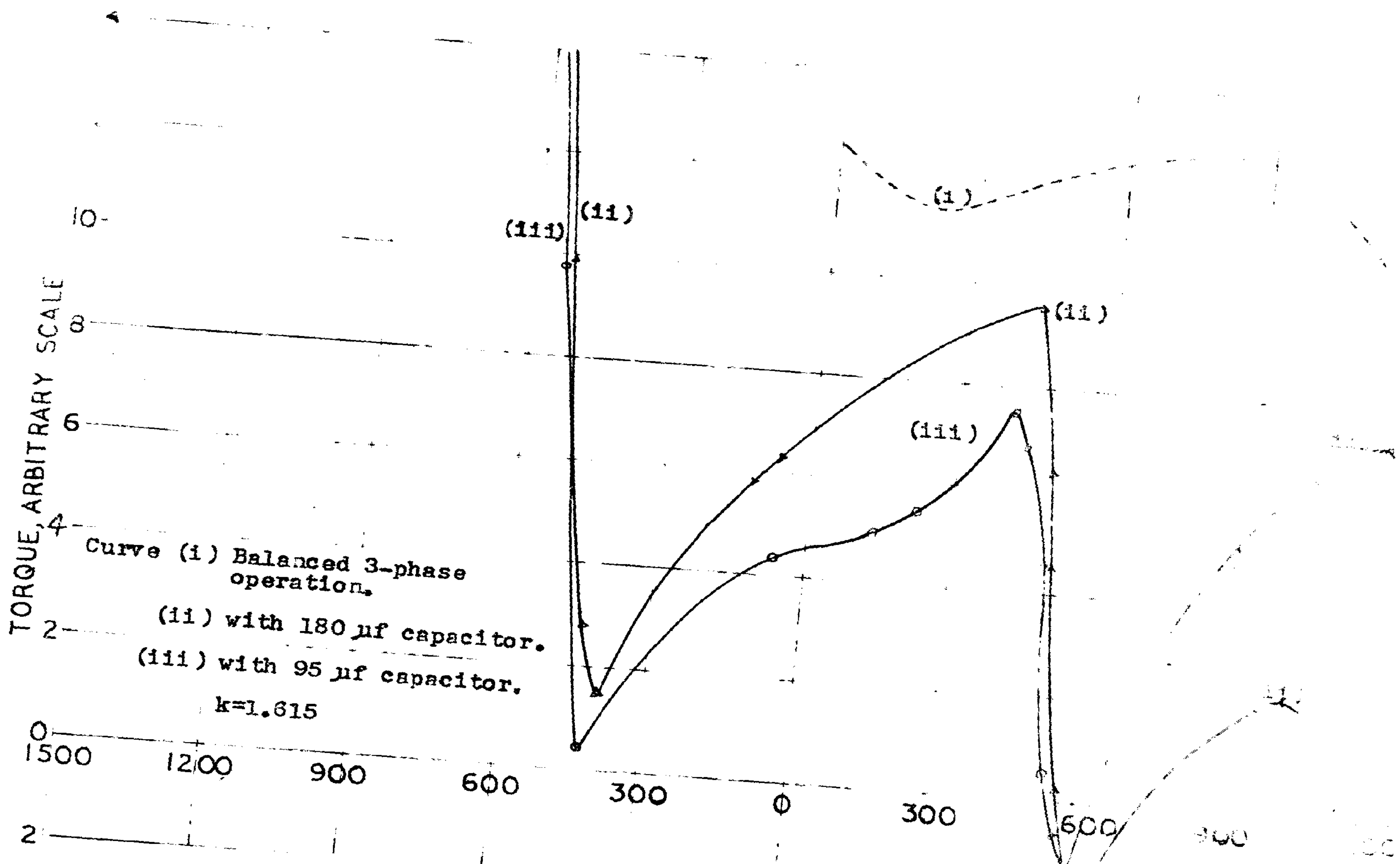


FIG. 4·24 TORQUE-SPEED CURVES FOR TEST MOTOR ... SINGLE-PHASE OPERATION WINDINGS AT 120° WITH A CAPACI...

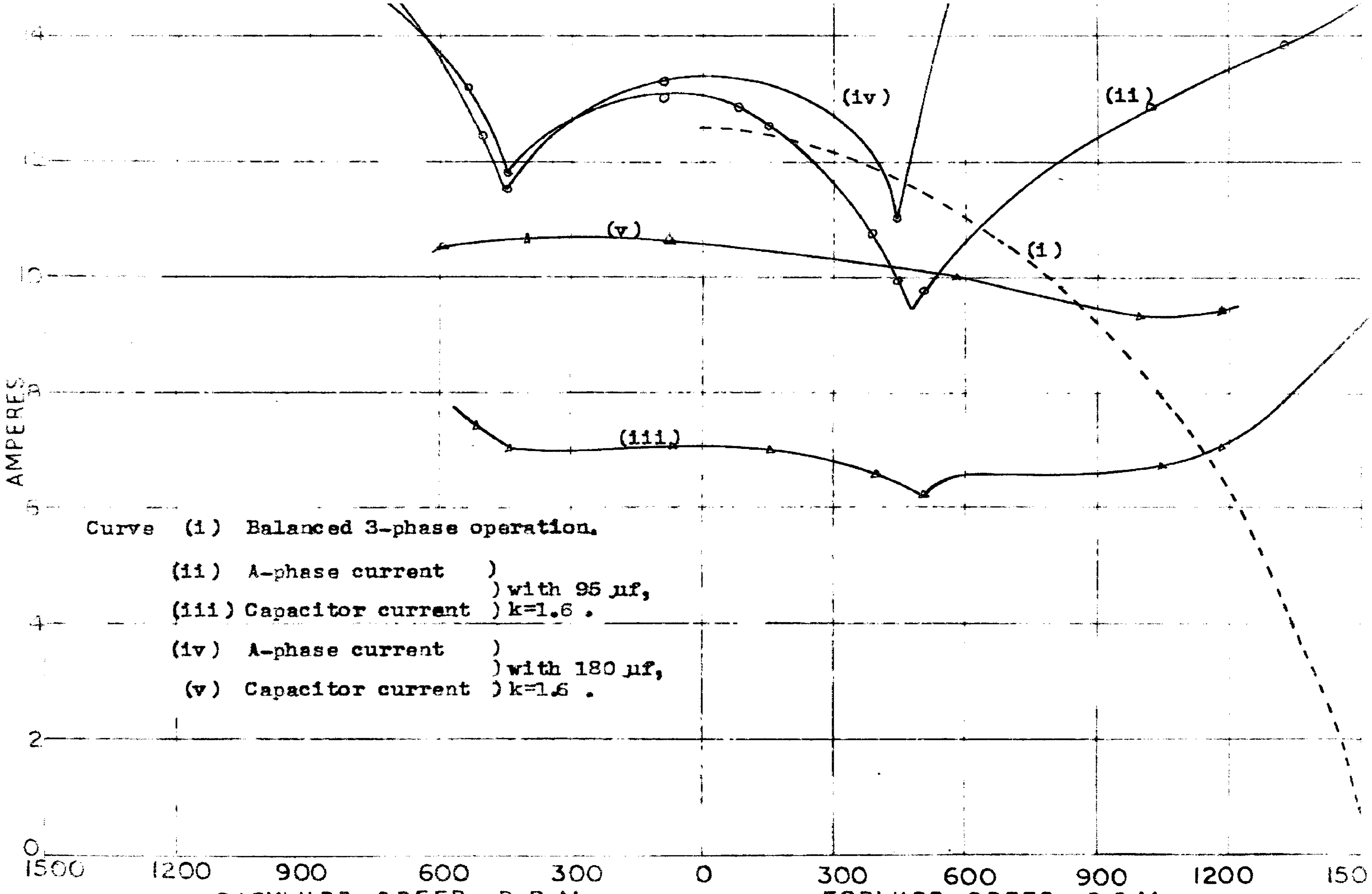


FIG. 4·25 CURRENT-SPEED CURVES FOR TEST MOTOR № 2
SINGLE-PHASE OPERATION WINDINGS AT 120° WITH A CAPACITOR

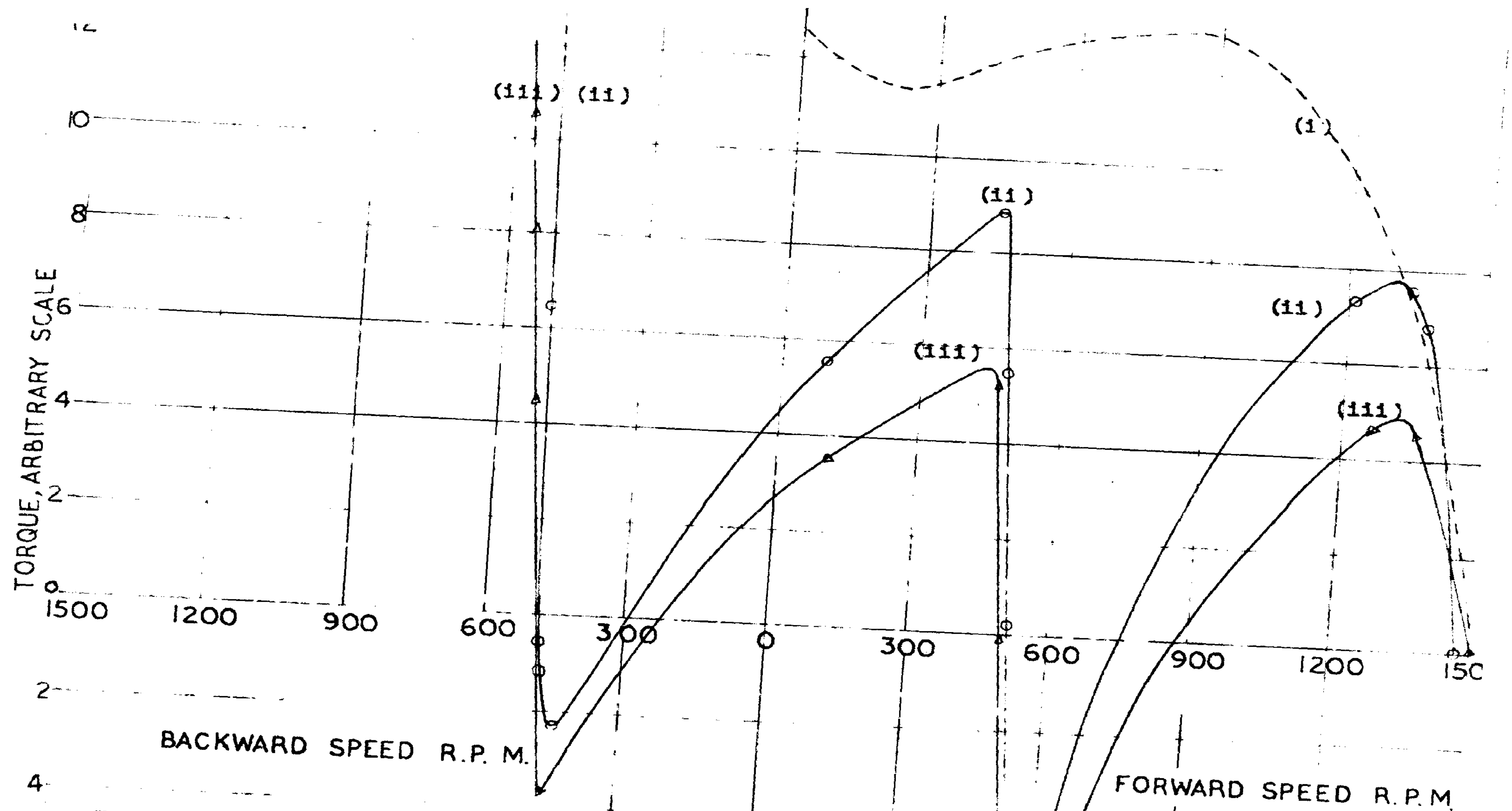


FIG. 4·26 TORQUE-SPEED CURVES FOR TEST MOTOR No. 2 SINGLE-PHASE OPERATION WINDINGS AT 60° WITH A CAPACITOR.

Curve (i) Balanced 3-phase operation.

(ii) with 160 μf capacitor. } k=1.
(iii) with 60 μf capacitor. }

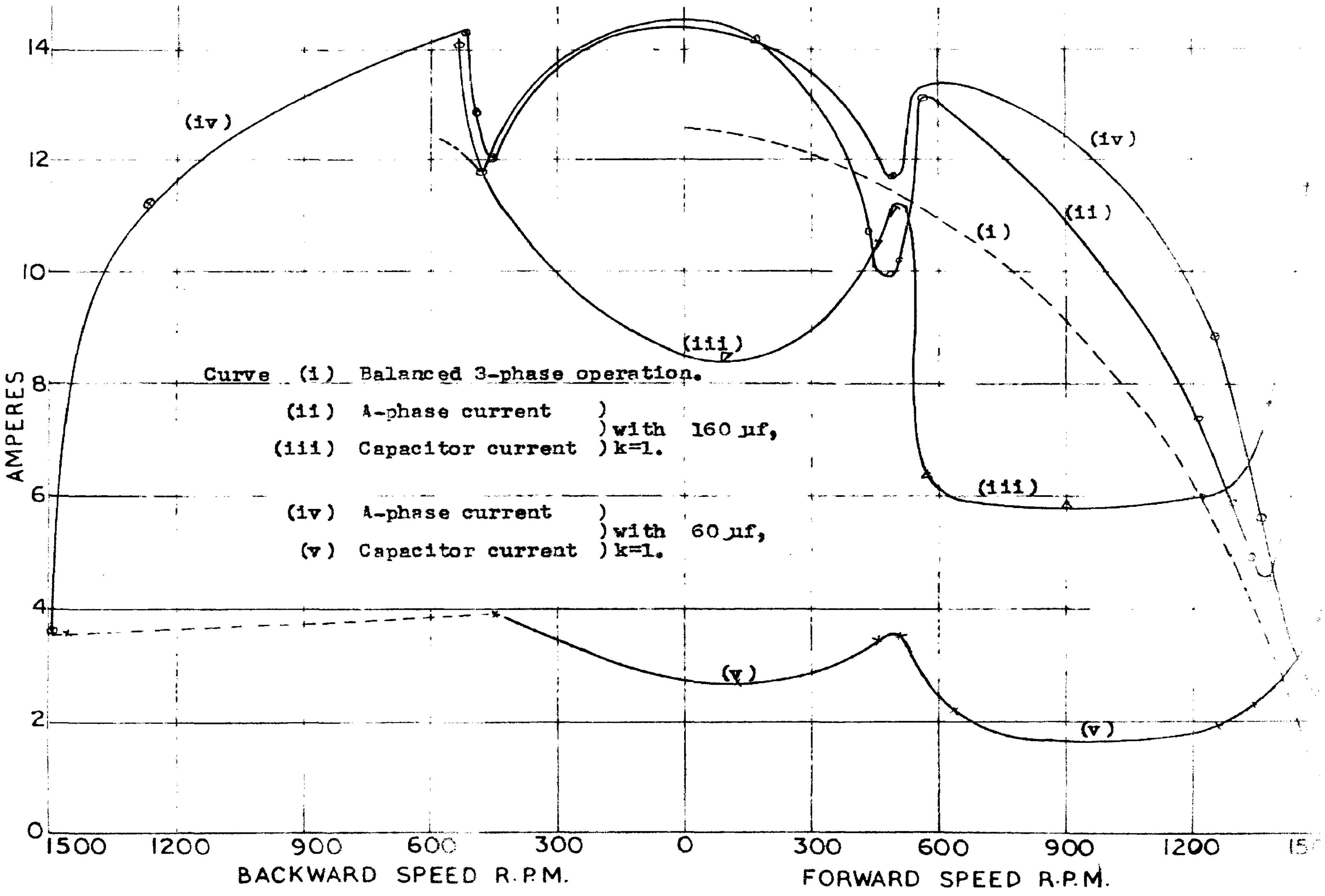


FIG. 427 CURRENT-SPEED CURVES FOR TEST MOTOR NO.2
SINGLE-PHASE OPERATION WINDINGS AT 60° WITH A CAPACITOR

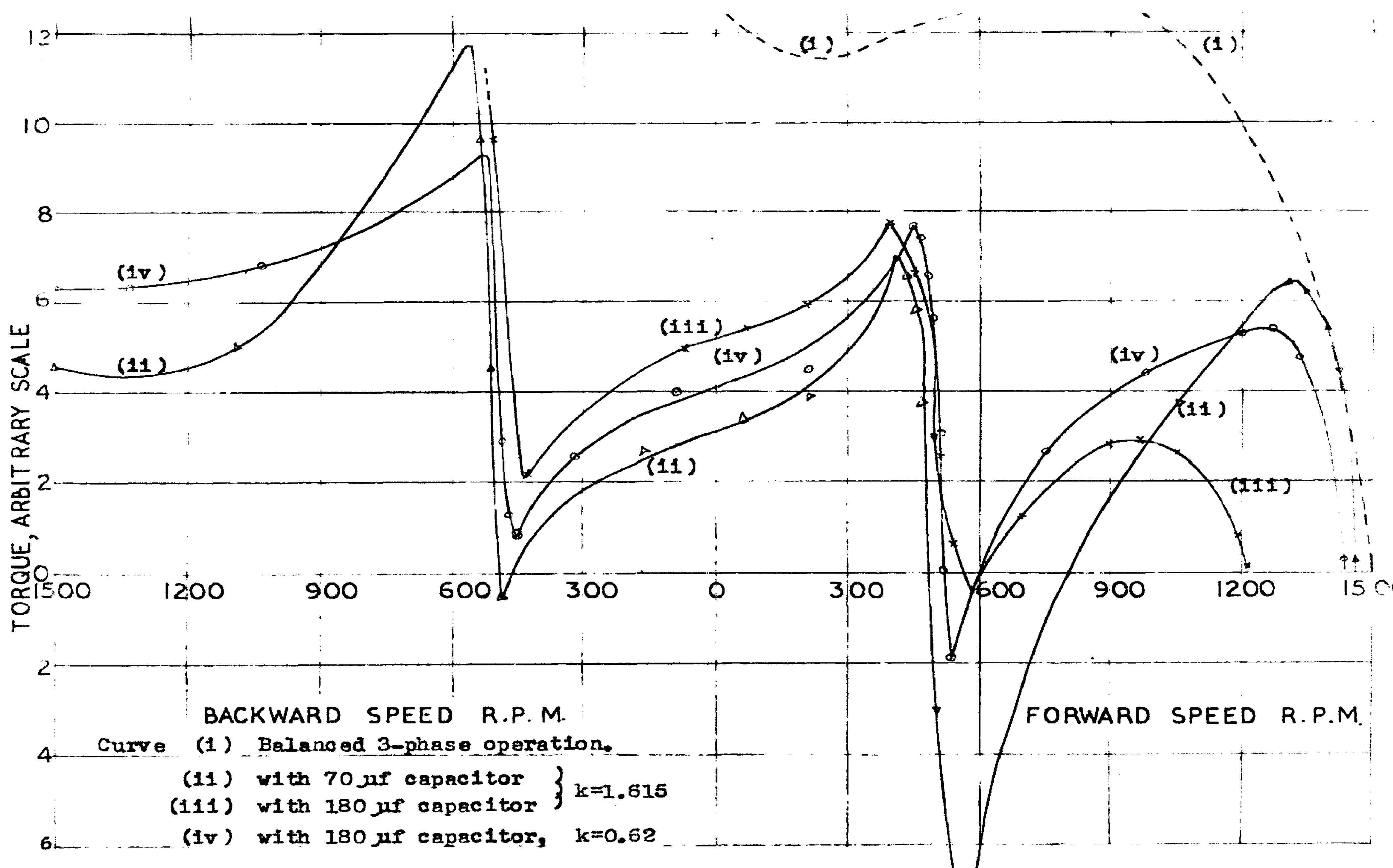


FIG. 4.28 TORQUE-SPEED CURVES FOR TEST MOTOR Nº 2 SINGLE-PHASE OPERATION WINDINGS AT 60° WITH A CAPACITOR.

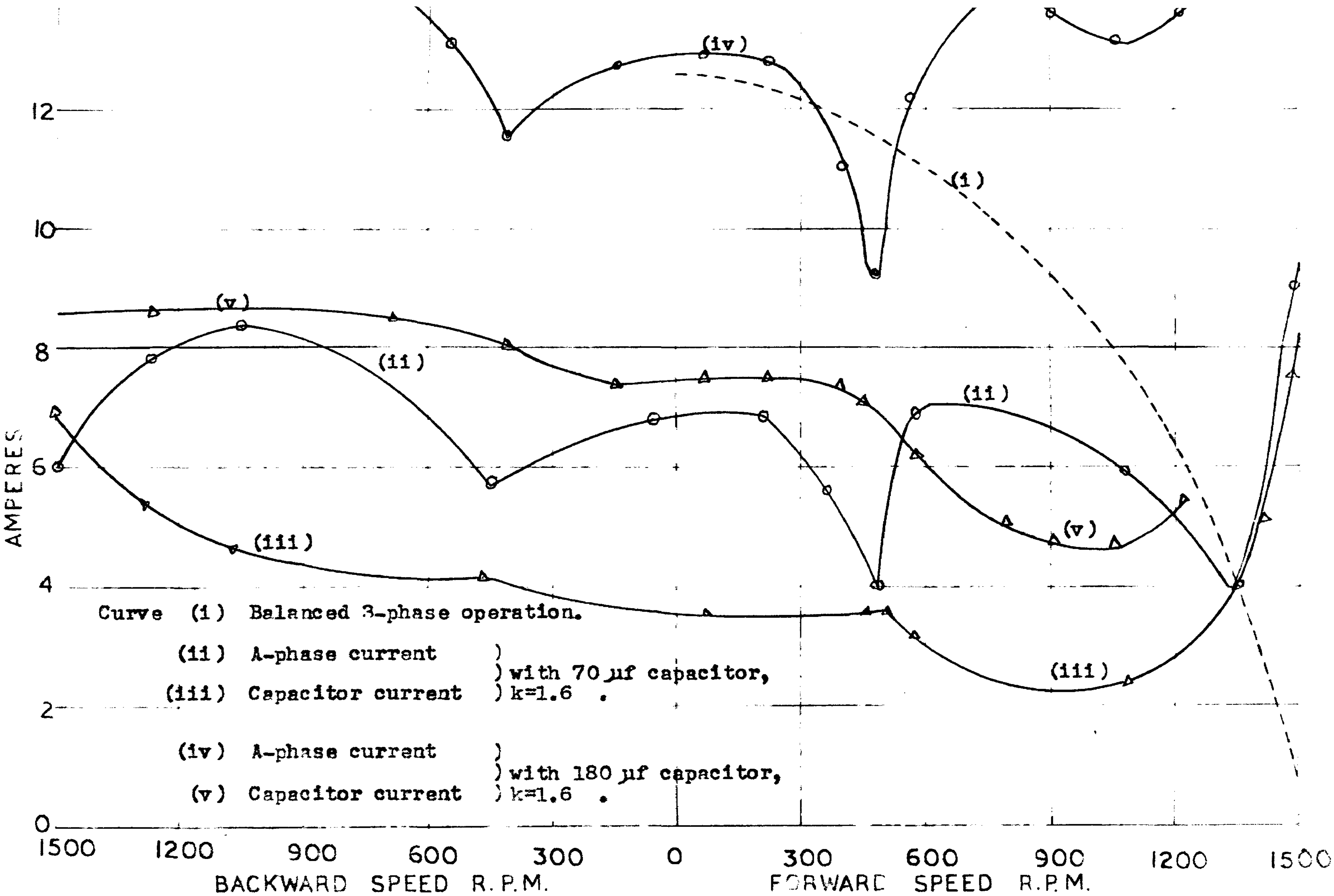


FIG 4.29 CURRENT-SPEED CURVES FOR TEST MOTOR № 2

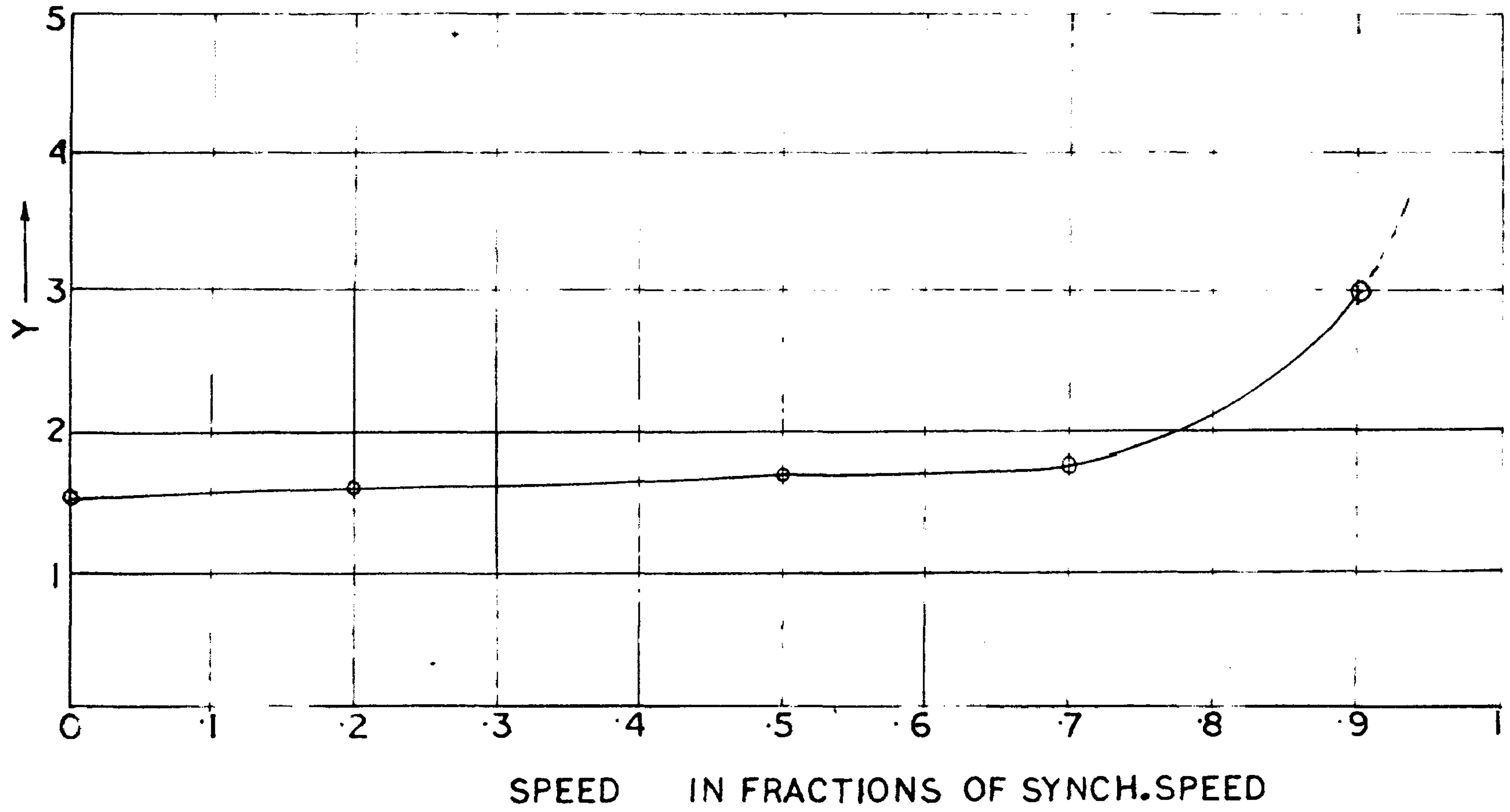
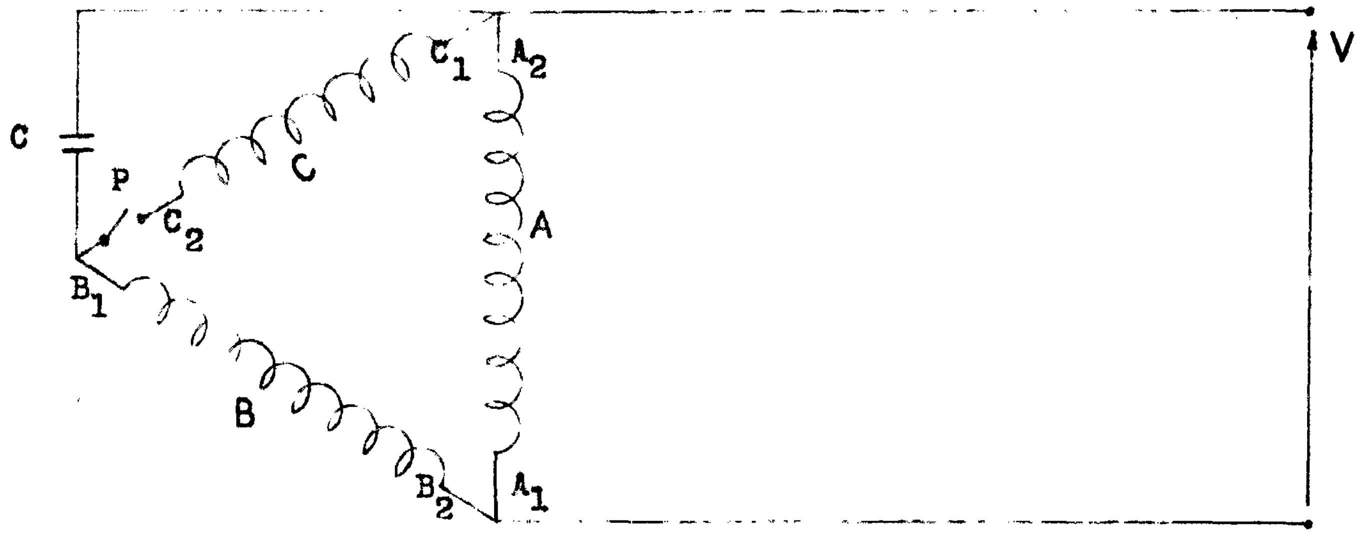


FIG.43 VARIATION OF Y WITH THE SPEED GIVING MAXIMUM TORQUE.

(SINGLE-PHASE OPERATION, WINDINGS IN STAR WITH A CAPACITOR)



·51 STATOR WINDING ARRANGEMENT FOR NORMAL & ONE-THIRD SPEED OPERATION.

C is a capacitor used as a phase-convertor.

Switch P is closed for normal speed operation. And is kept open for one-third speed operation.

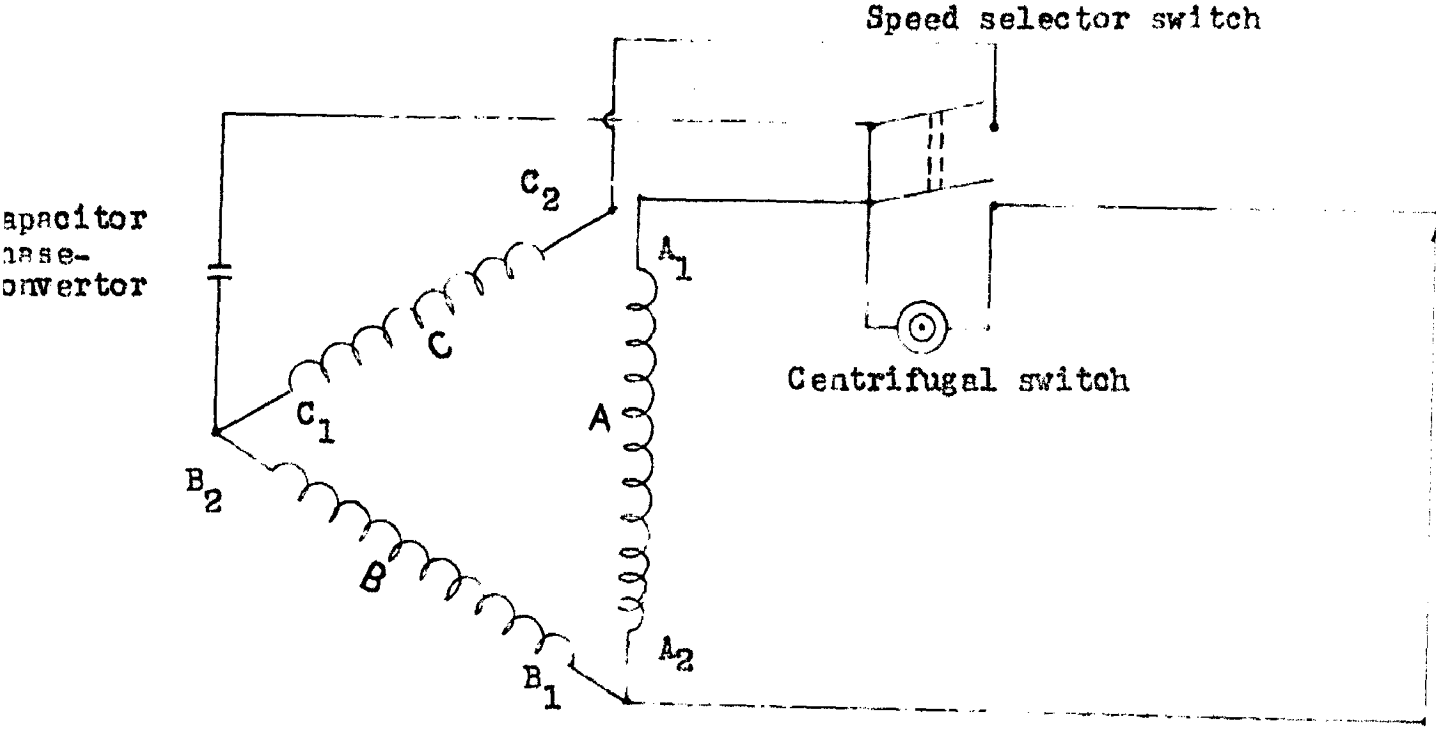
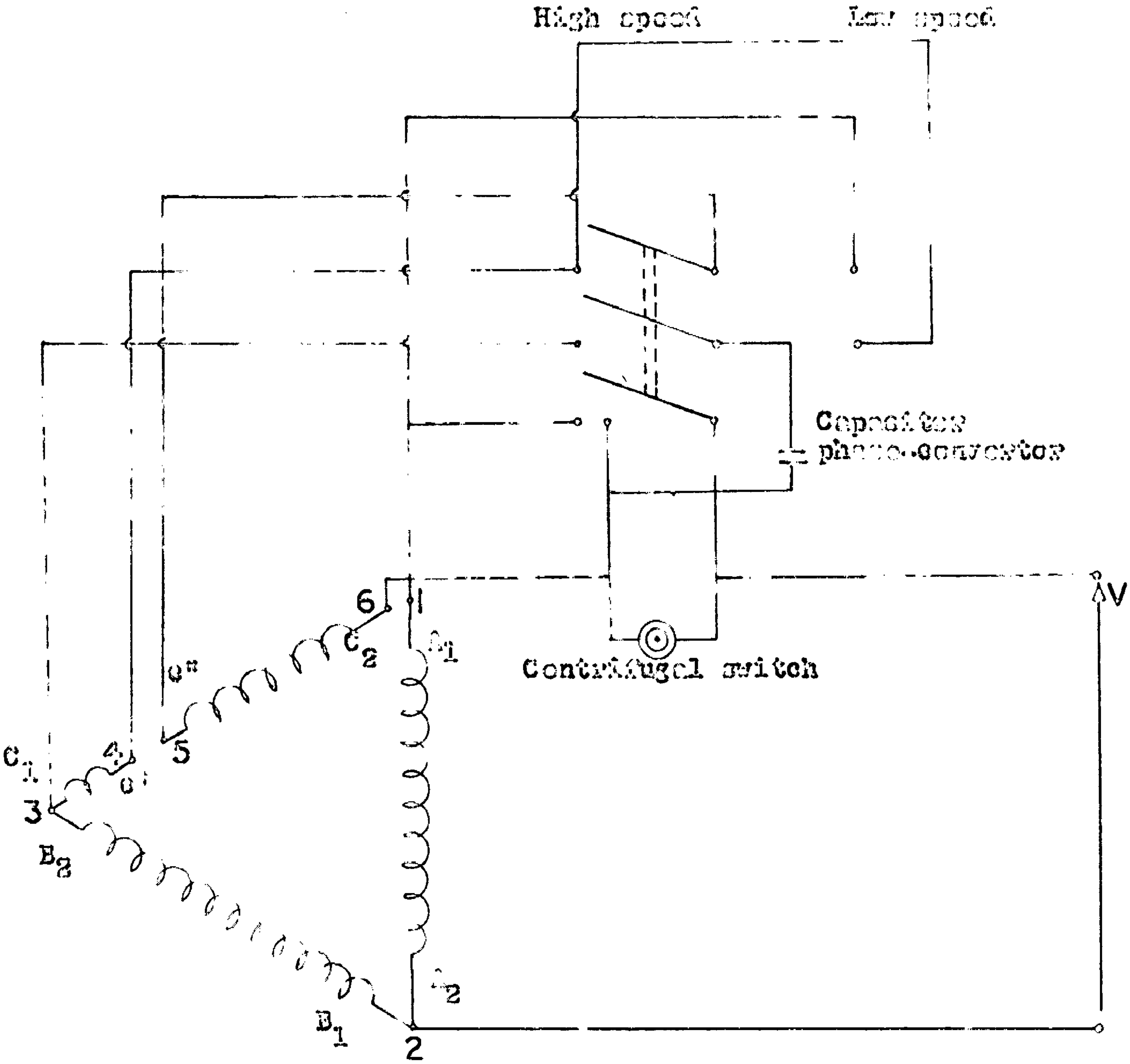


FIG.4·52 LOW-HIGH & HIGH-LOW SWITCHING CIRCUIT FOR A NORMAL 3-PH INDUCTION MOTOR.

Speed selector switch is closed for normal speed operation. And is opened for one-third speed operation.

Centrifugal switch { ON – below 35% normal speed
{ OFF – above 35% normal speed



.453 LOW-HIGH & HIGH-LOW SWITCHING CIRCUIT FOR PROPOSED TWO-SPEED CAPACITOR MOTOR.

Centrifugal switch: ON below 35% normal speed, OFF above [illegible]% normal sp

5. MAIN CONCLUSIONS, APPLICATIONS AND SUGGESTIONS FOR FUTURE WORK

5.1 Main Conclusions

The main purpose of the work embodied in this dissertation was to investigate the possibility of using a standard three-phase induction machine to run at two stable speeds in the ratio of 1:3 from a single-phase supply with the help of suitable convertors. Numerous different arrangements were analysed and experimented on and it has been shown that it is possible to operate a three-phase machine satisfactorily from a single-phase supply at 2-speeds. The main points of interest are:

i) The stator windings are connected in delta as shown in Figs.3.1(b) for the normal speed operation. Proper choice of capacitor gives a very satisfactory operation at this speed with normal rating.

ii) The windings are rearranged to be connected with displaceme angle of 60°, for the one-third speed operation (see Fig.7. Though considerable torque is obtained with high value of capacitor, it is recommended to use a lower value to enable currents to be low and get a higher rating of the machine.

iii) The switching arrangement for the machine is extremely simple and consists of only six terminals.

iv) Since the machine is standard three-phase, no extra labour is required in design except when it is desired to use all three phases in one-third operation, one of the windings ha to be splitted in the ratio 4:13. This does not involve a great deal of extra skill or labour. The improved performance with such arrangement would justify the slight extra labour cost of the winding.

v) When a three-phase motor is operated normally from a single-phase supply, the maximum safe out-put is usually about 63%. The 2-speed machine under investigation will also give about 63% power out-put at normal speed and 22% power out-put (equivalent to the same torque) at one-third speed within the permissible temperature limits. One interesting fact in favour of the one-third operation is that the motor at this speed could be loaded right upto the maximum pull-out torque at this speed without affecting the currents in the machine appreciably. It can be seen that upto about 33% power out-put could be continually obtained in this connection without inju to the motor or without much change in efficiency. In this respect therefore it differs from other induction machines which in general cannot be run near pull-out condition for more than a very short period.

vi) The experimental study of the motor has indicated that when the stator windings are in star the number of capacitors of different capacities can be reduced only to two for both the operations. But if the windings are in delta, the number of capacitors may rise to three for satisfactory operation of the machine at both the speeds.

5.2 Applications

The availability of a speed as low as one-third full speed is advantageous in a number of industrial drives. For example, those applications where operation is normally at full speed, but a low speed is also required for accurate positioning, such as various machine-tools. Again, in the case of reciprocating pumps and axialflow fans, the availability of one-third full speed facilitates economic operation during periods of low demand. Further, certain drives require two discrete speeds during each cycle of duty, such as machines using quick-return motion, automatic drilling and tapping machines using a slow feed and quick withdrawal and tool-feed motions for which a quick traverse is occasionally required.

5.3 Suggestions for Future Work

The work described in this thesis has been brought to a satisfactory conclusion by investigating and analysing the behaviour of a two-speed motor having the most commonly used type of stator winding. However there remain certain topics requiring further detailed investigation which are given below:-

In the text of this thesis, no consideration has been given to the use of an asymmetrical three-phase arrangement. Due to the asymmetrical windings a large third harmonic field will be developed in the air gap of the machine which may be used to improve the performance of the machine at one-third speed. Though the same will give the run-up troubles when the motor is connected for full-speed operation. If the amplitude of the forward-component of the third harmonic field could be kept small, when the motor is connected for full-speed operation, it is possible that the asymmetrical three-phas arrangement may prove to be a better economic proposition. In any case the problem provides interesting possibilities.

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CHAPTER-7

APPENDICES

7.1 Fourier Series for the M.M.F. Wave.

7.2 Design of the Induction Motor used for Testing.

7.1 Fourier Series for the m.m.f. Wave.

The m.m.f. of a single-phase belt of m coils fed with alternating current of frequency $\omega/2\pi$ cycles per second is trapezoidal in shape and can be expressed in terms of a Fourier series with constant co-efficients as

$$F_{ph} = (4/\pi)\, m\, F_m \left(K_1 \cos \omega t \cos x + \dots + \frac{1}{n} K_n \cos \omega t \cos nx + \dots\right) \qquad (7.11)$$

where F_m is the peak ampere turns per coil and the co-efficients K_1, K_2 .... K_n etc. are respectively the winding factors for the fundamental, the second .... and the n^{th} harmonic field.

In a symmetrical phase winding, the consecutive phase belts are spaced π electrical radians apart and carry currents that are opposit in time phase. Hence the even harmonic terms will disappear. The m.m.f. of a symmetrical phase winding is therefore given by

$$F_{ph} = (4/\pi)\, m\, F_m \cos \omega t \left(K_1 \cos x + \frac{1}{3} K_3 \cos 3x + \dots + \frac{1}{n} K_n \cos nx + \dots\right) \qquad (7.12)$$

The three phase winding which is distributed in space will carry the same current and the resultant m.m.f. will be the summation of the three m.m.f. waves as is represented in equation (7.12) but with the only change that 2nd and third phase m.m.f. will now have terms (x + 240) and (x + 120) instead of x.

The n^{th} harmonic component of m.m.f. wave for three phases will b

$$F_{1n} = (4/\pi)\, m\, F_m (K_n/n) \cos \omega t \cos nx \qquad (7.13)$$

$$F_{2n} = (4/\pi)\, m\, F_m (K_n/n) \cos \omega t \cos(n(x + 240) \qquad (7.14)$$

$$F_{3n} = (4/\pi)\, m\, F_m (K_n/n) \cos \omega t \cos n(x + 120) \qquad (7.15)$$

The resultant harmonic component will be

$$F_{nx} = F_{1n} + F_{2n} + F_{3n}$$
$$= (4/\pi)\, m\, F_m\, (K_n/n) \cos \omega t \left[\cos nx + \cos n(x + 240) + \cos n(x + 120)\right]$$
$$= K_n F_n' \cos \omega t \cos(nx + 2n\pi/3)(1 + 2\cos 2n\pi/3) \qquad (7.16)$$

where $F_n' = (4/\pi)(m/n) F_m$ or amplitude of the n^{th} harmonic m.m.f. of each phase, when each phase winding is considered to be of non-distributed and full pitch form.

7.2 Design of the Induction Motor used for Experimental Work.

For experimental work a motor was required in which the full periphery of the stator was used even when the resultant angle between the two winding axes is either 60^o or 120^o. Also as the motor is to run as a balanced three-phase machine when connected for full speed operation. So the motor is to be designed as a normal three-phase induction motor. To limit the number of terminals of the motor, it was supposed convenient that while the two windings of the two phases are connected either at 60^o or 120^o the third one should be split up into two parts in such a way that when the two parts are connected to the other windings give a resultant angle of 60^o or 120^o.

Fig.7.1(a&b) represent such connections for 60^o and 120^o operations respectively. Referring to Fig.7.1(a), let $\angle B_2B_1c' = \delta$ as $\angle B_2B_1A_1 = \angle c'A_2C_2$, $\angle C_2A_2A_1 = \delta$

Also let $B_1B_2 = A_1A_2 = a$, $C_1c' = x$ and $A_2c' = m$, $A_2C_2 = n$

From $\triangle A_2A_1C_2$,

$$(a - x)/\sin \delta = a/\sin(60 - \delta) = n/\sin 120 \qquad (7.21)$$

From $\triangle\ c'A_2C_2$,

$$m/\sin(30 - \delta) = n/\sin(60 + \delta) = 2(a - x)/\sin 60 \qquad (7.22)$$

From equations (7.21) and (7.22)

$$(a - x)/n = \sin\delta/\sin 120 = \sin 60/2\sin(60 + \delta) \qquad (7.23)$$

The solution of equation (7.23) is $\delta = 22.2^\circ$ (7.24)

Then from equations (7.21) and (7.22) it can be shown that

$$x/(a - x) = 4:13 \qquad (7.25)$$

$$m : n = 1:1.615 \qquad (7.26a)$$

$$n : m = 1:0.62 \qquad (7.26b)$$

hence the C winding should have two parts with a distribution of turns in the ratio 4:13.

The only available machine for the purpose was one having the cage rotor with following specifications:

Inner diameter of the stator, D = $5\frac{1}{8}$"

Axial length of the stator, l_a = $4\frac{1}{4}$"

Number of the stator slots, S = 48

Number of the rotor slots, S_r = 56

Width of the stator tooth, t = 5/32"

(the stator teeth were parallel sided)

Stator slot width at air gap = 7/32"

Depth of the slot = 1"

tappings are to be provided in C phase winding for 4:13 distribution and in A phase winding at $1/\sqrt{3}$. Specifications of the winding to be designed:

400 volts, star connected, 50 c.p.s, 4 poles.

Design of the Windings:

As $E = 4.44\ K_w\ f\ T_{ph}\ \phi \times 10^{-8}$ volts (7.27)

where K_w = winding factor

f = frequency in c.p.s

T_{ph} = number of turns in series in one phase

ϕ = flux in lines

As E = 231 volts per phase,

f = 50 c.p.s

for full pitch coils and 4 slots per pole per phase, $K_w = 0.958$

the pole arc, $\tau_p = 4.326''$

Assuming the average flux density in the air gap (B_g'') to be 25,000 lines per square inch,

$\phi = \tau_p \times l_a \times B_g''$

$= 46.25 \times 10^4$ lines.

Substituting the above in equation (7.27), $T_{ph} = 235$

Number of conductors per slot = 235 x 2/16 = 29.5, say 30

Number of conductors in one part of the C winding =(4/17)30 = 7

Number of conductors of the tapping in A winding $=(1/\sqrt{3})30$

= 17.3, say 17

Hence it was decided to take 30 conductors per slot.

Then the T_{ph} = 30 x 16/2 = 240

New value of B_g'' = 235 x 25000/240 = 24500 lines per square inch

The maximum tooth density $B_t = (\pi/2) B_g''\ \lambda l_a / t\ l_n$

where λ = slot pitch at the air gap

t = tooth width

l_a = gross axial length of the stator core

l_n = net iron length of the stator core.

Substituting the values of the above quantities

B_t = 93,500 lines per square inch.

The maximum value of tooth density is 110,000 lines per square inch for 50 c.p.s motors, so the above value is well within limits.

Slot pitch at the bottom of slots = π x 7.5/48 = 0.47 inch

Slot width at bottom = 0.47 - 0.156 = 0.434 inch

Slot width at top = 0.218 inch

Area of the slot = (0.314 + 0.218) x 1/2

= 0.266 square inch

Let the slot space factor be = 50%

Net area for winding = 0.266 x 0.5 = 0.133 sq.inch

Area per conductor = 0.133/30 = 0.0044 sq.inch

The nearest S.W.G. No. to this area is "15".

Assuming the value of specific electric loading to be 400 amper conductors per inch,

The current per conductor = (400 x π x 5.5)/(30 x 48)

= 5.15 amps, say 5.0 amps.

Assuming the current density to be 1500 amps per square inch

Area of each conductor = 5/1500 = 0.0033 sq.inch

The nearest S.W.G. No. to this area is "16", whose area is 0.003217 sq.inch. But the S.W.G. No.16 wire was not available in the store, two wires in parallel of S.W.G.No.19 can be used instead.

The S.W.G.No.19 wire has the following particulars:

Bare dia. = 0.04 inch, Dia. over insulation = 0.046 inch (supper enamelled)

Area = 0.0012569 sq.inch, Resistance at 25°C = 6.51 ohms/1000'

Hence the new current density = 5/(2 x 0.0012569) = 1985 amps/Sq.in

The pitch of the winding in terms of slots = 48/4 = 12. So the winding throw will be from first slot to thirteenth slot. As the pitch is an even number so the single layer full pitch coils cannot be used. For the full pitch winding the double layers will have to be used. As the number of conductors per slot is 30, so the number of conductors per layer will be only 15 and the tappings will become difficult as far as the accuracy is concerned. But the number of conductors per layer will be increased to 30 as there are two conductors in parallel. So the windings can be completed taking 30 conductors per layer and the final connections to bring the two coils in parallel can be made while connecting the ends of the respective coils of a phase group.

Slot Details (see Fig.7.2)

Slot lining, 10 mils + 5 mils	= 0.015"
Separators, 4 x 5 mils	= 0.02"
Tooth thickness	= 0.0625"
Wedge (fibre)	= 0.0625"
Gross slot area	= (0.218 + 0.314) x 0.9375/2
	= 0.25 sq.inch
Insulation area:	
Slot lining	= 0.015(0.9375 + 0.9375 + 0.314
	= 0.0328 sq.inch
Top wedge	= 0.0625 x 0.218 = 0.0136 Sq.in
Separators	= 0.005 (.218+.242+.266+.29)
	= 0.00508 Sq.inch
Net slot winding area (SWA)	= 0.1985 sq.inch
Diameter of the wire with insulation	= 0.045 inch

Space required by one wire, treating the conductor as if it were a square = 0.02025 Sq.inch

Space required by 60 wires = 0.1215 Sq.inch

Slot fullness = 0.1215/0.25

= 48.7%

hence the winding can be accommodated in slots well.

stance of the Winding

The axial length of the stator core = 4.25",using

ond shape coils, the length of the active coil sides can be n as 5.25" with ½" projected outside the slots on each side.

As the coils are full pitch coils the coil throw will be nearly l to the pole pitch or 4.3", say 4.5". Also let the total lengt he over hang on one side of the coil be 6". The axial length of over hang will be about 2" which is sufficient for insulation can be well accommodated in the end plates of the frame. The nsions of the coil will be as shown in Fig.7.3.

The mean length per turn = 22.5 inch

Total length of the wire per phase = 22.5 x 240 = 5400 inc

= 450 feet

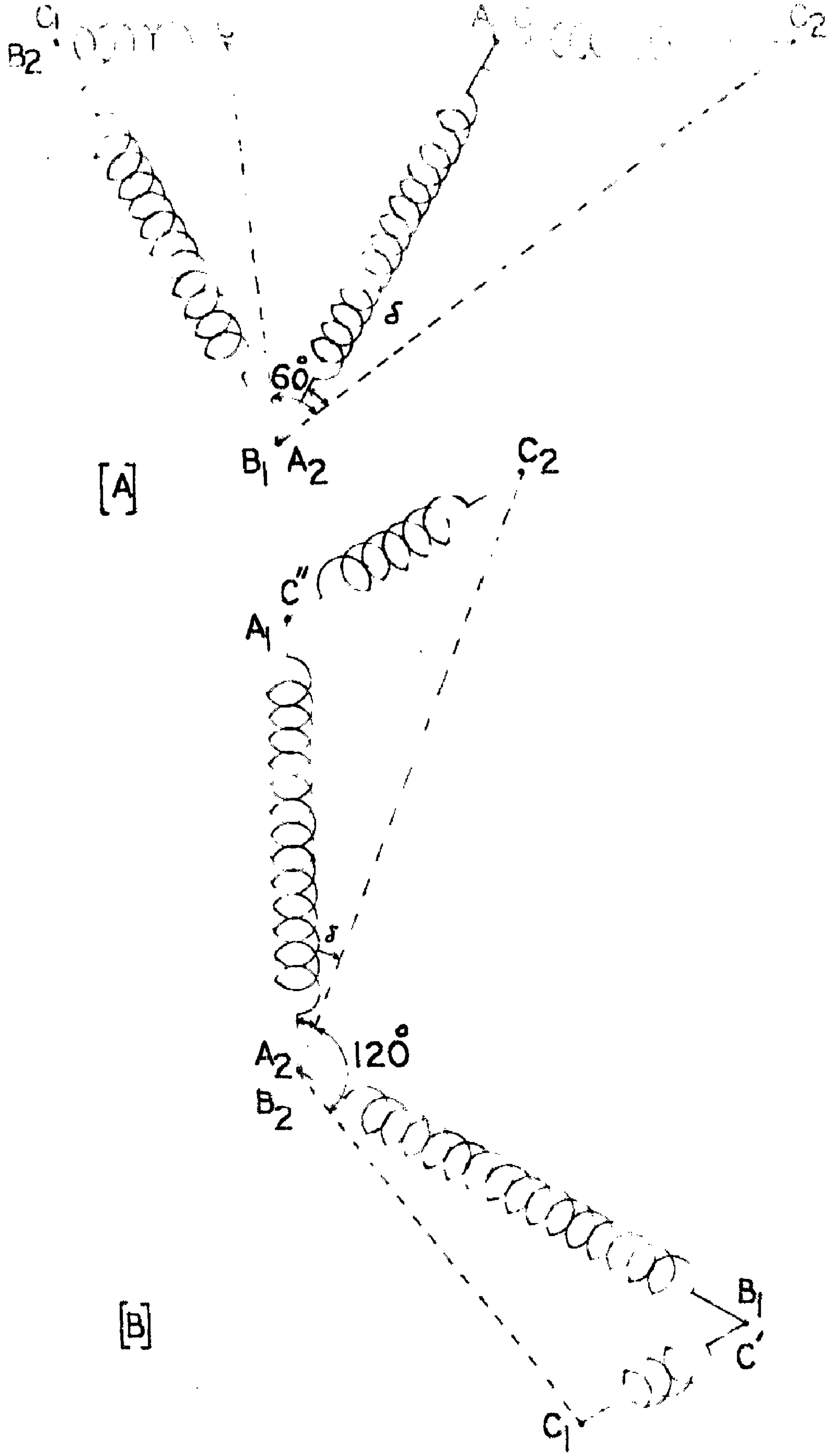
Hence the resistance at 25°C = (450 x 6.51)/(1000 x

= 1.465 ohms per phase

Resistance at 60°C = 1.65 ohms per phase

Resistance at 40°C = 1.52 ohms per phase

...



7·1 CONNECTIONS OF THE STATOR WINDINGS TO UTILIZE ALL TH
WINDING SPACE FOR (A) 60°, (B) 120° OPERATION.

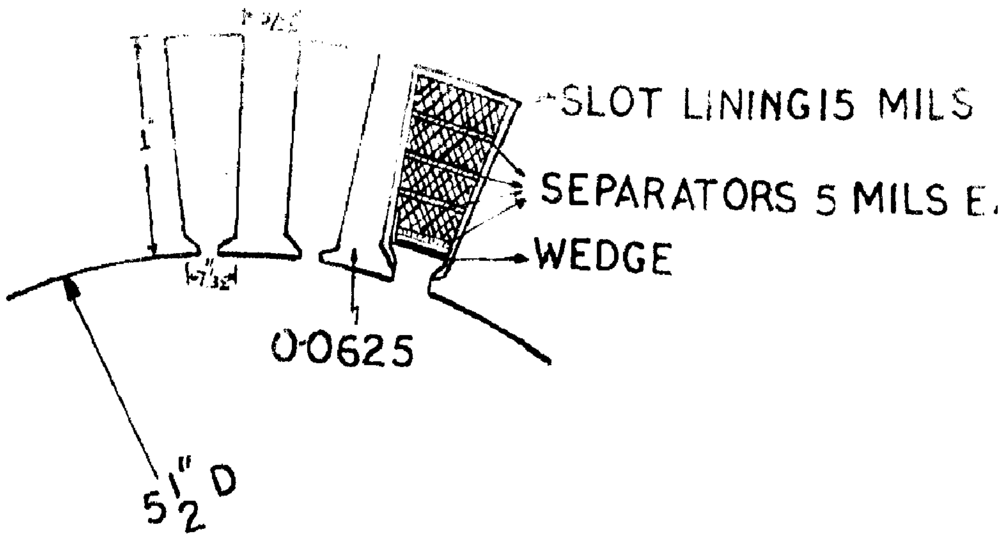


FIG. 7·2 SLOT DIMENSIONS.

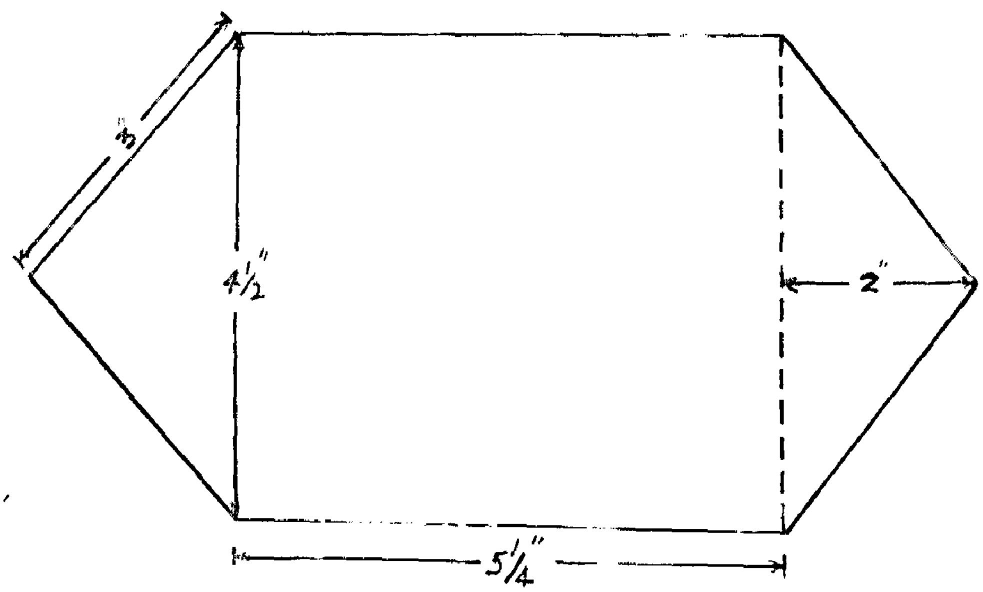


FIG. 7·3 THE COIL DIMENSIONS.