To the Graduate Council:

I am submitting herewith a thesis written by Awad Iskander Shenouda entitled "Speed Control With Twin Stator Cage Induction Motor." I recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Electrical Engineering.

F. W. Symonds

F. W. Symonds, Major Professor

We have read this thesis
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J M Bailey

Marshall Pace

Accepted for the Council:

L Evans Roth

Vice Chancellor
Graduate Studies and Research

SPEED CONTROL WITH TWIN STATOR CAGE INDUCTION MOTOR

A Thesis
Presented for the
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Awad Iskander Shenouda

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ABSTRACT

The objective of this thesis was to propose another method of Speed Control with the twin stator induction motor arrangement. The method centered around the slip power extracted from the rotor circuits by induction to one set of stator windings, from which it was dissipated in an external resistor connected to that set of windings. Speed Control was accomplished by changing the value of this resistor.

The machine configuration to implement this consisted essentially of two identical polyphase wound rotor induction motors having their shafts coupled and their rotor circuits interconnected, with one set of stator windings fed from a balanced polyphase power supply voltages and the other set of the stator windings connected directly to an external variable polyphase resistor.

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CHAPTER I

INTRODUCTION

For many years an economical method of obtaining a Variable Speed drive has been sought. For many applications the ideal motor is the squirrel-cage induction motor, widely regarded as the "work-horse" motor of industry because of its ruggedness, low cost, reliability and ease of maintenance. However it suffers from the disadvantage that its running speed is not variable.

If some degree of economical speed variation could be added, the Squirrel Cage induction machine would become even more useful than it is at present. Many schemes have been developed which provide speed or torgue control for induction machines. Of these the only methods which enable the squirrel cage motor to retain the essential properties of simplicity and ruggedness are that of pole changing, by means of which usually two different synchronous speeds may be obtained, and that of stator voltage control, by means of which the output torgue can be varied, and hence with certain loads a small amount of economical speed variation may be accomplished.

By feeding the machine from a frequency converter which provides a voltage proportional to frequency, speed variation could be obtained; however the cost of the converter which must handle the total requirements makes the scheme unattractive.

Any attempt to change the operating speed of an induction machine without changing its synchronous speed must take account of the fact that, of the power Pg passing across the air gap from the stator to rotor, only a fraction (1-s) Pg appears as mechanical output. Thus for efficient operation, the fraction SPg must be either returned to the supply or converted to useful mechanical power by some means. This power SPg may be extracted as electrical power of slip frequency from the rotor circuits by induction.

In this thesis it is suggested that an induction machine fitted with two independent sets of windings on the stator and two suitably interconnected rotor windings or cages (Twin Stator arrangement) can be used as a variable machine, in which the slip power SPg from the rotor circuits can be transferred by induction to one set of stator windings, from which it is dissipated through an external resistor in the stator circuits. Speed control is accomplished by changing the value of this resistor.

The theory, application and performance of the proposed machine are given in this thesis. For purposes of analysis, the 3-phase twin stator induction machine may be represented by two identical wound rotor 3-phase induction motors with their rotors connected mechanically and electrically.

A steady state equivalent circuit and expressions for current, power and electromagnetic torgue were obtained. The effect of the controlling parameters on the steady state torgue was investigated and it was found that speed control can be achieved by varying the external resistor in the stator circuits.

The measured results of practical tests are presented for two identical 3-phase wound rotor induction motors having their rotors connected mechanically and electrically, with one of the stator windings connected to the 3-phase power supply and the other stator winding connected to an external resistor. The measured torgue slip and current-horsepower characteristics were plotted for two values of external resistor for comparison with calculated values.

From the equations developed for the composite machine, the predicted performance characteristics have been calculated using the equivalent circuit parameters per phase given in Chapter IV, and the same two values of external resistor were used in the measured results. These were plotted together with the measured characteristics for comparison. The agreement between the measured and calculated performance characteristics was good, which indicated that the equivalent circuit is valid for extended prediction of calculated performance characteristics. Because the operation of this machine is best described in terms of the external resistor added in the stator circuit, the extended predicted calculated performance characteristics were plotted for several values of external resistor for more investigations.

The lower motor efficiency shown suggested that a better quality machine, having lower winding resistances than the machine under test and hence a practical machine of reasonable operating efficiency and torgue might be possible. For ultimate realization, the composite machines would be an induction motor with two isolated sets of stator windings and a common cage rotor. Since the analysis of performance can be carried out using the developed steady state equivalent circuit in Chapter III, parameter optimization could be easily done.

This work has shown by analysis and test that the twin stator cage induction motor introduces some properties of slip ring induction motor without introducing its disadvantages; in other words it is possible to combine the versatility of wound rotor machine and the ruggedness of the cage induction motor.

CHAPTER II

THEORY AND APPLICATIONS OF TWIN STATOR INDUCTION MOTORS

A serious inherent disadvantage of the polyphase induction motor is that its speed is generally difficult and expensive to control, especially when it is necessary to do so efficiently and steplessly over a rather wide range. This is in contrast with the D. C. Motor whose speed may be readily adjusted by the use of simple, inexpensive control devices and equipment.

The speed of the polyphase induction motor is an asynchronous speed which may be varied:

(a) by the well-known methods based on the insertion of rotor resistance which are not efficient. (for woundrotor only)

(b) by changing the applied frequency to the stator, which is infrequently used because it requires an expensive motor-generator set.

(c) by pole-changing, which is limited only to poly phase and single phase squirrel cage motors.

(d) by concatenation, which requires two induction motors coupled mechanically to the same shaft and load and connected electrically so that the second motor receives its stator excilation input from the rotor of the first motor, the two windings of this motor having one-to-one ratio, as shown in Figure 2-1. [9]

Motors which do not have unity ratios of transformation but which do have the same ratio of transformation can be connected as shown in Figure 2-2. In this connection the rotors are electrically as well as mechanically connected together.

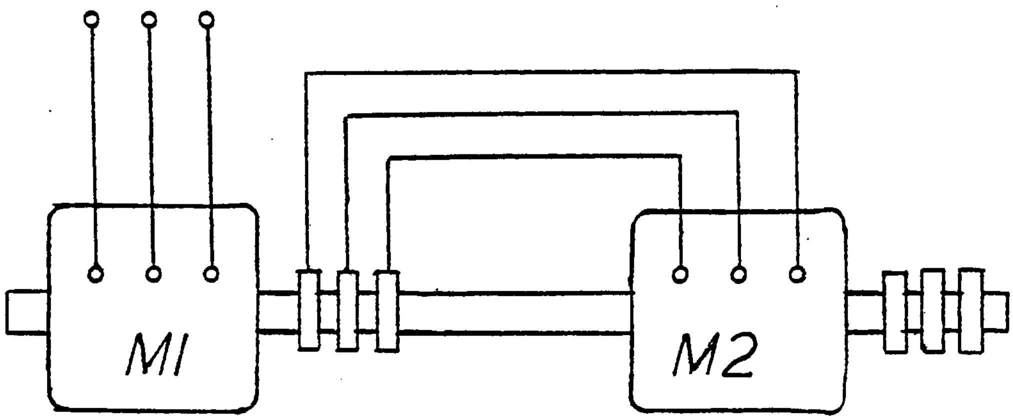

Figure 2-1. Concatenation; motors having 1:1 winding ratio. [9]

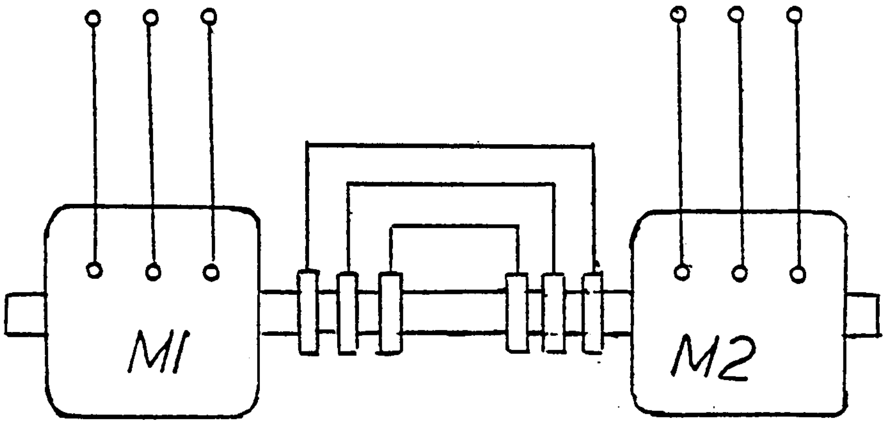

Figure 2-2. Concatenation; motors having same winding ratio but not unity.

The synchronous speed of the system = $\frac{120 \times f_1}{P1 + P2}$ where P1 and P2 are the number of poles of M1 and M2 respectively. If the two machines are identical, the synchronous speed of the set is equal to one-half the synchronous speed of either. When the machines have different numbers of poles the set can operate at three different synchronous speeds, namely the synchronous speed of either M1 or M2 when acting alone and that of the two when connected in concatenation.

From the concatenation arrangement shown in Figure 2-2, the set was combined to establish an induction machine with two independent sets of windings on the stator and a suitably modified squirrel-cage rotor common to both stators, which is called the twin stator common squirrel-cage rotor machine and shown in Figure 2-3 [1].

The arrangement of the twin stator common squirrel-cage rotor machine may be represented by two wound rotor induction motors whose rotors are mechanically and electrically connected as shown in Figure 2-4 for the purposes of analysis.

Applications to Speed Control with Twin Stator Induction Motors

1. Two Stators are Fed in Parallel [1].

When the two sets of stator windings are fed from 3-phase sources whose relative phase and magnitude may be controlled, the rotor performance is similar to that of a simple squirrel-cage motor fed by a voltage equal to the magnitude of the phasor sum of the two stator voltages. Control over the relative phase of rotor voltages

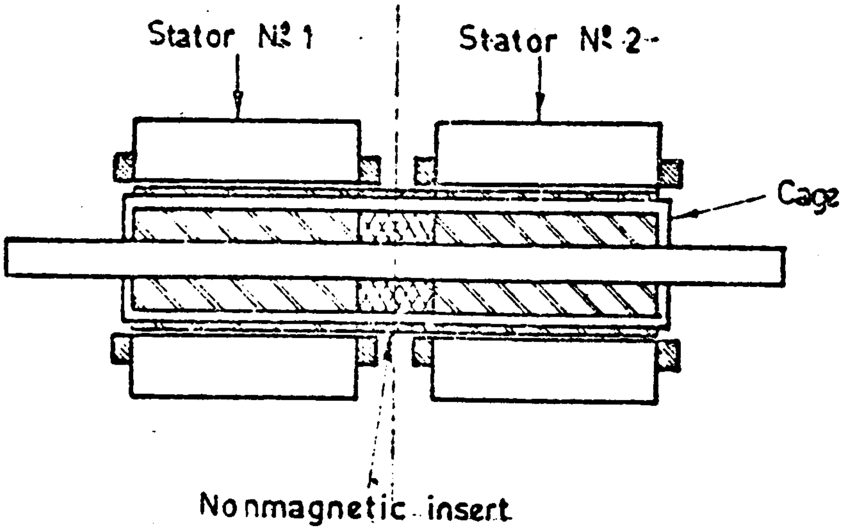

Figure 2-3. Schematic of twin stator common squirrel-cage induction machine.

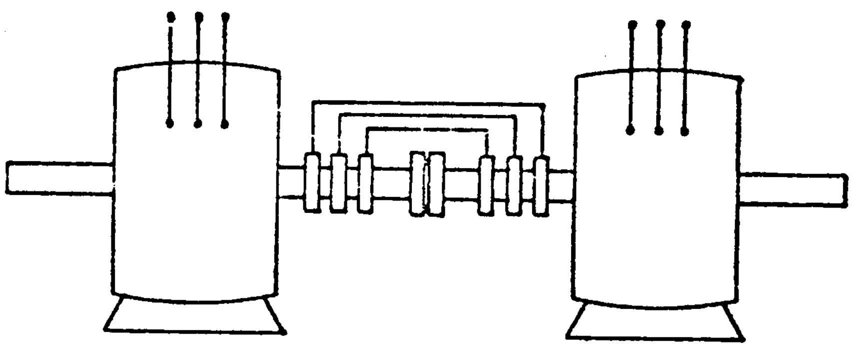

Figure 2-4. Simulation of machine suggested in Figure 2-3 by means of two slip-ring induction motors.

may be accomplished by any of the followings:

(1) rotating one rotor with respect to the other.

(2) rotating one stator winding with respect to the other.

(3) shifting the phase of the voltage applied to one stator with respect to that applied to the other.

The relative phase or magnitude of the rotor voltages determines the circulating current in the rotor circuits and, therefore the torgue.

Both the variation of the relative magnitude of the rotor voltages and shifting the phase of the voltage applied to one stator with respect to that applied to the other, require the provision of a considerable amount of external equipment, while rotating one rotor with respect to the other is inappropriate for a squirrel-cage motor. Thus particular interest centers around rotating one stator winding with respect to the other, which may be accomplished either by physically rotating one statator with respect to the other or by electrically reconnection to a multitap winding as suggested in Figure 2-5.

The twin stator common rotor machine will be considered for purposes of analysis as a pair of wound rotor machines with their rotors connected mechanically and electrically as in Figure 2-6. There is no reason why the two sections should be identical. However, identical windings will be postulated.

In this particular case, there are two such machines connected as shown in Figure 2-6, with provision to rotate one set of stator

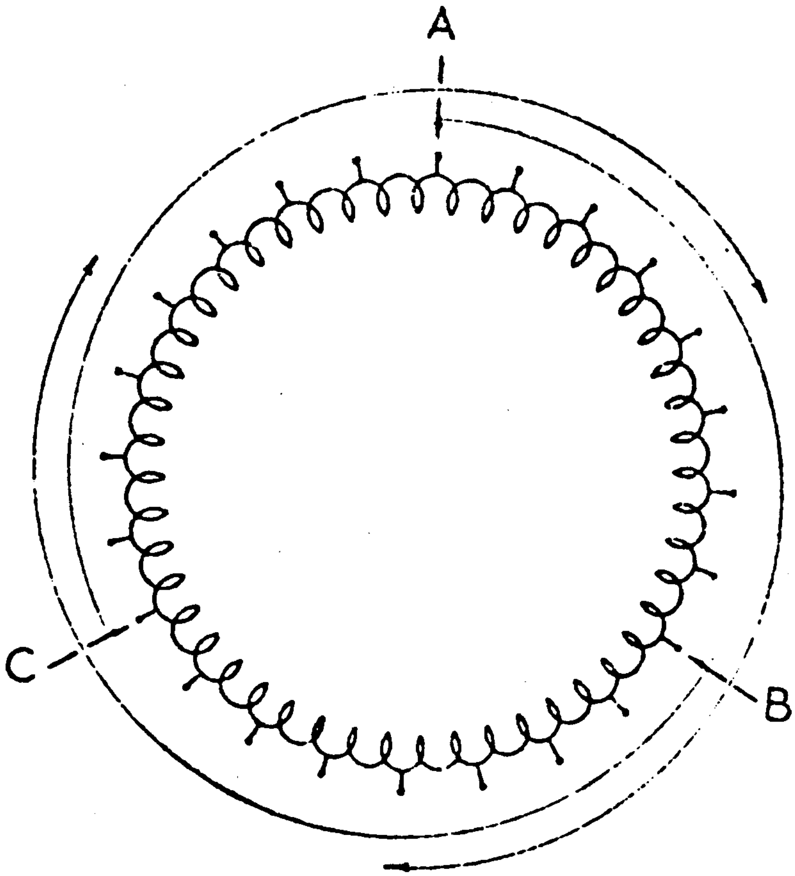

Figure 2-5. Tapped 3-phase stator winding for altering relative phase of rotor voltages [1].

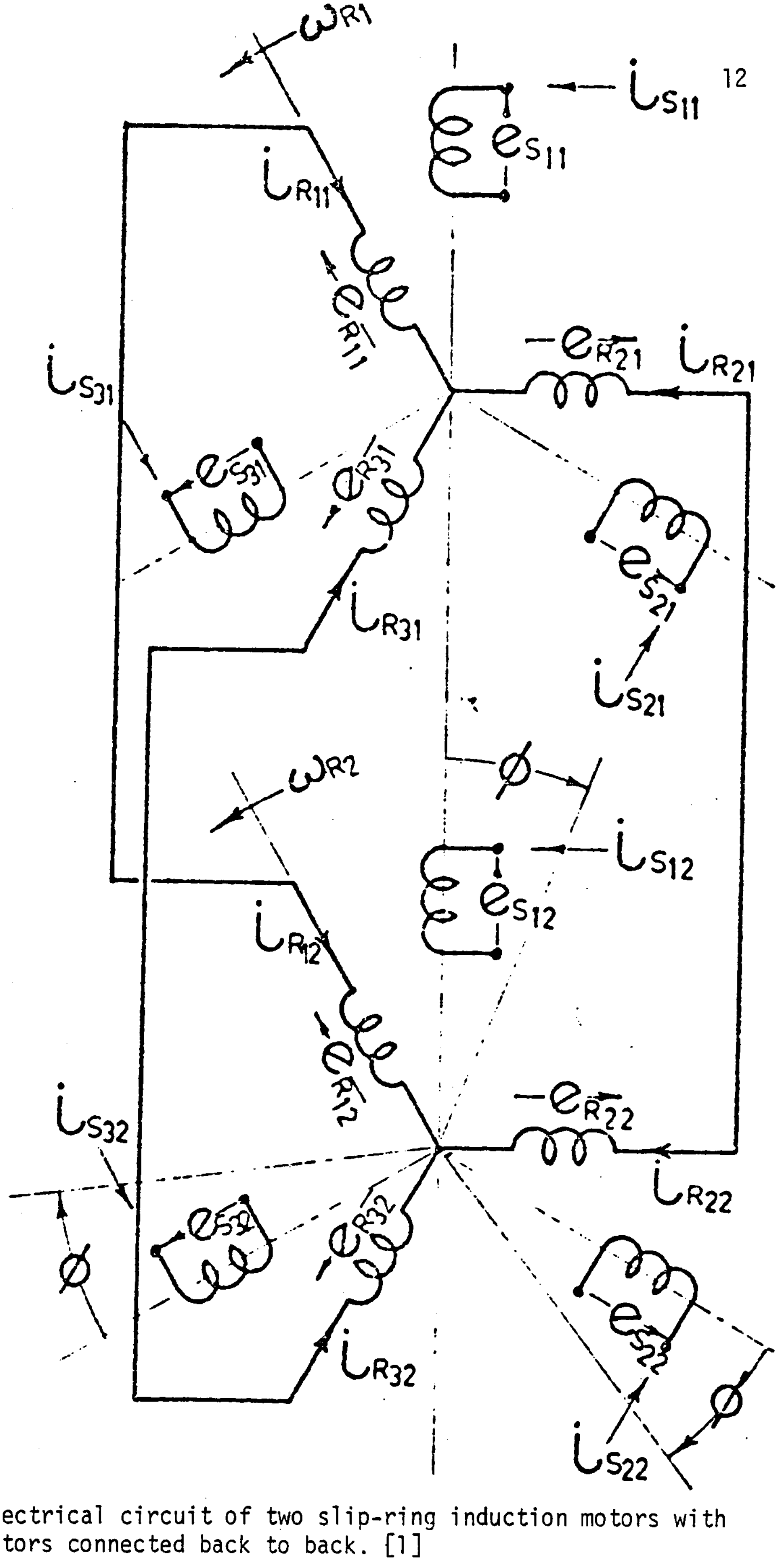

Figure 2-6. Electrical circuit of two slip-ring induction motors with rotors connected back to back. [1]

windings with respect to the other, either electrically or physically. The windings on stator [2] make an electrical degree Ø with those on stator [1]. This is equivalent to leaving the two sets of stator windings aligned, i.e. Ø = 0, and feeding the windings of stator [2] with a balanced set of 3-phase voltages which lag those applied to stator [1] by an electrical angle Ø (Figure 2-7).

Figure 2-8 shows that at small values of Ø it is possible for one section of the machine to feed power back into the supply as the slip increases, because this section of the machine is developing a negative net torque and thus is delivering power back to the supply.

The analysis of the performance of a pair of 3-phase slip ring induction motors, whose rotors are electrically and mechanically connected and whose stators are fed in parallel, showed that by altering the relative phase of the voltage induced in the two rotors, the speed torque characteristics of the composite machine are identical to those of a pair of normal machines fed with a stator voltage reduced by a factor (1-cosØ)/2 where Ø is the relative phase angle of the rotor voltages in the composite machine, Figure 2-7.

2. One Stator is Fixed and the Second Stator is Rockable [2].

Another method is suggested for continuous variation of the speed of the cage induction motor. Varying the speed by this method results not only in continuous speed variation but also in a fairly good motor efficiency due to the presence of feedback path for the input power via rockable stator.

A schematic diagram is shown in Figure 2-9 for a twin stator cage induction motor arrangement. This machine consists of two

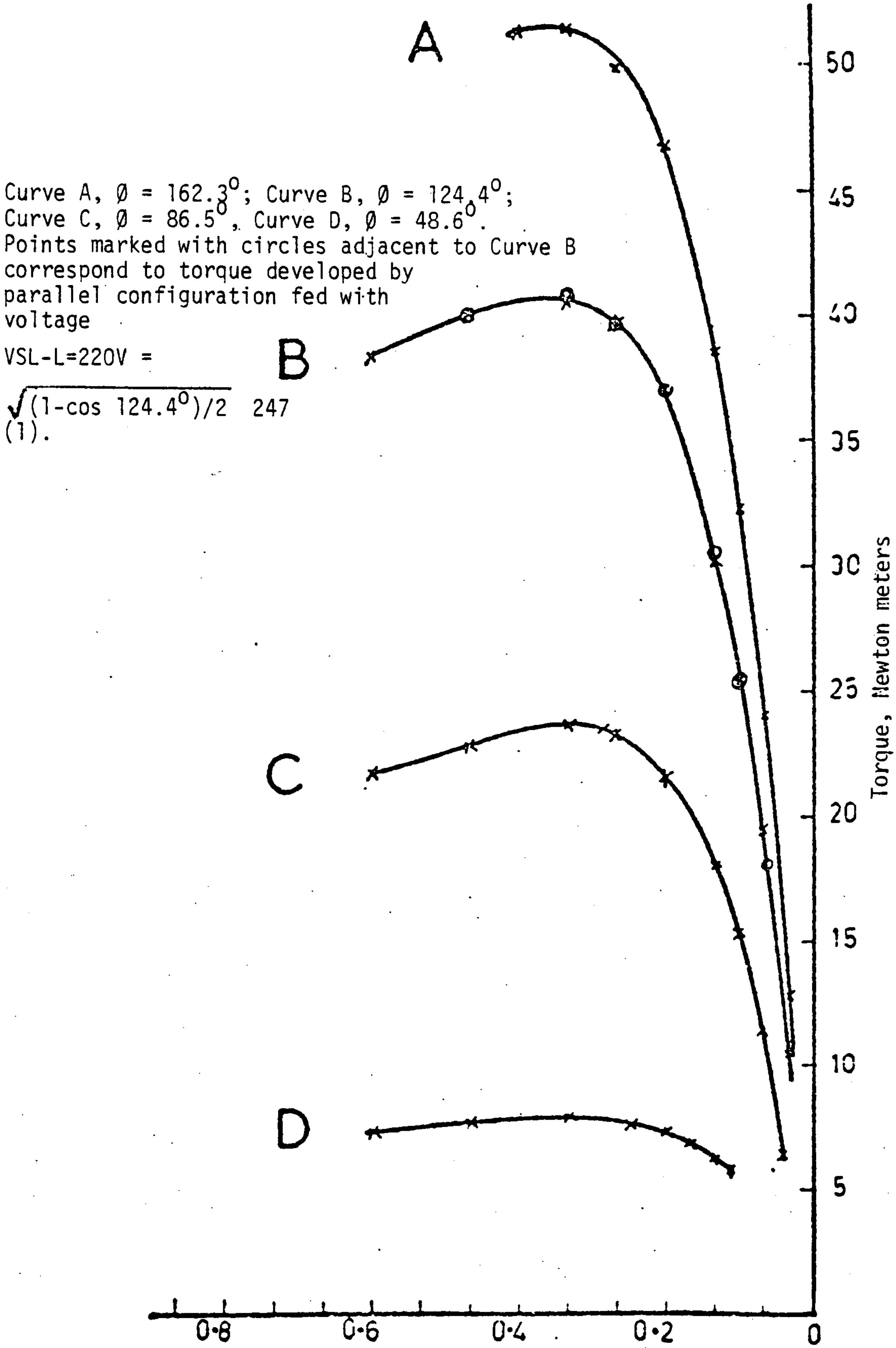

Figure 2-7. Electromagnetic torque developed by back to back configuration plotted as function of slip with Ø as parameter and VSL-L=247. [1]

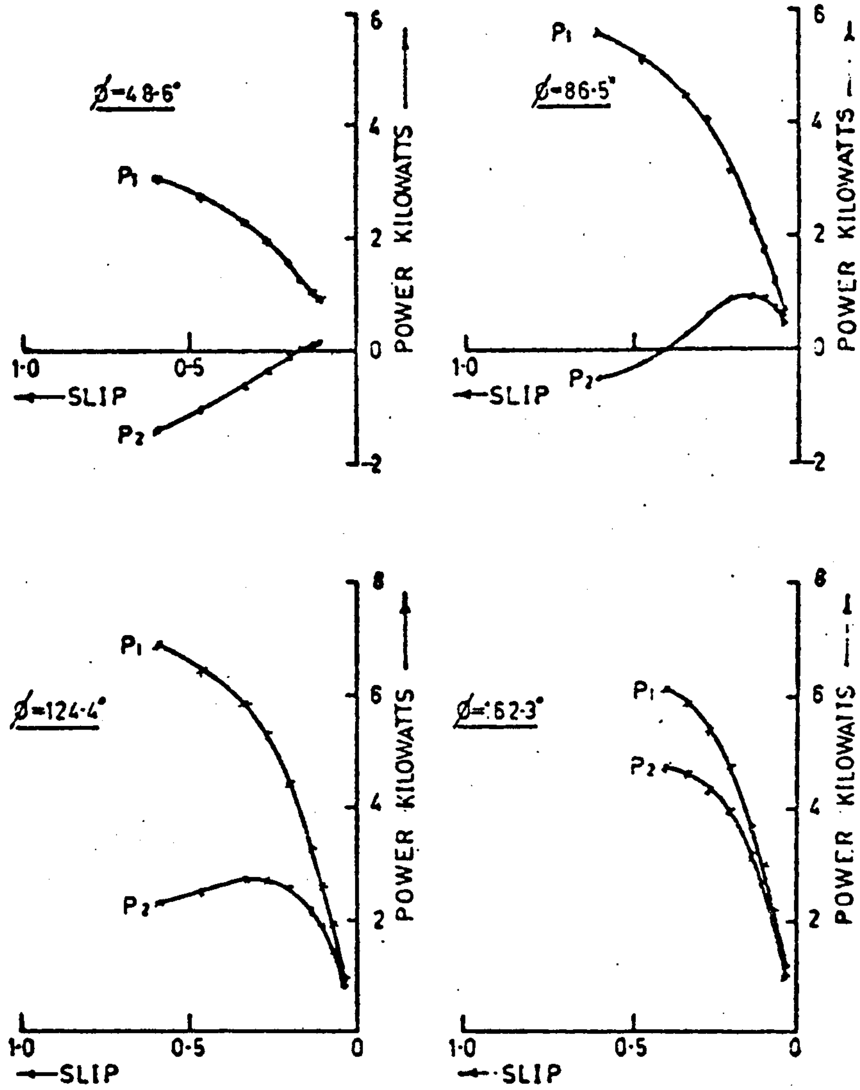

Figure 2-8. Input power vs slip to each stator for four values of ∅. [1]

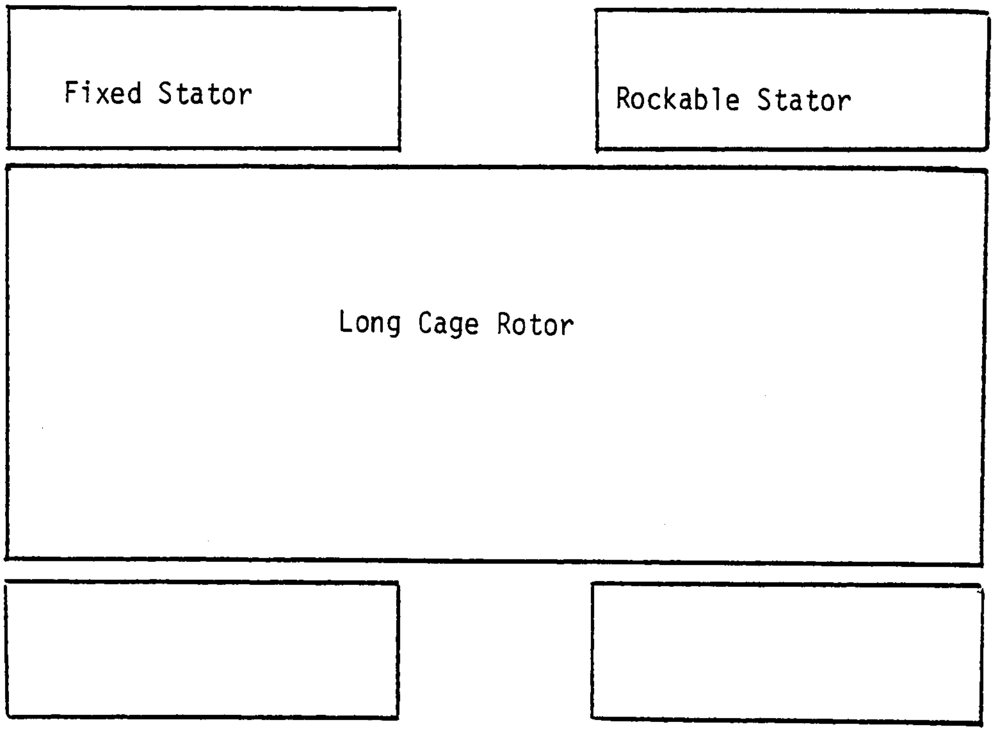

Figure 2-9. A twin stator cage induction motor.

identical stators wound for 3-phase and for the same number of poles and relatively long cage rotor. The first stator is fixed and the second stator is rockable with respect to first stator in space by an electrical angle δ. A long cage rotor provides indirect coupling between the two stators. When the stators are fed from a balanced 3-phase supply, two rotating mmfs are produced in the airgap. If $\delta = 0$, i.e. the axes of phases of the first stator are parallel to the axes of phases of the second stator respectively, the two mmfs will be rotating in the same direction with zero phase shift.

In this situation the voltages induced in the rotor circuit due to the two rotating mmfs will be in phase and the resultant electromagnetic torque of the machine will be double that due to a single rotating field.

In case the second stator is rotated in space by an electrical angle δ and locked in that position, the voltage induced in the rotor circuit due to two rotating mmfs will be equal in magnitude but out of phase by 180^0. As a result the resultant emf in the rotor circuit will be zero, and this makes the squirrel-cage rotor open circuited although physically the electrical rotor circuit is closed. The net developed torque will be zero. These are two extreme values of δ.

By rocking the stator for any intermediate value of δ the desired speed torque control can be achieved. The variation in speed can also be obtained by feeding either one or both the stator windings from a phase variac.

In Figure 2-10 a single relatively long cage rotor is replaced by two equivalent 3-phase wound rotors connected electrically and mechanically.

3. Slip Power Dissipation

Consideration of these devices suggested another method of speed control. It appeared that the use of a variable external resistor in the second stator circuit, as shown in Figure 3-1 would also provide the means of slip power dissipation necessary for induction motor speed control.

An investigation of this concept was the subject of this thesis.

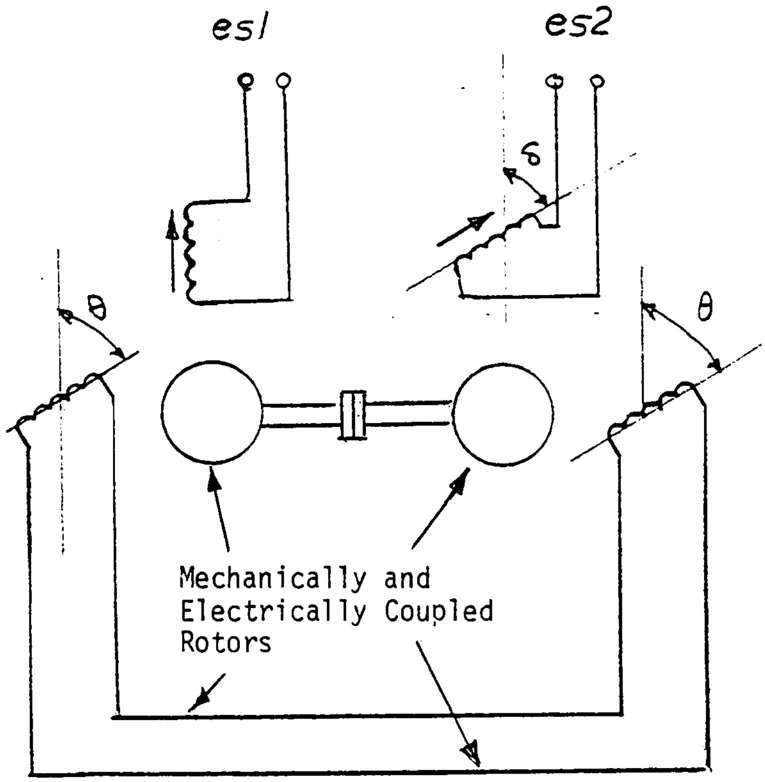

Figure 2-10. A single relatively long cage rotor is replaced by two equivalent 3-phase wound rotors connected electrically and mechanically.

CHAPTER III

ANALYSIS

This analysis was confined to the steady-state performance of the machine. The twin stator cage induction motor was considered for purposes of analysis as a pair of wound rotor induction motors with their rotors connected mechanically and electrically as in Figure 3-1.

In order to present the essential behavior in as clear and concise a manner as possible, linearity has been assumed, core losses neglected, and the two machines have been taken as identical with 6-pole.

Induction motor theory has been well established for many years and this machine is equivalent to two interconnected 3-phase induction motors. There was no need for any more sophisticated approach to the steady-state behavior than to take the appropriate per phase equivalent circuits for each machine and connect them in accordance with the terminal conditions. Figure 3-2 shows an equivalent connected model of the twin stator cage induction motor where it is replaced by two equivalent 3-phase wound rotors connected as shown. Figure 3-3 shows the interconnected equivalent circuit.

As a first step in the analysis, all the interconnections were removed. For Machine #1, referring the rotor parameters to its stator circuit, the equivalent circuit is shown in Figure 3-4, where

$$RR_1' = RR_1(K)^2 \tag{3-1}$$

$$XR_1' = XR_1(K)^2 \tag{3-2}$$

K = turns ratio

For Machine #2, first referring the stator parameters to its rotor circuit is shown in Figure 3-5, where

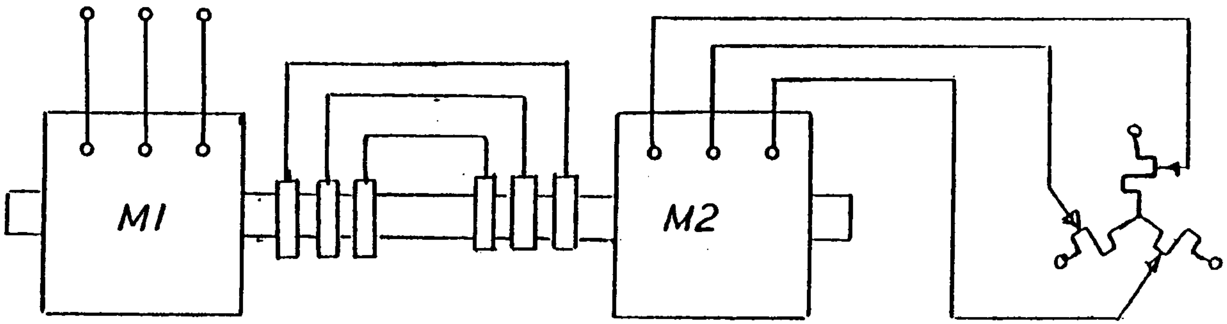

Figure 3-1. Two wound rotor induction motors with their rotors connected mechanically and electrically.

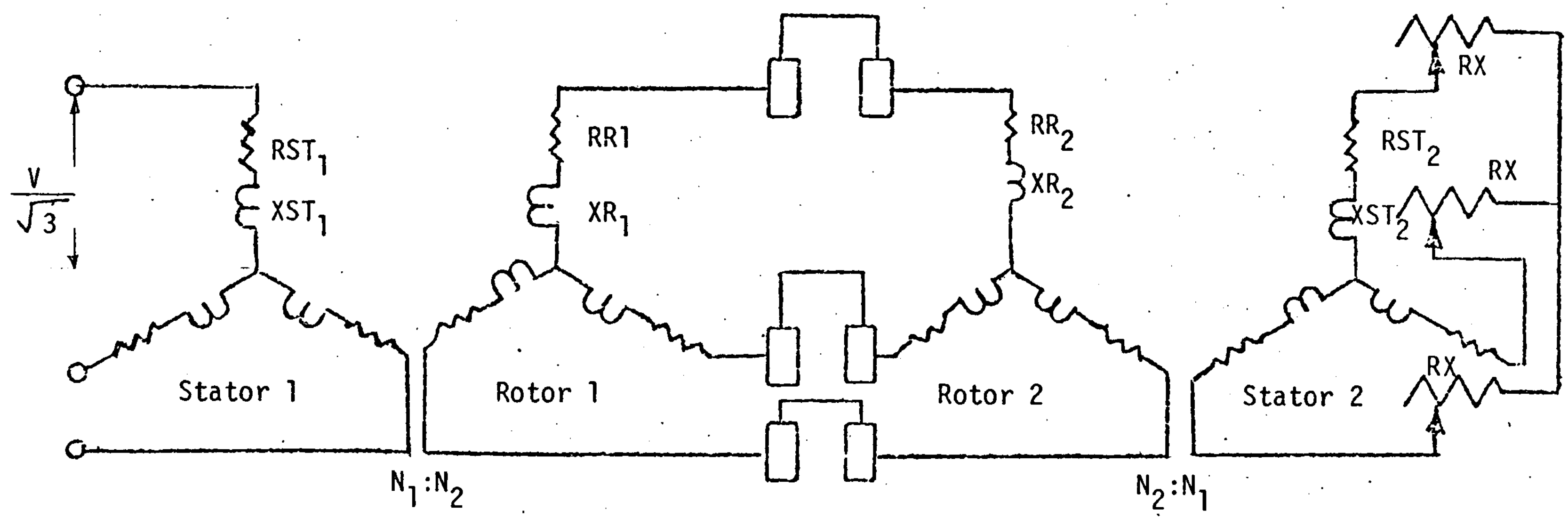

Figure 3-2. Equivalent interconnected model of the twin stator cage induction motor.

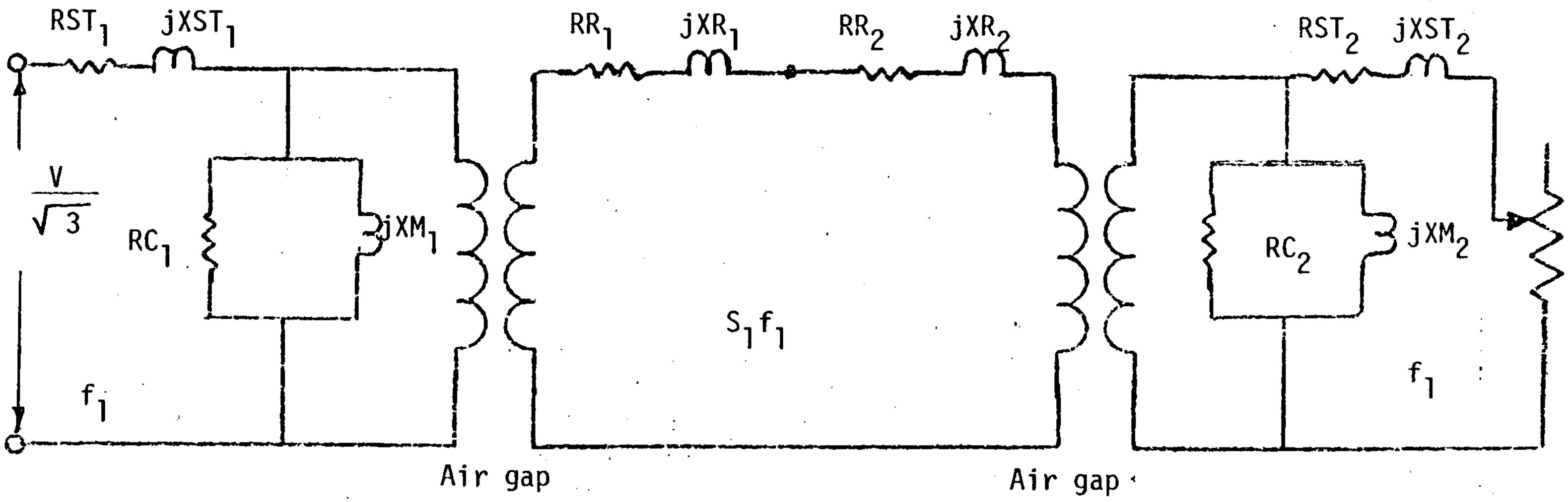

Figure 3-3. Interconnected equivalent circuit.

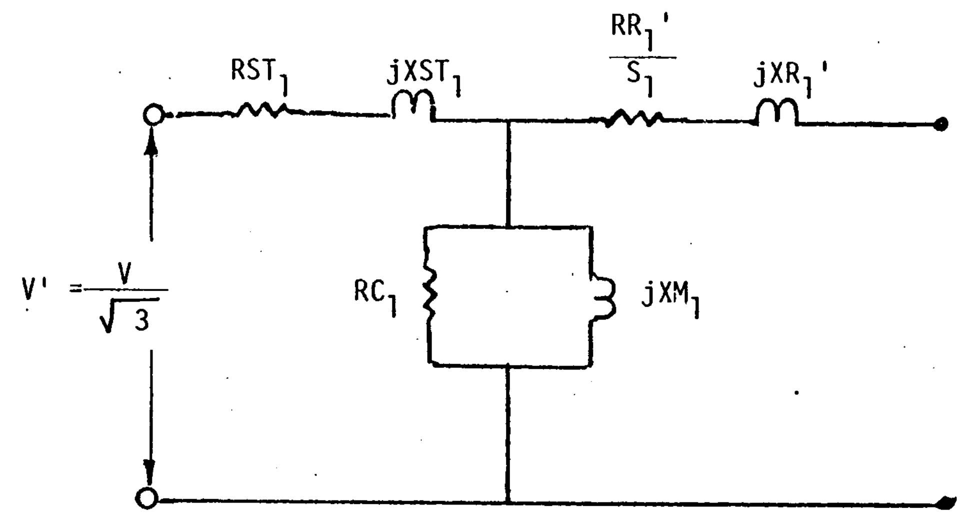

Figure 3-4. Equivalent circuit of Machine No. 1 with the rotor parameters referred to its stator circuit.

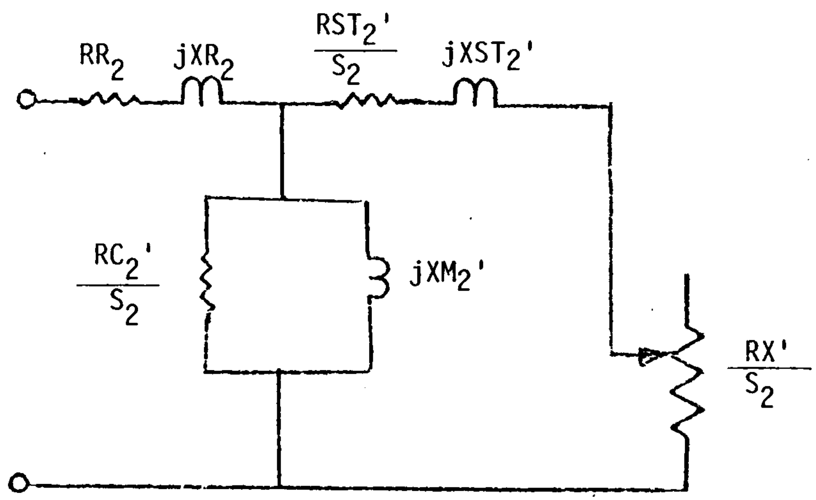

Figure 3-5. Equivalent circuit of Machine No. 2 with the stator parameters referred to its rotor circuit.

$$RST_2' = RST_2(\frac{1}{K})^2 \quad (3\text{-}4)$$

$$RC_2' = RC_2(\frac{1}{K})^2 \quad (3\text{-}5)$$

$$RX' = RX(\frac{1}{K})^2 \quad (3\text{-}6)$$

$$XM_2' = XM_2(\frac{1}{K})^2 \quad (3\text{-}7)$$

To obtain the combined equivalent circuit for Machine #1 and Machine #2, the equivalent circuit of Machine #2 referred to the stator of Machine #1 as in Figure 3-6, where

$$RR_2' = RR_2(K)^2 \quad (3\text{-}8)$$

$$XR_2' = XR_2(K)^2 \quad (3\text{-}9)$$

$$RC_2'' = RC_2'(K)^2 = RC_2(\frac{1}{K})^2(K)^2 = RC_2 \quad (3\text{-}10)$$

$$XM_2'' = XM_2'(K)^2 = XM_2(\frac{1}{K})^2(K)^2 = XM_2 \quad (3\text{-}11)$$

$$RST_2'' = RST_2'(K)^2 = RST_2(\frac{1}{K})^2(K)^2 = RST_2 \quad (3\text{-}12)$$

$$XST_2'' = XST_2'(K)^2 = XST_2(\frac{1}{K})^2(K)^2 = XST_2 \quad (3\text{-}13)$$

$$RX'' = RX'(K)^2 = RX(\frac{1}{K})^2(K)^2 = RX \quad (3\text{-}14)$$

Now the per phase combined equivalent circuit is shown in Figure 3-7. To reduce the equivalent circuit shown in Figure 3-7, it can be shown in block diagrams from Figure 3-8 to Figure 3-12, where:

$$Z_1 = RST_1 + jXST_1 \quad (3\text{-}15)$$

$$Z_2 = \frac{jXM_1(RC_1)}{RC_1 + jXM_1} \quad (3\text{-}16)$$

$$Z_3 = (\frac{RR_1'}{S_1} + \frac{RR_2'}{S_1}) + j(XR_1' + XR_2') \quad (3\text{-}17)$$

$$Z_4 = \frac{jXM_2''\ (\frac{RC_2''}{S_1S_2})}{\frac{RC_2''}{S_1S_2} + jXM_2''} \quad (3\text{-}18)$$

$$Z_5 = (\frac{RST_2''}{S_1S_2} + \frac{RX''}{S_1S_2}) + jXST_2'' \quad (3\text{-}19)$$

In Figure 3-9 this can be shown, where:

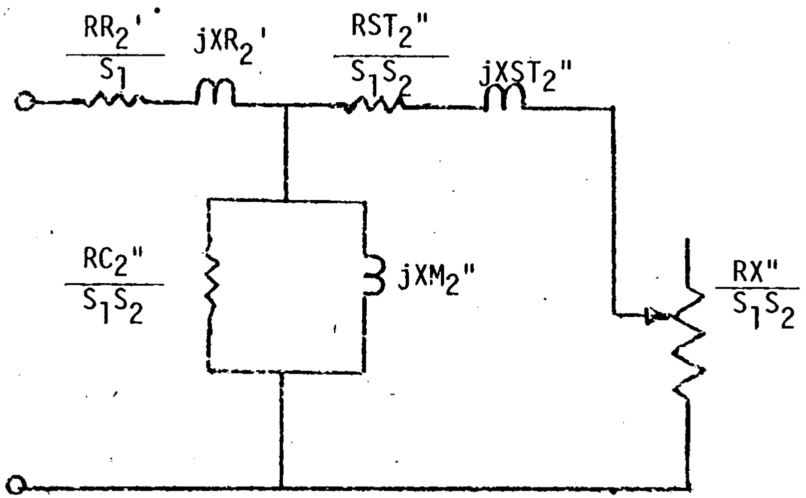

Figure 3-6. Equivalent circuit of Machine No. 2 shown in Figure 3-5 with all the parameters referred to the stator of Machine No. 1.

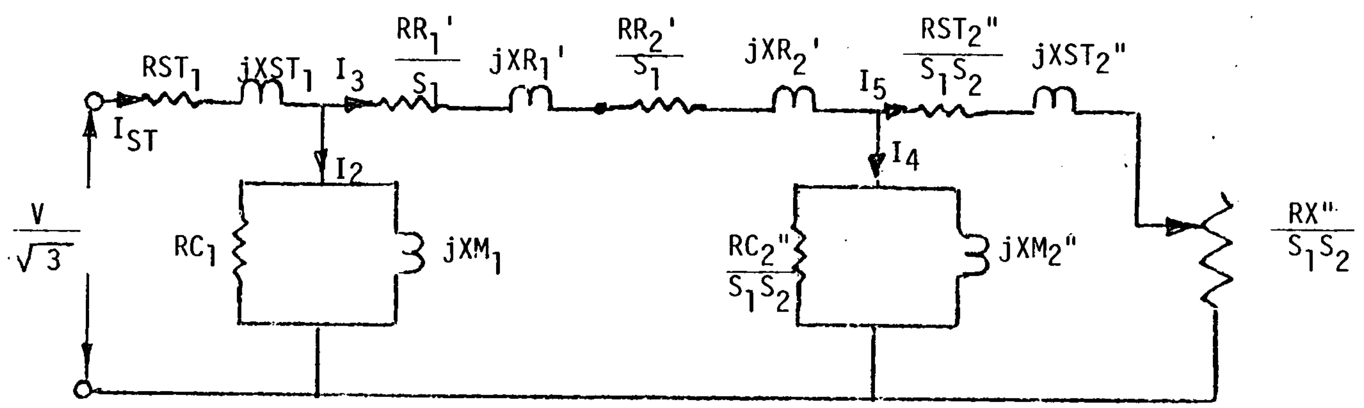

Figure 3-7. Combined equivalent circuit of Machine No. 1 and Machine No. 2.

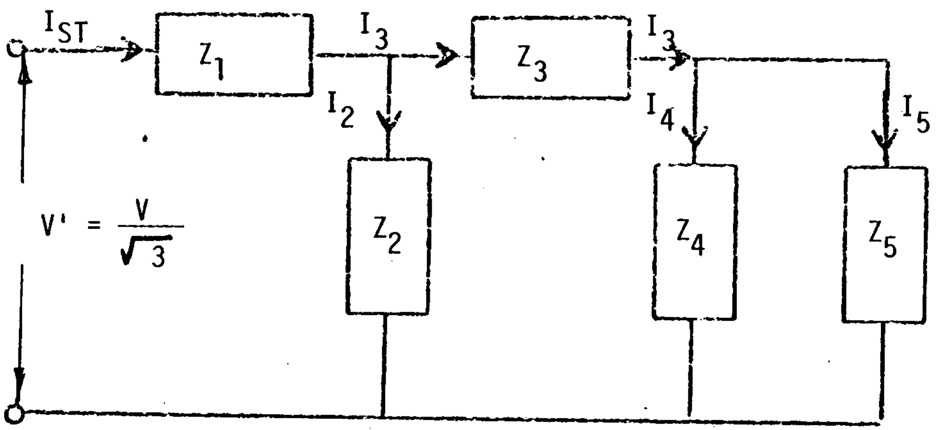

Figure 3-8. Block diagram of the combined equivalent circuit of Machine No. 1 and No. 2.

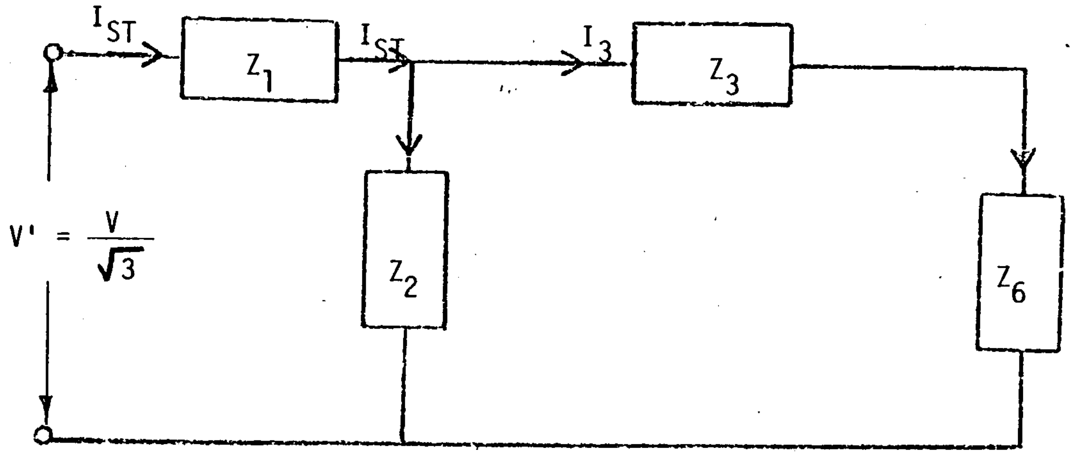

Figure 3-9. Reduced block diagram.

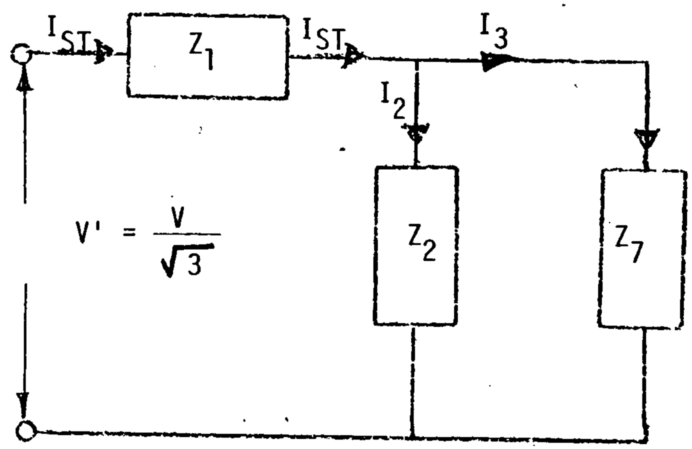

Figure 3-10. More reduced block diagram.

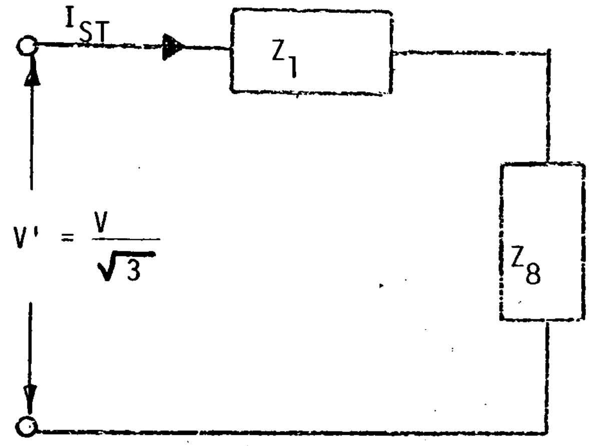

Figure 3-11. Further reduced block diagram.

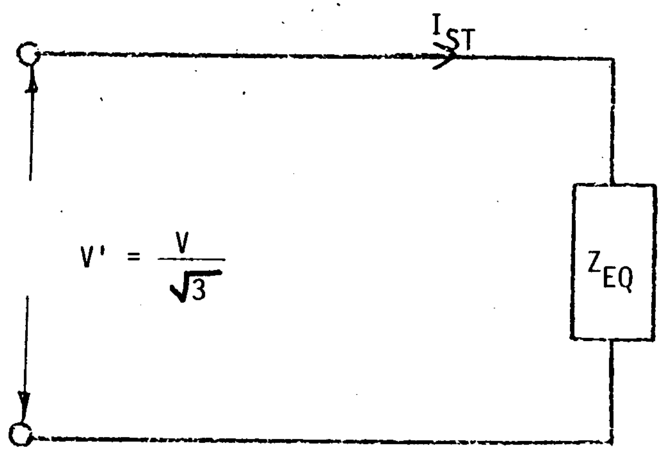

Figure 3-12. The equivalent impedance of the combined equivalent circuit of Machine No. 1 and Machine No. 2.

$$Z_6 = \frac{Z_4 Z_5}{Z_4 + Z_5} \qquad (3\text{-}20)$$

In Figure 3-10, this is shown where

$$Z_7 = Z_3 + Z_6 \qquad (3\text{-}21)$$

and in Figure 3-11, this is shown where

$$Z_8 = \frac{Z_2 Z_7}{Z_2 + Z_7} \ . \qquad (3\text{-}22)$$

In Figure 3-12 this is shown where

$$Z_{EQ} = Z_1 + Z_8 \ . \qquad (3\text{-}23)$$

Relationship between the Slip (S_1) of Machine #1 and the Slip (S_2) of Machine #2

For Machine #1:

$$N_1 = \frac{120 f_1}{P_1} (1 - S_1)$$

For Machine #2:

$$N_2 = \frac{120 f_2}{P_2} (1 - S_2)$$

As Machine #1 is coupled to Machine #2

$$\therefore N_1 = N_2$$

$$\frac{120 f_1}{P_1} (1 - S_1) = \frac{120 f_2}{P_2} (1 - S_2)$$

$$\frac{120 f_1}{P_1} (1 - S_1) = \frac{120 S_1 f_1}{P_2} (1 - S_2)$$

$$\left(\frac{120 f_1}{P_1}\right)(1 - S_1) = \frac{120 f_1}{P_1} \quad \frac{P_1}{P_2} \quad S_1 (1 - S_2)$$

As the machines are identical

$$\therefore P_1 = P_2$$

$$\therefore (1 - S_1) = S_1 (1 - S_2)$$

$$1 - S_1 = S_1 - S_1S_2$$

$$1 = 2S_1 - S_1S_2$$

$$1 = S_1 (2 - S_2)$$

$$\therefore S_1 = \frac{1}{2 - S_2} \quad (3\text{-}24)$$

or

$$S_2 = (2 - \frac{1}{S_1}) \quad (3\text{-}25)$$

Derivation of Expressions for Current, Power and Torque

From Figure 3-8 to Figure 3-12 expressions for currents in the different branches of the circuit were developed as follows.

From Figure 3-12:

$$I_{ST} = \frac{V'}{Z_{EQ}} \quad (3\text{-}26)$$

From Figure 3-10:

$$I_3 = I_{ST} \frac{Z_2}{Z_2 + Z_7} \quad (3\text{-}27)$$

From Figure 3-8:

$$I_4 = I_3 \frac{Z_5}{Z_4 + Z_5} \quad (3\text{-}28)$$

From Figure 3-3:

$$I_{RC_2} = I_4 \frac{jXM_2''}{\frac{RC_2''}{S_1S_2} + jXM_2''} \quad (3\text{-}29)$$

From Figure 3-8:

$$I_5 = I_3 \frac{Z_4}{Z_4 + Z_5} \quad (3\text{-}30)$$

As shown in Figure 3-13, the power input to the rotor of Machine #1 per phase was equal to:

$$P_{g1} = (I_3)^2 \left[\frac{RR_1'}{S_1} + \frac{RR_2'}{S_1}\right] \quad (3\text{-}31)$$

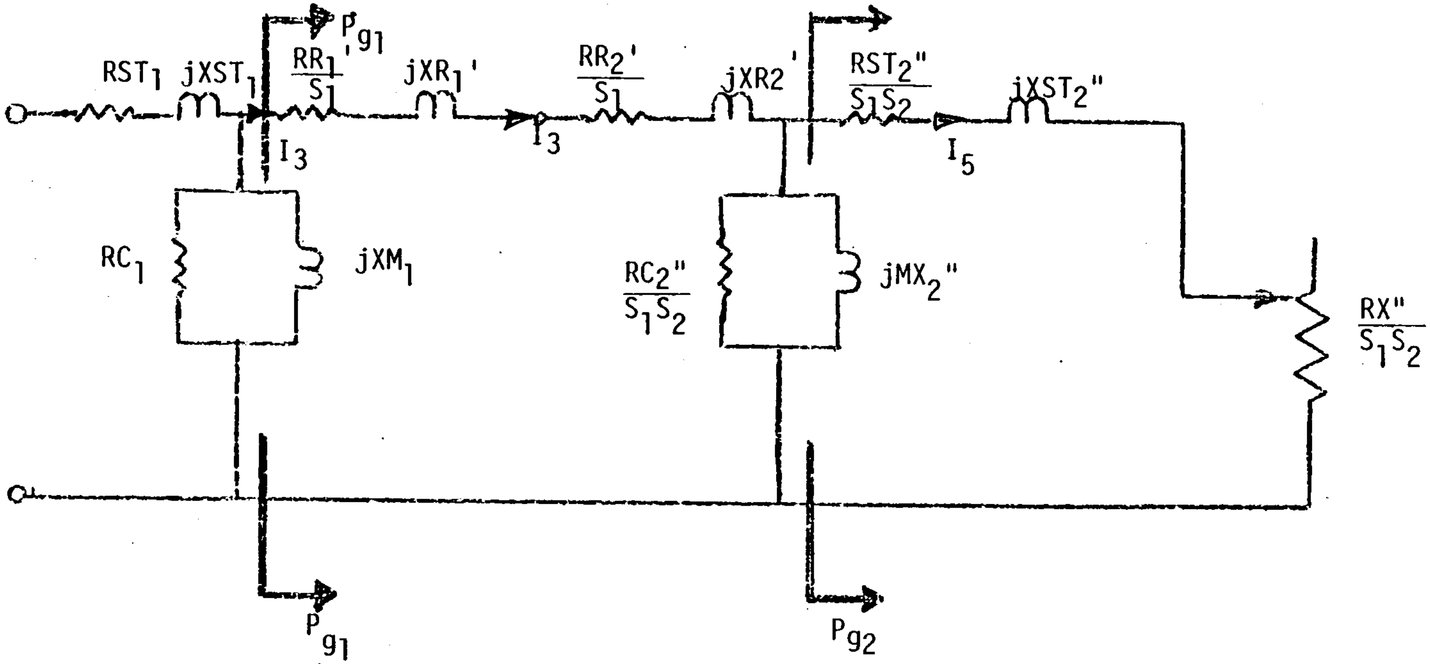

Figure 3-13. Combined equivalent circuit of Machine No. 1 and Machine No. 2.

Also as shown in Figure 3-13, the power input to the stator of Machine #2 was equal to:

$$P_{g2} = (I_5)^2 \left[\frac{RST_2''}{S_1S_2} + \frac{RX''}{S_1S_2}\right] \tag{3-32}$$

From Eq. (3-25)

$$S_2 = (2 - \frac{1}{S_1})$$

$$\therefore S_1S_2 = (2S_1 - 1)$$

$$\therefore P_{g2} = (I_5)^2 \left[RST_2'' + RX''\right] \frac{1}{(2S_1 - 1)} \tag{3-33}$$

To find the mechanical power developed Figure 3-13 was modified to Figure 3-14. Figure 3-14 was more modified to Figure 3-15. Then from Figure 3-15, the mechanical power developed per phase (P_{em}):

$$P_{em} = \Big[(I_3)^2(RR_1' + RR_2')(\frac{1-S_1}{S_1}) + (IRC_2)^2(\frac{RC2''}{S_1})\ (1 - S_1 + \frac{1 - S_2}{S_2}) + (I_5)^2(\frac{RST2''}{S_1})(1 - S_1 + \frac{1-S_2}{S_2}) + (I_5)^2(\frac{RX''}{S_1})(1 - S_1 + \frac{1-S_2}{S_2})\Big] \tag{3-34}$$

From Eq. (3-25) substituting the value of S_2 in terms of S_1 in Eq. (3-34) we get

$$P_{em} = (1 - S_1)\left[(I_3)^2(\frac{RR_1'+RR_2'}{S_1}) + 2(IRC_2)^2(\frac{RC2''}{2S_1-1}) + 2(I_5)^2(\frac{RST2'' + RX''}{2S_1 - 1})\right] \text{ per phase .} \tag{3-35}$$

The developed electromagnetic torque, $(Tem) = \frac{P_{em}}{W_m}$

$$T_{em} = \frac{P_{em}}{\frac{2\pi N}{60}} = \frac{P_{em}}{\frac{2\pi}{60}(1-S_1)N_{syn}}$$

$$T_{em} = \frac{P_{em}}{\frac{2\pi}{60}(1-S_1)\frac{120f}{P}}$$

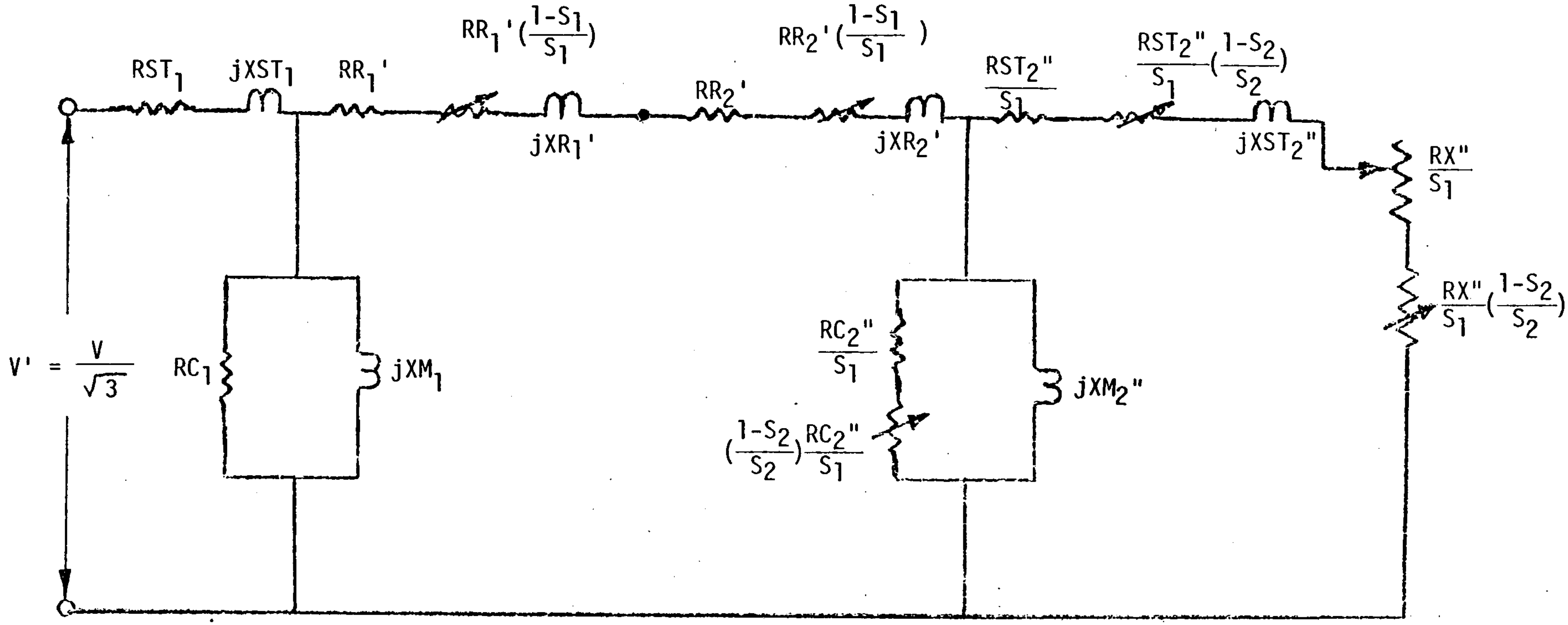

Figure 3-14. Modified combined equivalent circuit of Machine No. 1 and Machine No. 2.

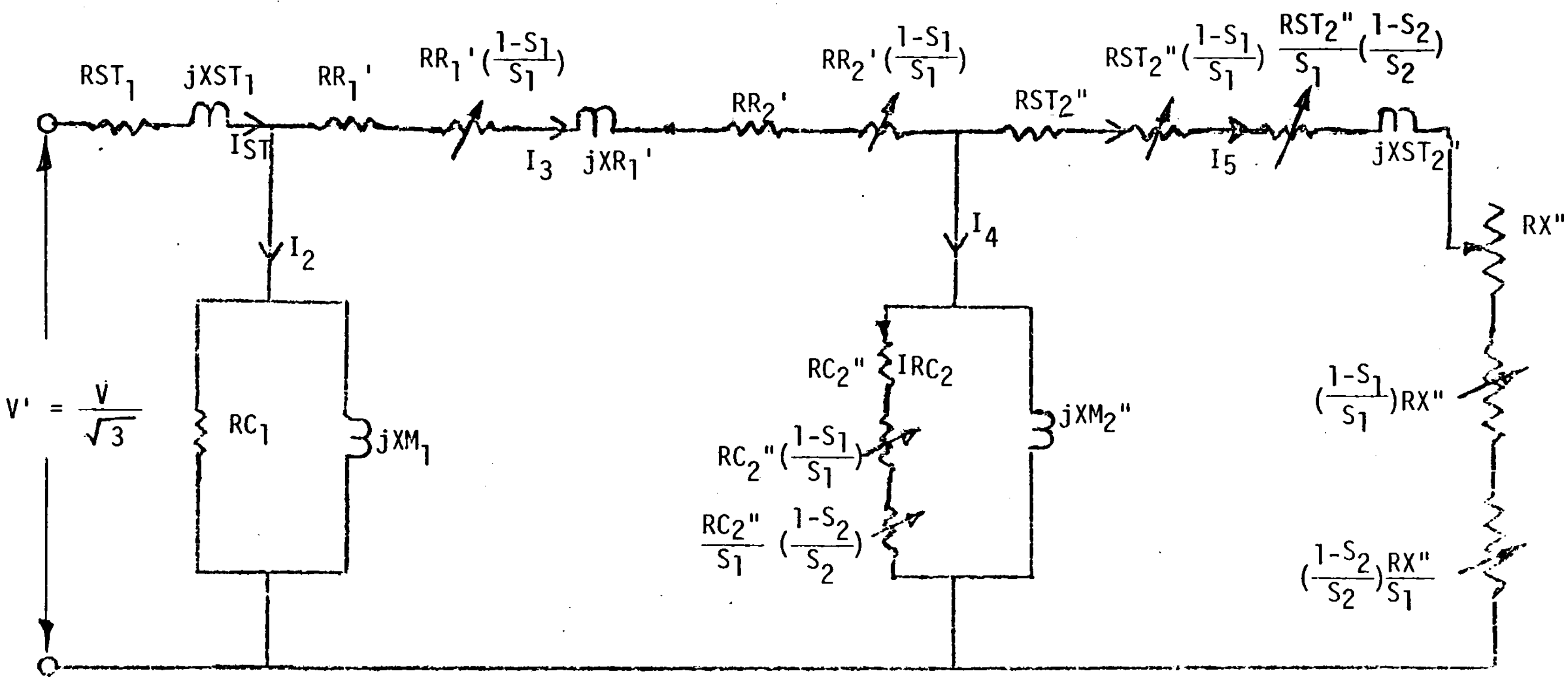

Figure 3-15. More modified combined equivalent circuit of Machine No. 1 and Machine No. 2.

where F = the frequency of the supply voltage

= 60 Hz/sec

and P = number of poles of the machine.

$$\therefore \text{Tem} = \frac{P_{em} \cdot P}{4\pi(1-S_1)60} \tag{3-36}$$

For a 6-pole machine and from Eq. (3-35)

$$T_{em} = \frac{1}{40\pi}\left[(I_3)^2 \left(\frac{RR_1' + RR_2'}{S_1}\right) + 2(IRC_2)^2 \left(\frac{RC_2''}{2S_1 - 1}\right) + 2(I_5)^2 \left(\frac{RST_2'' + RX''}{2S_1 - 1}\right)\right] \text{ per phase} \tag{3-37}$$

$$\text{For the Total Tem} = \frac{3}{40\pi}\left[(I_3)^2 \left(\frac{RR_1' + RR_2'}{S_1}\right) + 2(IRC_2)^2 \left(\frac{RC_2''}{2S_1 - 1}\right) + 2(I_5)^2 \left(\frac{RST_2'' + RX''}{2S_1 - 1}\right)\right] \tag{3-38}$$

Taking the losses in consideration,

$$P_{mech} = 3P_{em} - (P_{fw} + P_{stray}) \tag{3-39}$$

$$\text{Horsepower (HP)} = \frac{P_{mech}}{746} \tag{3-40}$$

$$\text{Power input } (P_{in}) = 3V' \, I_{ST} \cos\theta \tag{3-41}$$

$$\text{Efficiency} = \frac{P_{mech}}{P_{IN}} \tag{3-42}$$

$$\text{Torque (T)} = \frac{P_{mech}}{W_M} \text{ N-m/rad} \tag{3-43}$$

From the equations developed in this chpater, the predicted performance characteristics were calculated. Inspection of Eq. (3-38) showed that the external resistor (RX) added in the stator circuit was a controlling parameter by which speed control was accomplished.

The results of practical tests are given in Chapter IV to confirm the application of the analysis to speed control.

CHAPTER IV

APPLICATION OF THE ANALYSIS TO SPEED CONTROL

An analysis of a test and calculated performance characteristics of a pair of identical 3-phase slip ring induction motors whose shafts were coupled and their rotor circuits were interconnected; one set of the stator windings connected directly to a 3-phase external variable resistor, is presented in this chapter with the results confirmed by tests.

Before conducting the tests, which were performed in the Machinery Laboratory of the Electrical Engineering Department at The University of Tennessee, the various parameters indicated in the equivalent circuit in Figure 3-2, Chapter III, were obtained by the following tests: [6]

(a) No load and locked rotor tests

(b) A D. C. volt drop test

(c) Turns ratio (K)

The measuring instruments used in the tests were not sensitive enough to measure lower frequencies with lower voltages in the rotor circuits. From the above tests, the constants of the test machines were as follows:

Equivalent Single-Phase Quantities

Stator (ohms)	Rotor (ohms)
Stator resistance (R_{st}) = 0.30	Rotor resistance (R_R) = 0.1126
Stator leakage reactance (X_{st}) = 1.208	Rotor leakage reactance (X_R) = 0.1436

Stator (ohms) Rotor (ohms)

Magnetizing Reactance (X_M) = 17.029

Core-Loss Resistor (R_C) = 137.32

Each motor was 5HP220-V three phase 60 HZ 6-pole wound rotor induction motor, having the above data and its stator and rotor connected in WYE. The ratio of effective stator turns to effective rotor turns was K = 2·9:1. The windage and friction losses were 250 watts at rated speed and may be assumed constant from no load to full load. The only available external resistor (Rx) in the lab. was measured by the D.C. Volt drop test and was 1.25 ohms per phase.

For the test performance, the test machines were set up in line with their shafts coupled and their rotor circuits suitably interconnected to run close to synchronous speed.

A D-C shunt generator was arranged to be driven by the set. The output of the D.C. Generator can be either fed back into a D-C power system or dissipated in a resistance as in this test. Ammeters were placed in the field and load circuits and a voltmeter is connected across the generator terminals. A torquemeter and speedometer were connected to measure the torque and speed respectively. The stator windings of the second machine was short circuited, i.e. external resistor equals to zero. The stator windings of the first machine were connected to a 3-phase 220V balanced supply through an autotransformer and circuit breaker for the protection of the motors from the high inrush currents. A voltmeter, ammeter and wattmeter were placed in the supply circuit to measure the supply voltage which was kept constant during the test, the line currents which varied with D.C. load and the power input with different loading. In the test a maximum variation from 1170 rpm to 950 rpm was possible.

Because the operation of this machine is best described in terms of the external resistor, the test was repeated with the external resistor added to the stator circuit of the second machine. From the measured results with the external resistor equal to zero and the external resistor equal to 1.25 ohms, torque VS speed, current VS horsepower and efficiency VS horsepower were plotted for comparison. Figure 4-1 to Figure 4-6).

For the calculated performance characteristics, the test machine data was used in the equations developed for the torque, current and efficiency in Chapter III. The characteristic curves, torque VS speed, current VS horsepower and efficiency VS horsepower were plotted with external resistance equals to zero and equals to 1.25 ohms. in Figure 4-7 to Figure 4-12.

The agreement between the measured and calculated results were good, which indicated that the equivalent circuit approach is valid for extended prediction of more calculated performance characteristics. These calculated characteristic curves are plotted with different values of external resistor for more investigation as in Figure 4-13 to Figure 4-27.

From the measured and calculated results, the characteristic of induction motors can be readily seen. Slip depends upon the developed torque and the resistor added in the stator circuit.

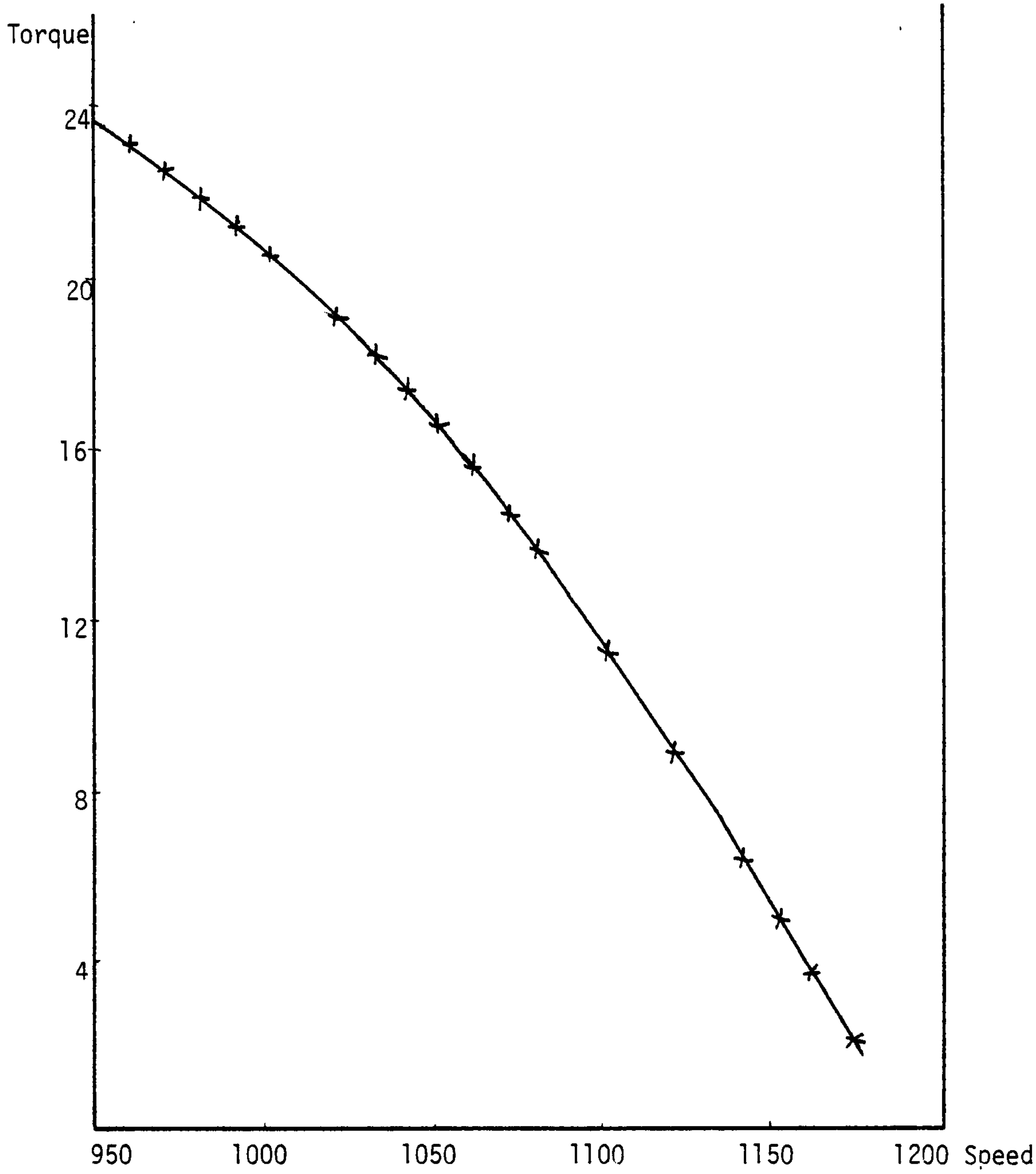

Figure 4-1. Measured results; torque vs speed, with R_X=0 ohm.

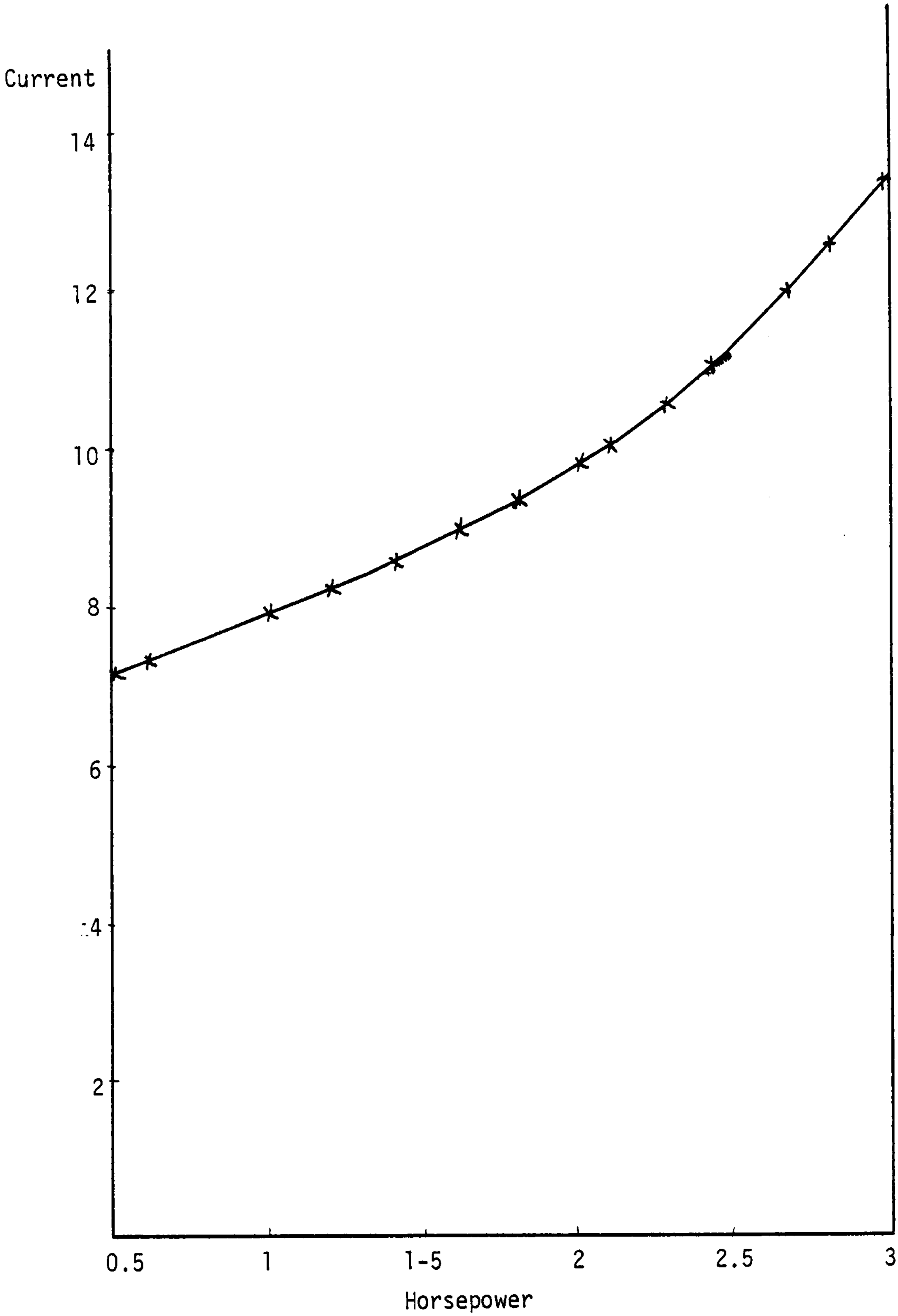

Figure 4-2. Measured results; current vs horsepower, with R_X=0 ohm.

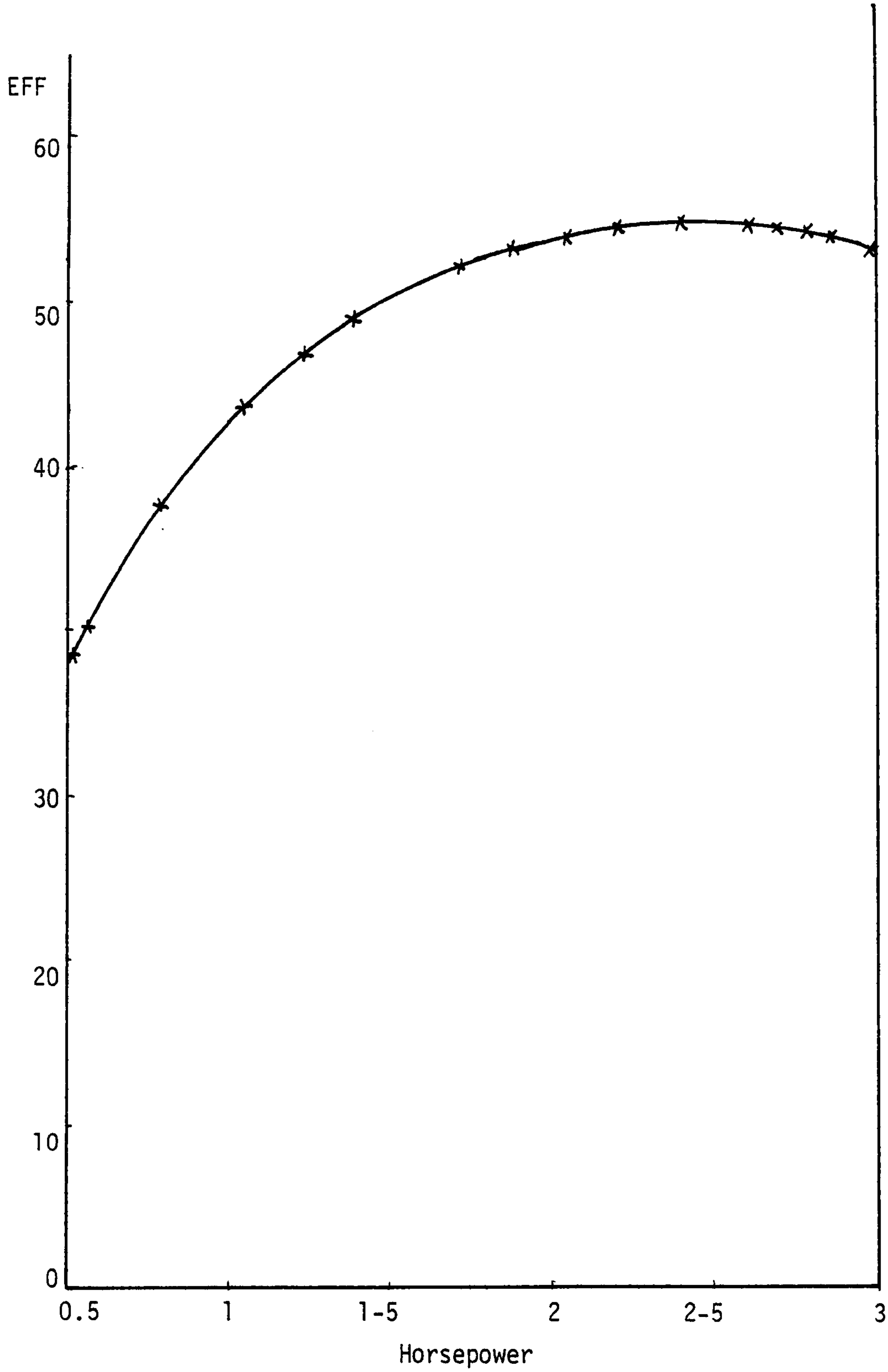

Figure 4-3. Measured results; efficiency vs horsepower, with R_X=0 ohm.

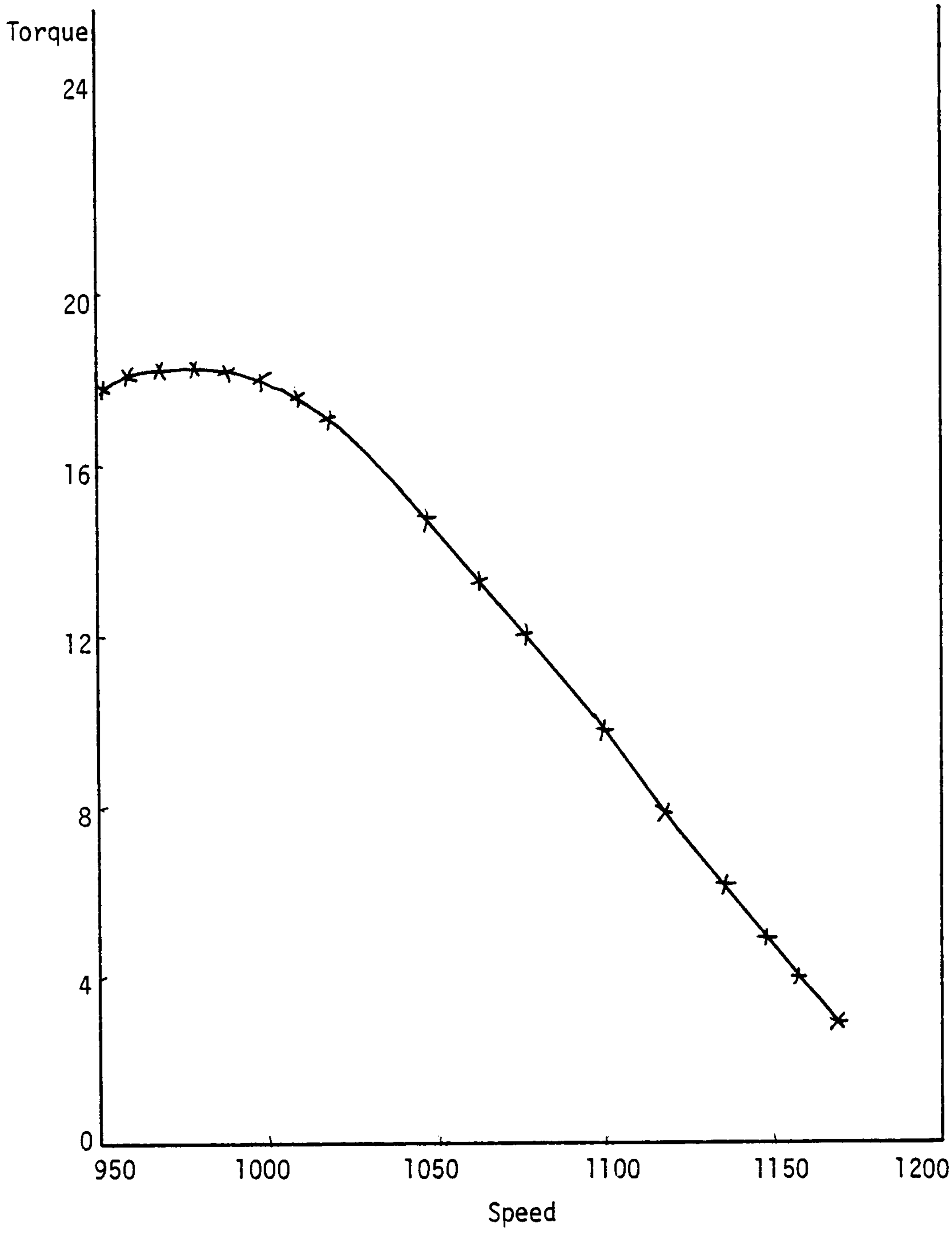

Figure 4-4. Measured results; torque vs speed, with R_X=1.25 ohms.

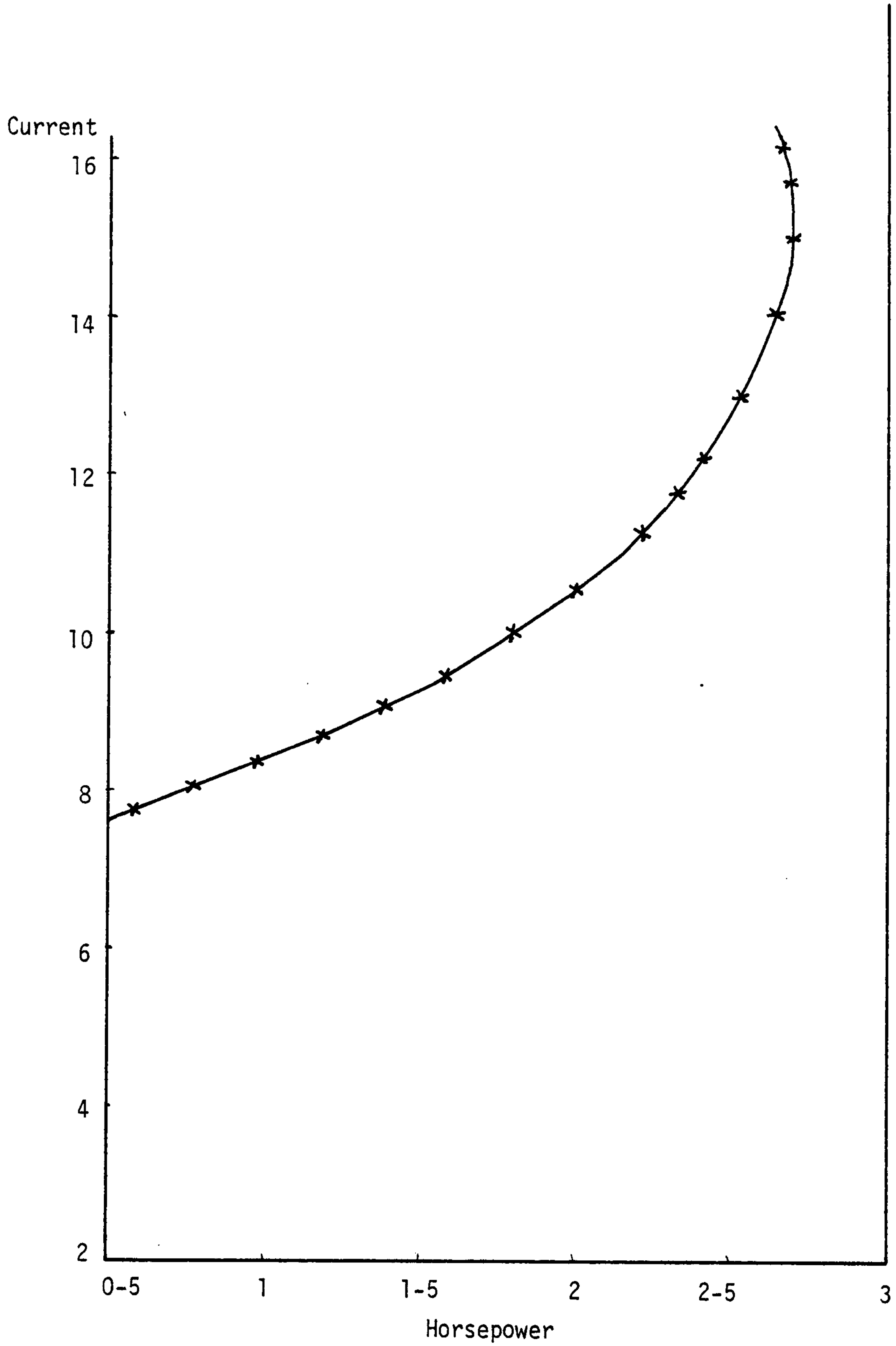

Figure 4-5. Measured results; current vs horsepower, with R_X=1.25 ohms.

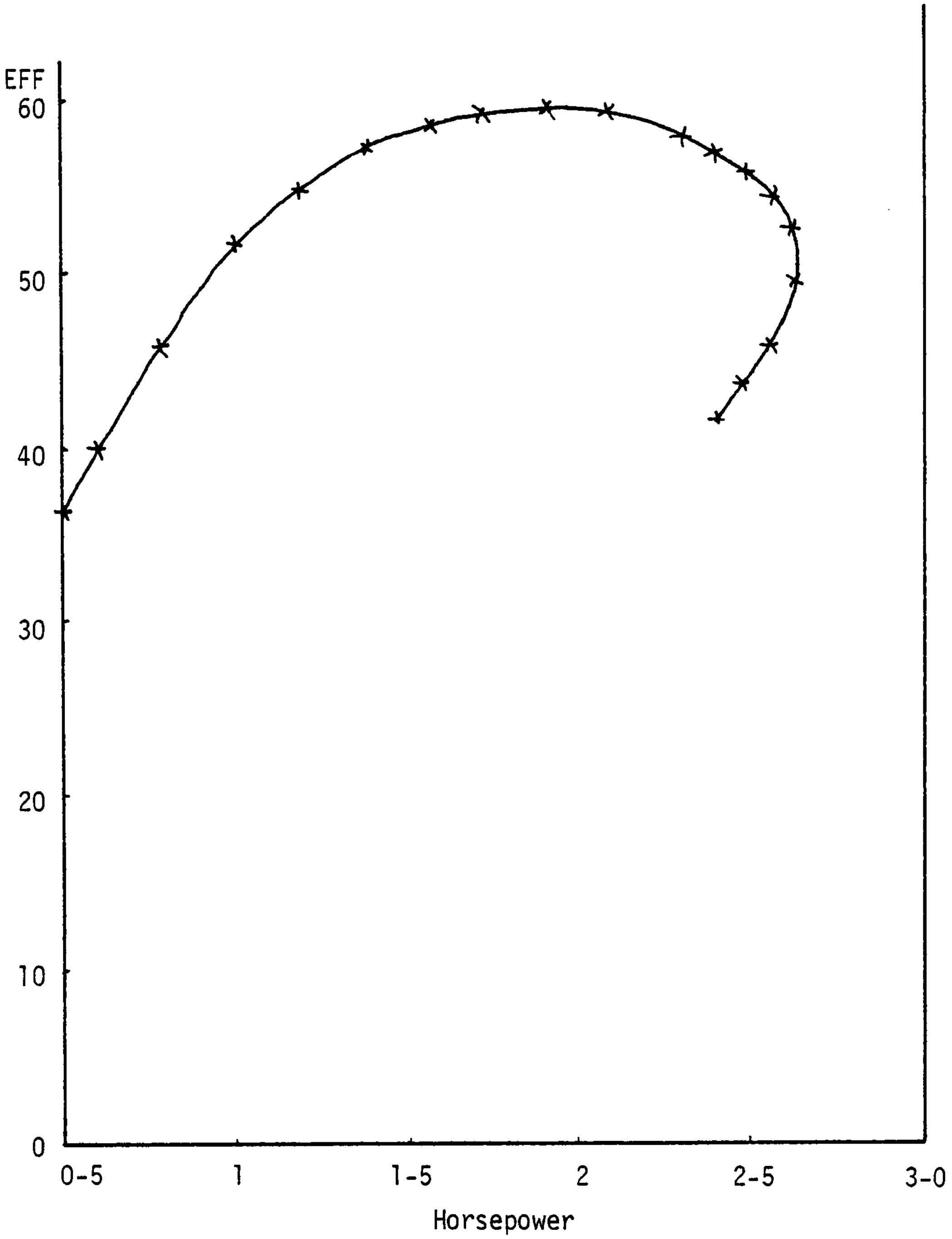

Figure 4-6. Measured results; efficiency vs horsepower, with R_X=1.25 ohms.

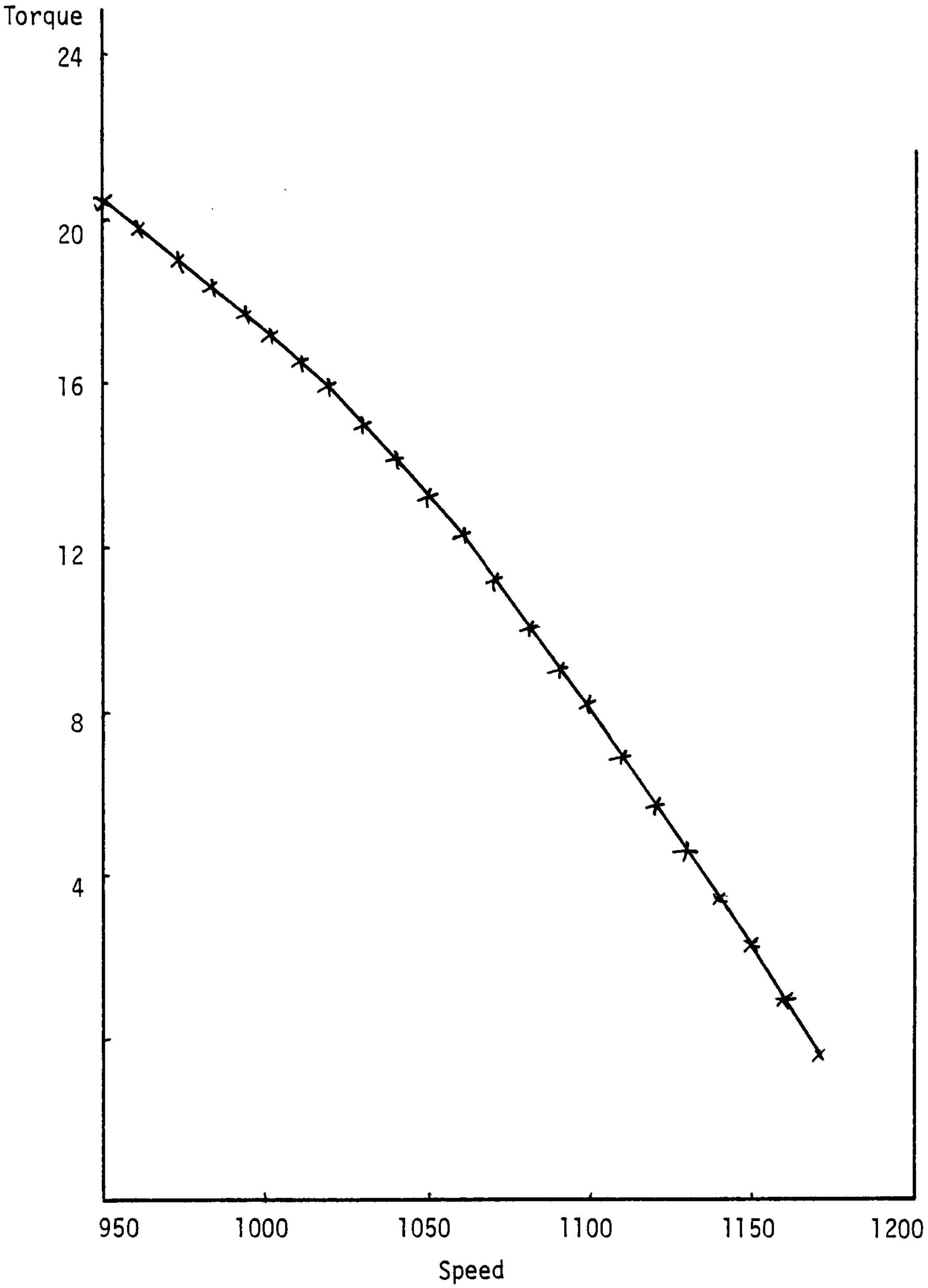

Figure 4-7. Calculated results; torque vs speed, with R_X=0 ohm.

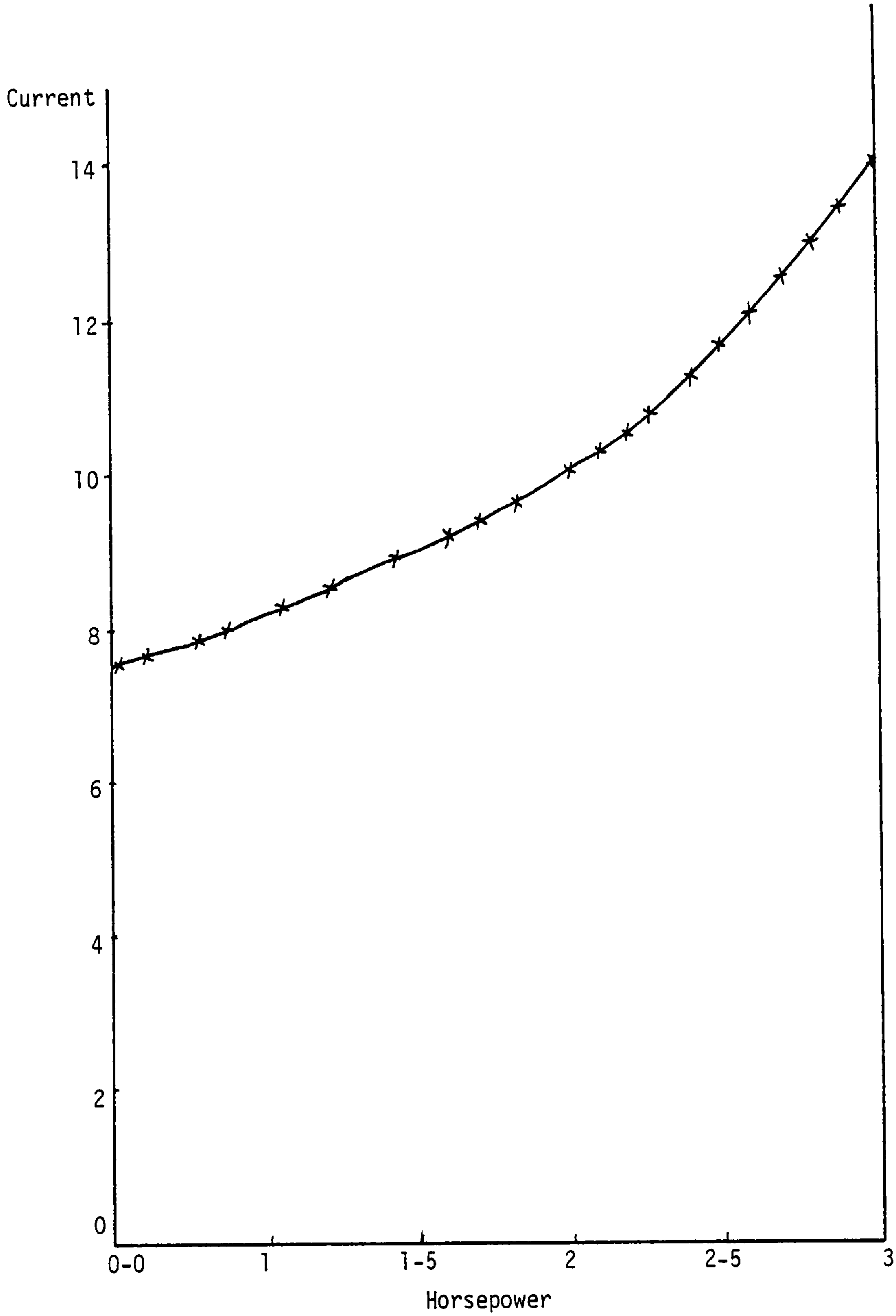

Figure 4-8. Calculated results; current vs horsepower, with R_X=0 ohm.

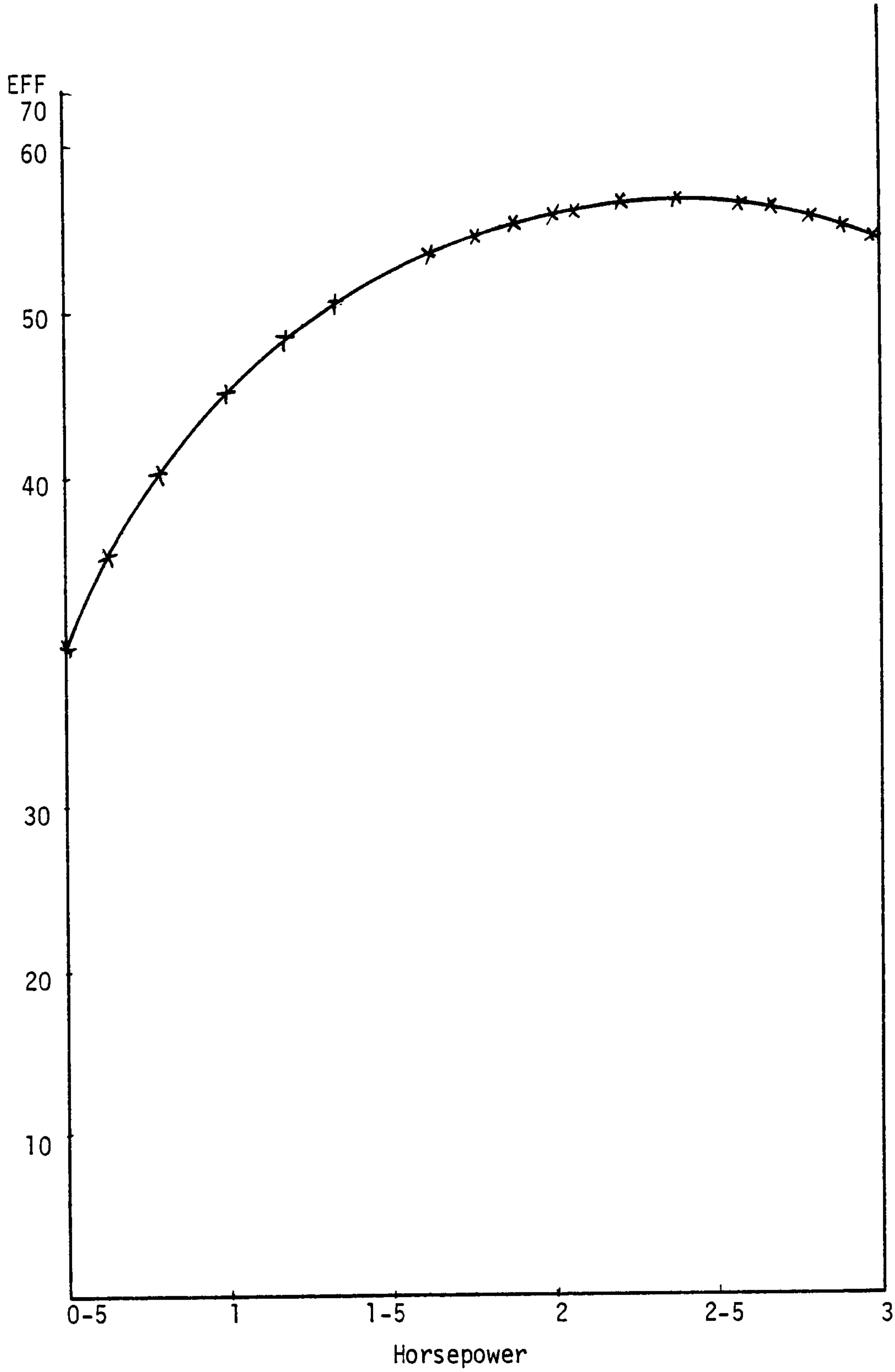

Figure 4-9. Calculated results; efficiency vs horsepower, with R_X=0 ohm.

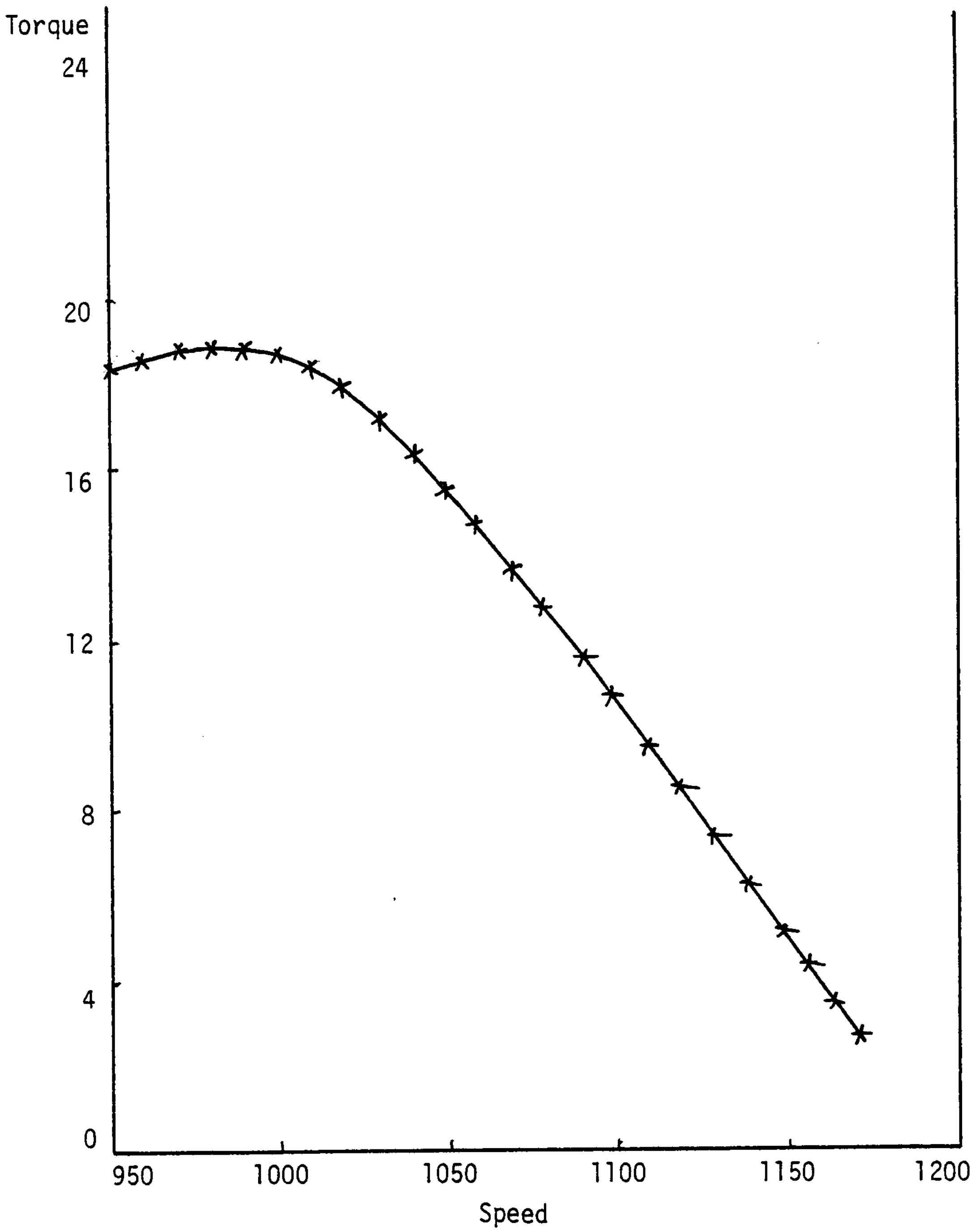

Figure 4-10. Calculated results; torque vs speed, with R_X=1.25 ohms.

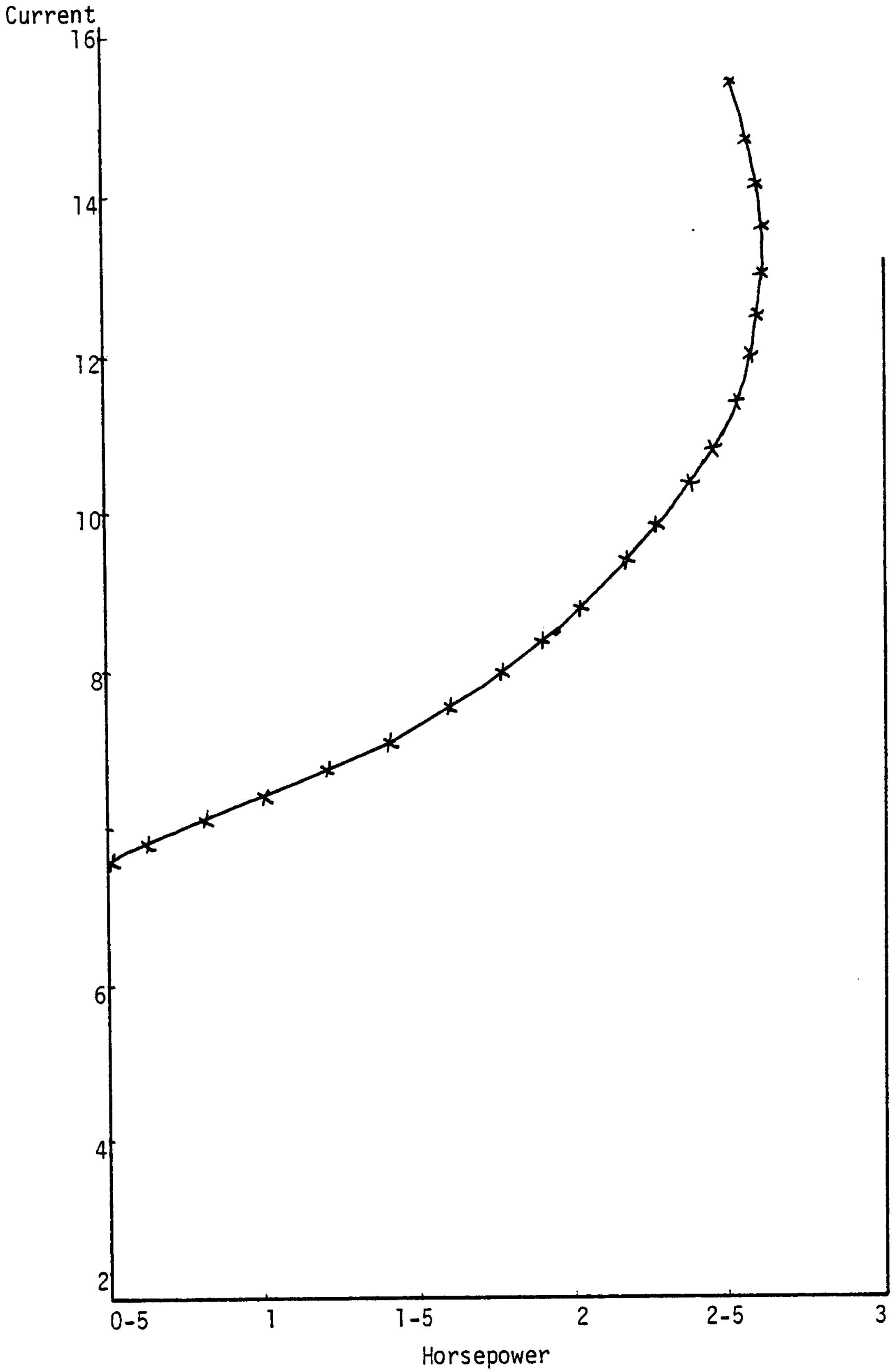

Figure 4-11. Calculated results; current vs horsepower, with R_X=1.25 ohms.

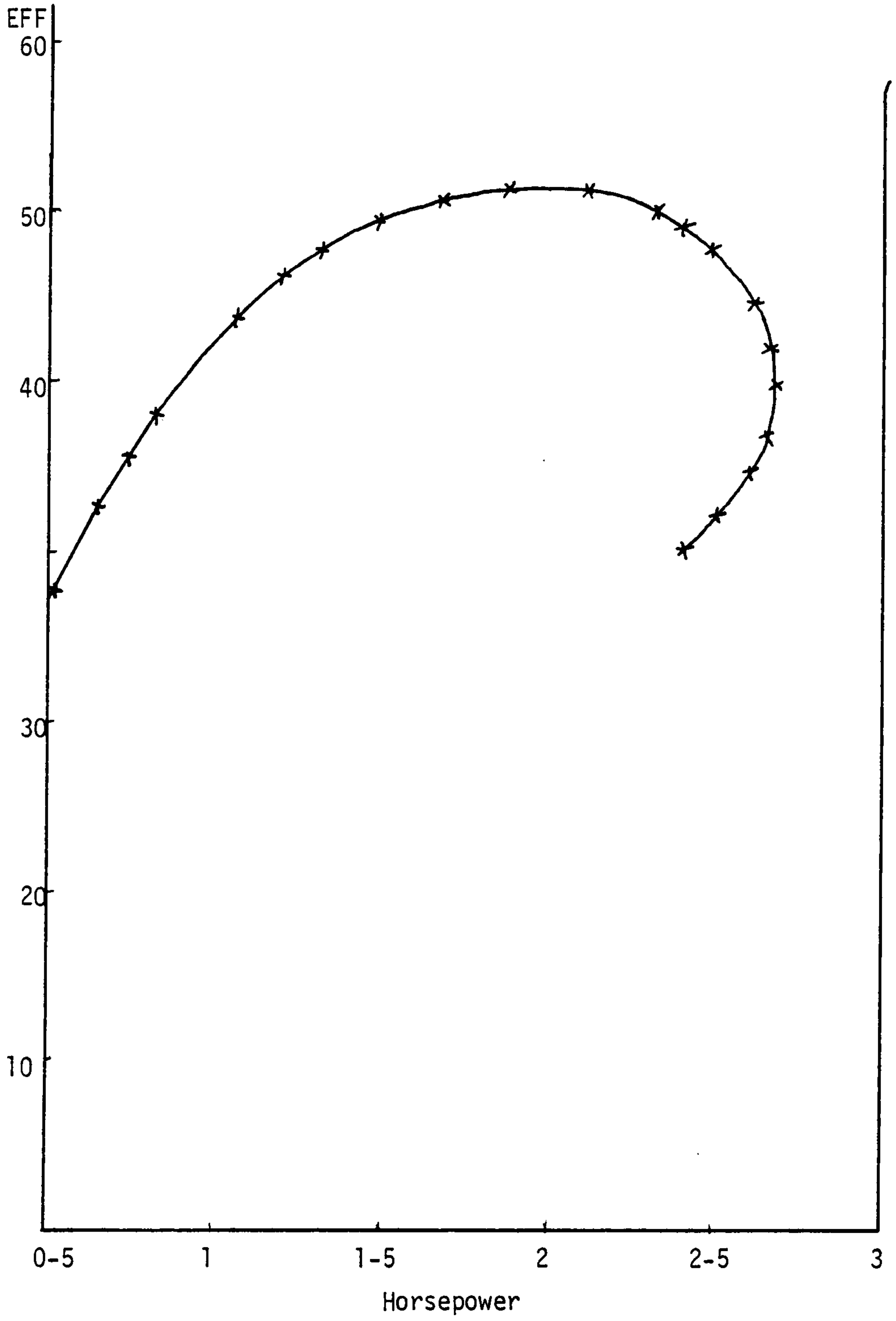

Figure 4-12. Calculated results; efficiency vs horsepower, with R_X=1.25 ohms.

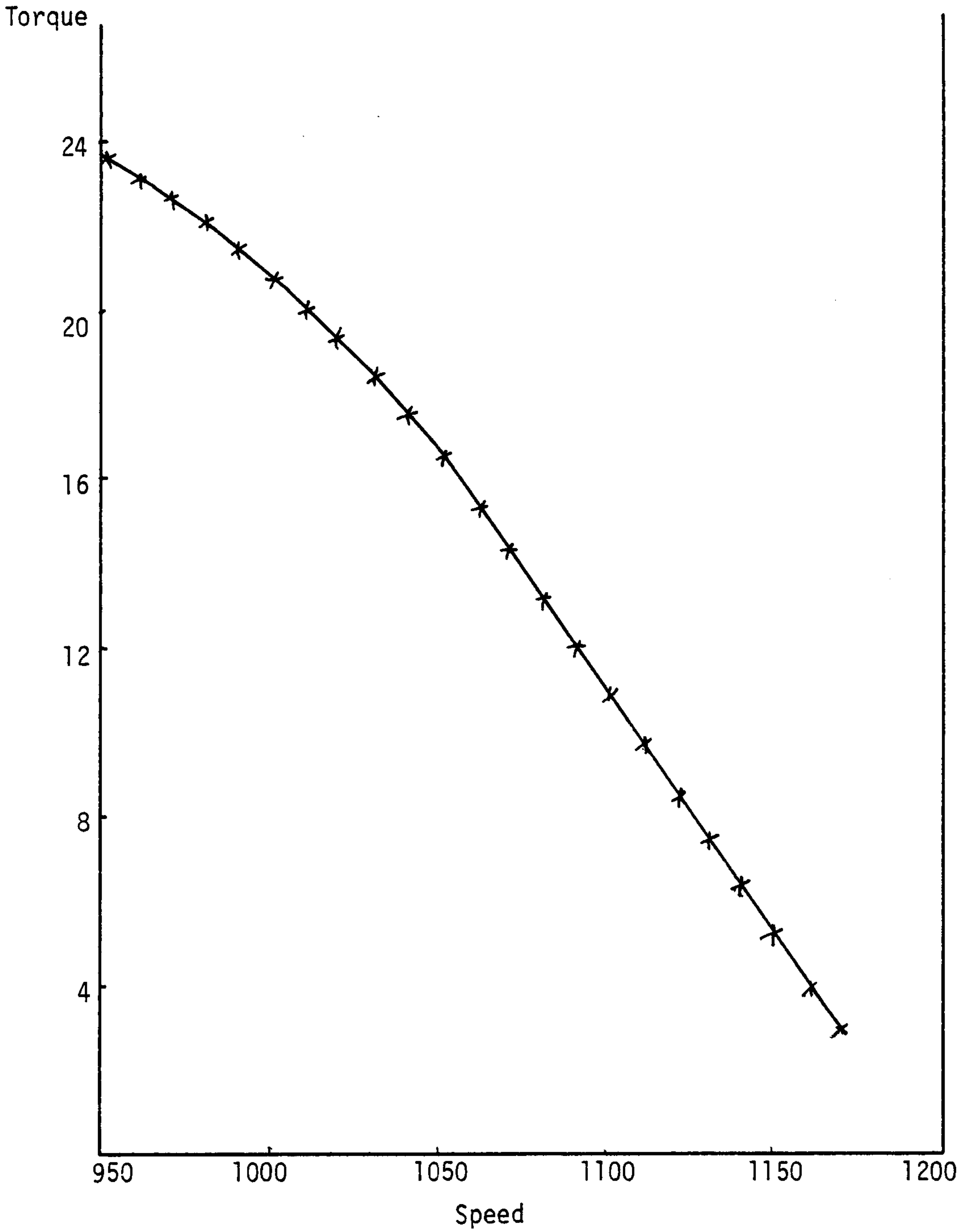

Figure 4-13. Calculated results; torque vs speed, with R_X=0.25 ohm.

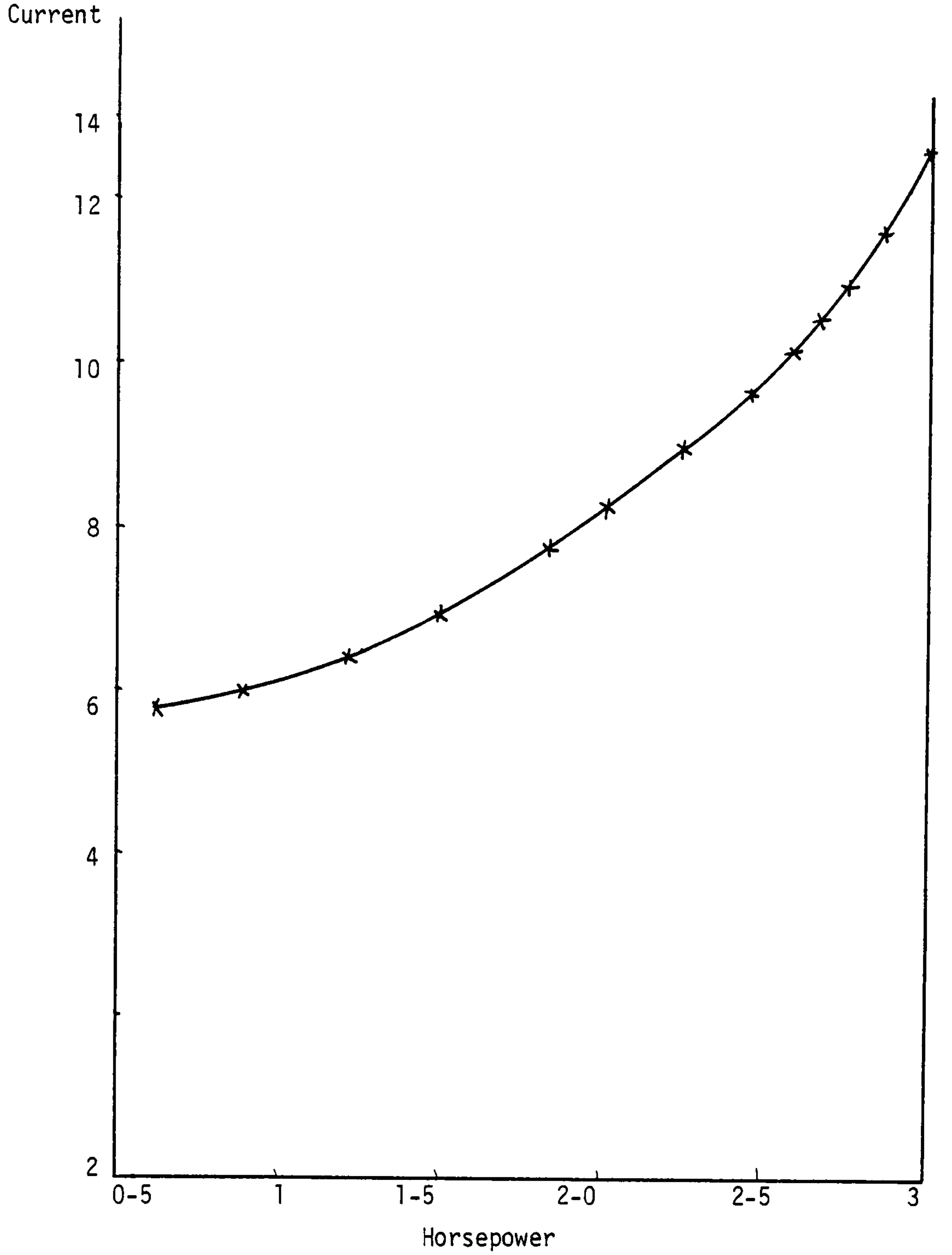

Figure 4-14. Calculated results; current vs horsepower, with R_X=0.25 ohm.

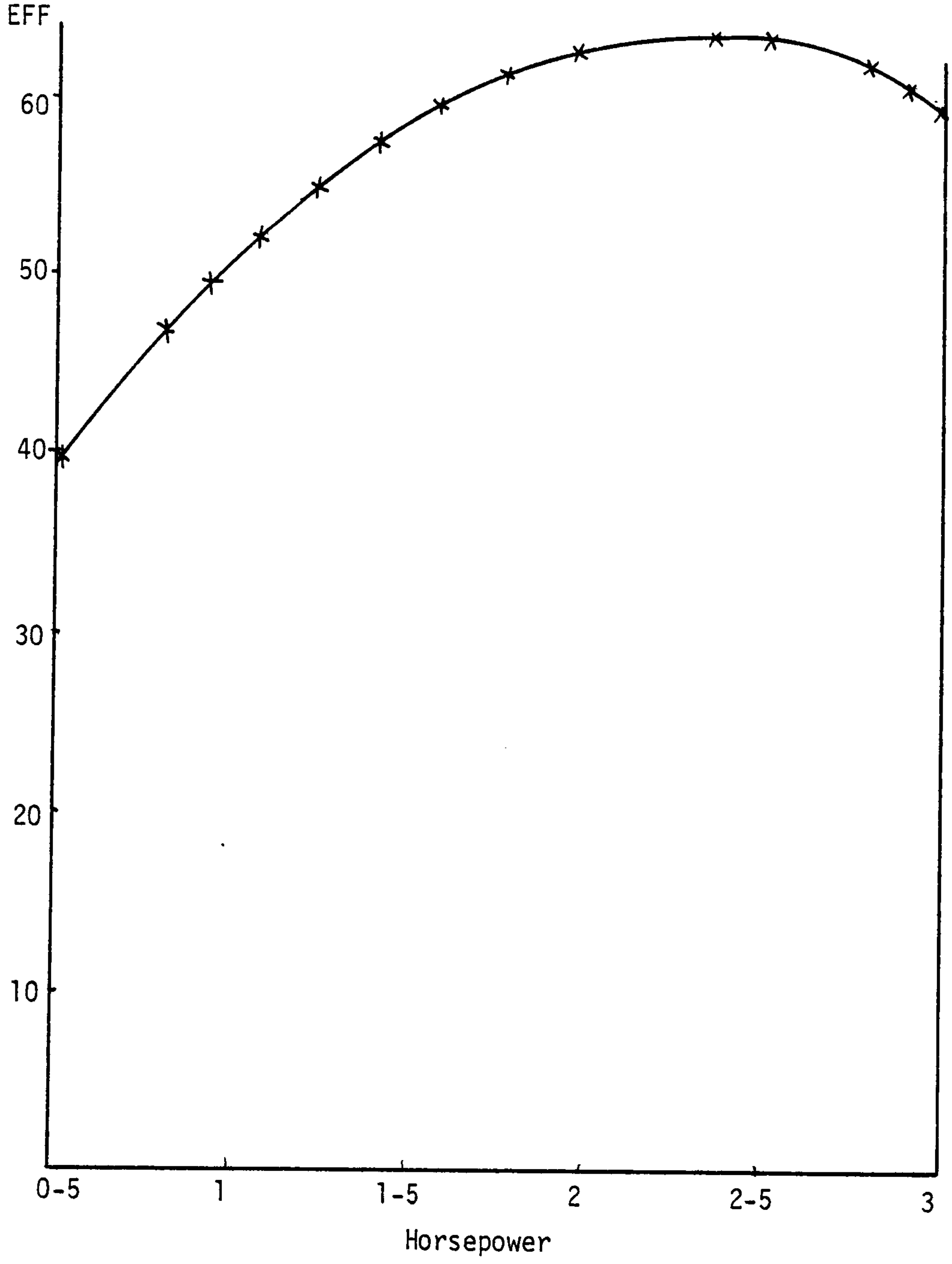

Figure 4-15. Calculated results; efficiency vs horsepower, with R_X=0.25 ohm.

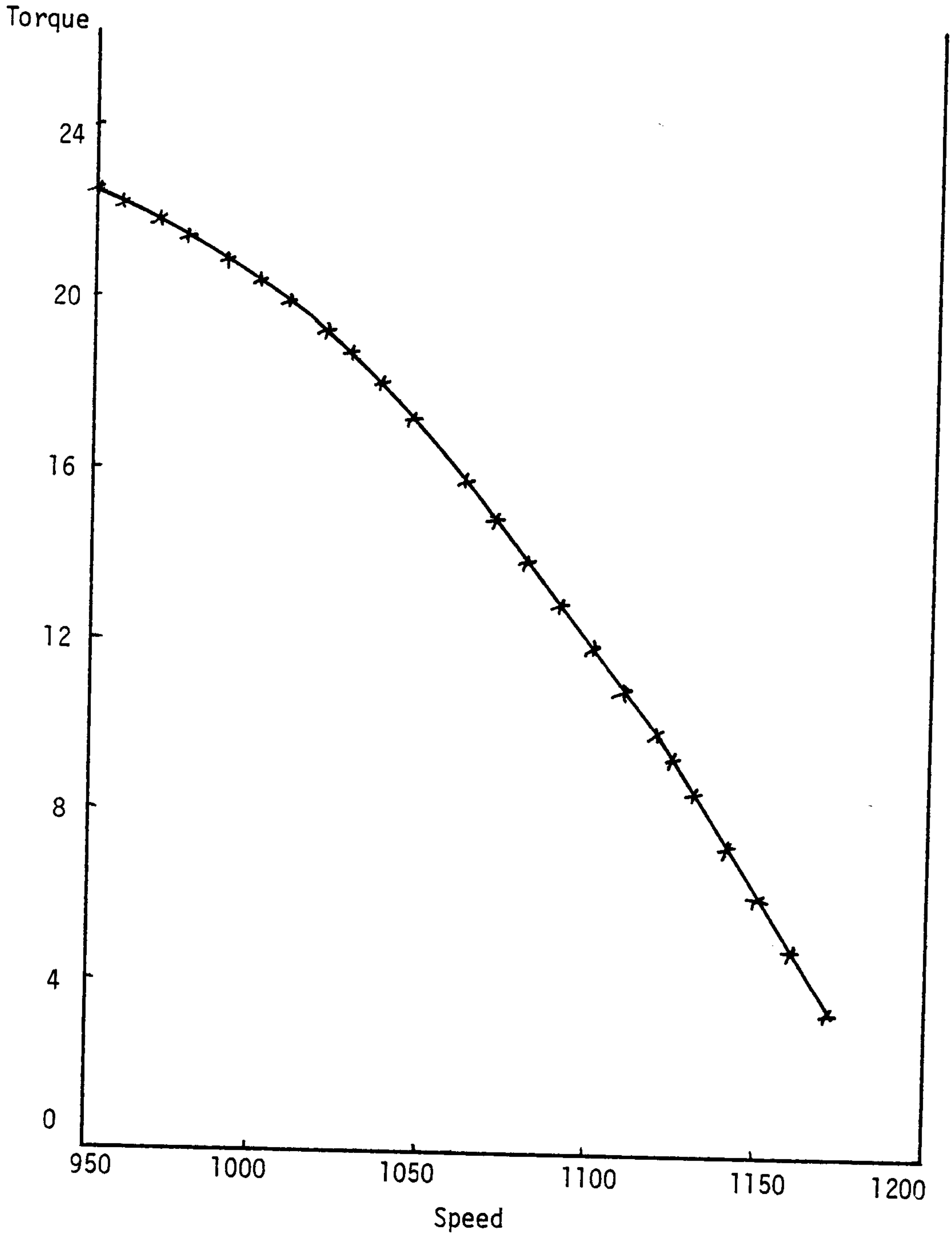

Figure 4-16. Calculated results; torque vs speed, with R_X=0.5 ohm.

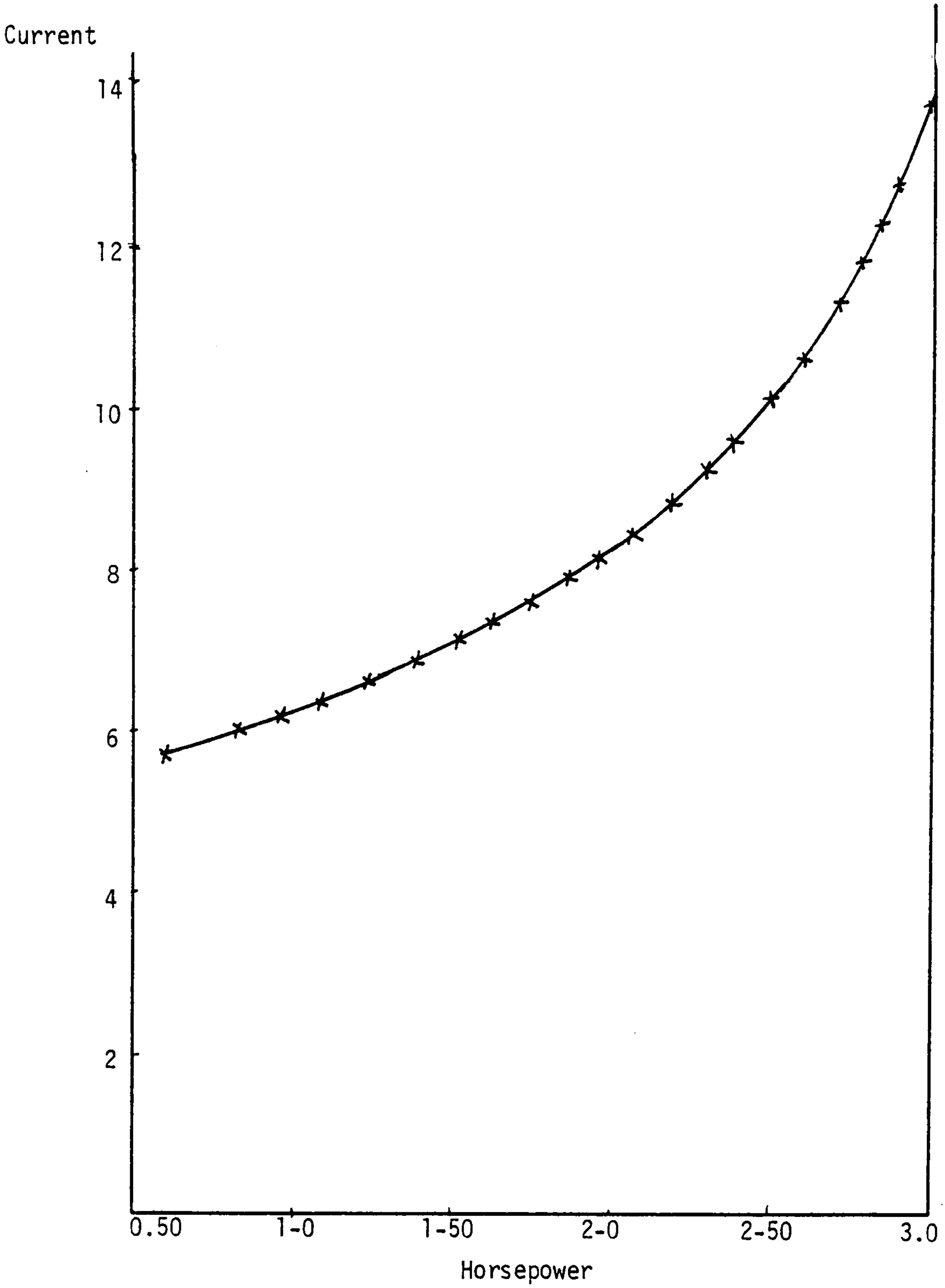

Figure 4-17. Calculated results; current vs horsepower, with R_X=0.50 ohm.

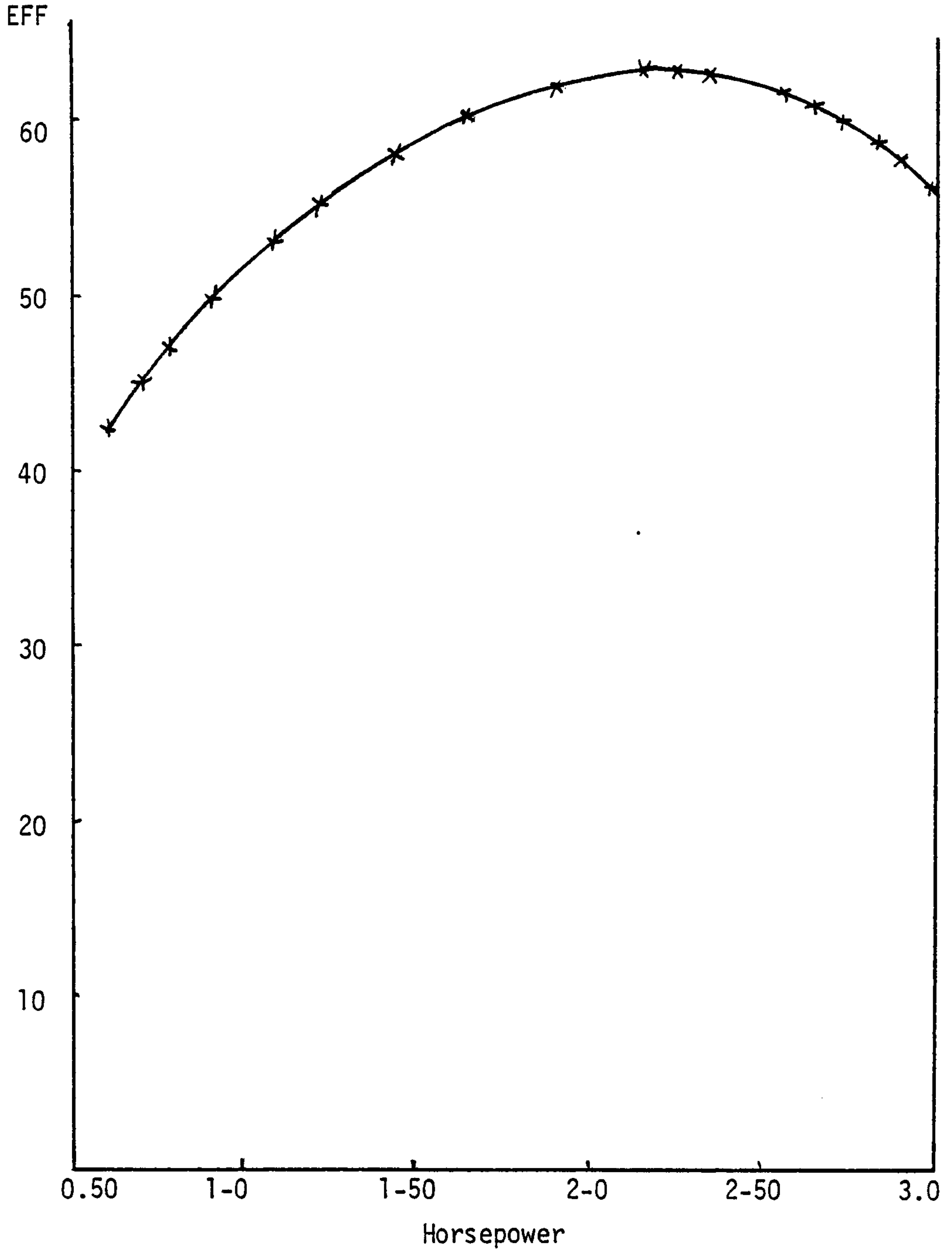

Figure 4-18. Calculated results; efficiency vs horsepower, with R_X=0.5 ohm.

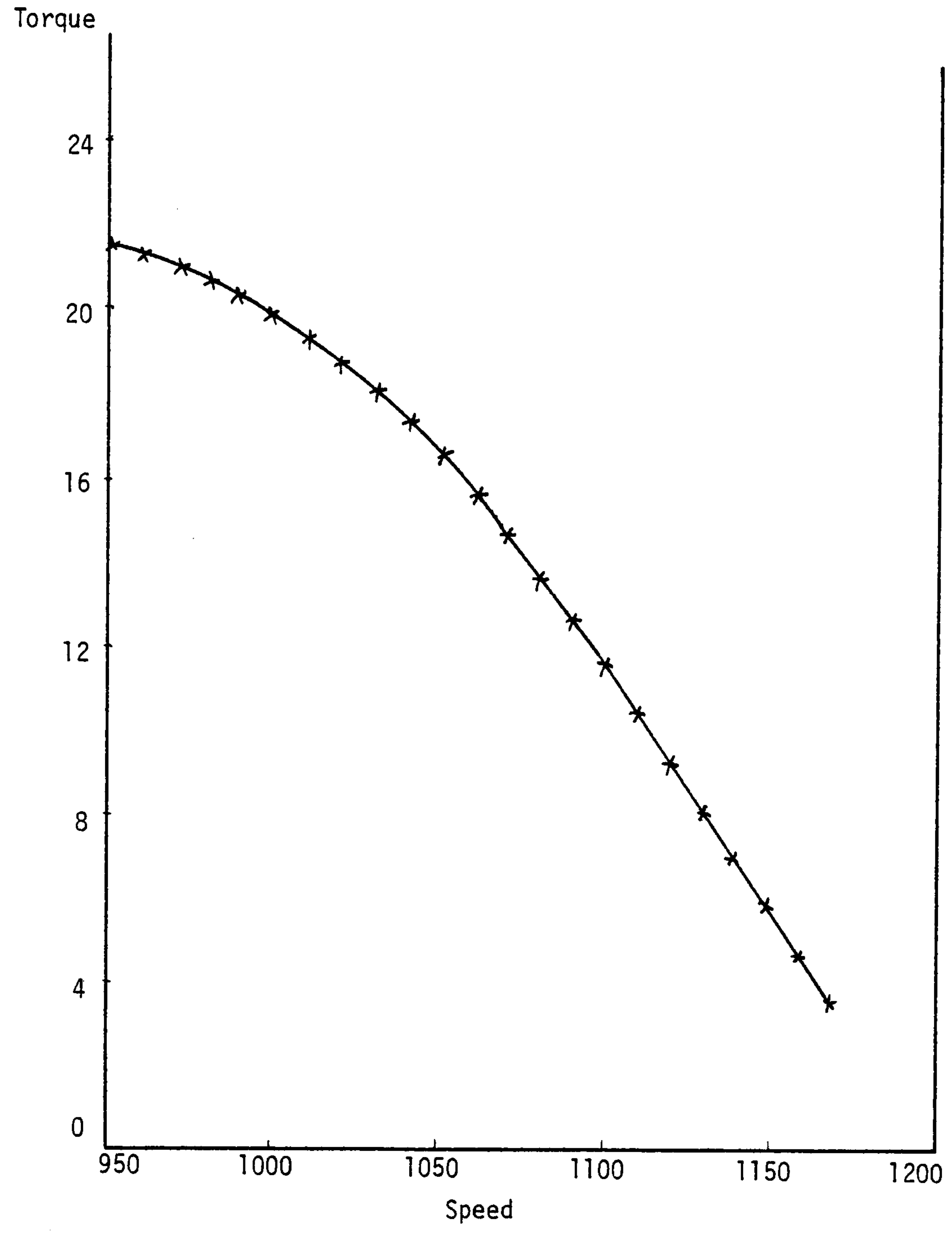

Figure 4-19. Calculated results; torque vs speed, with R_X=0.75 ohm.

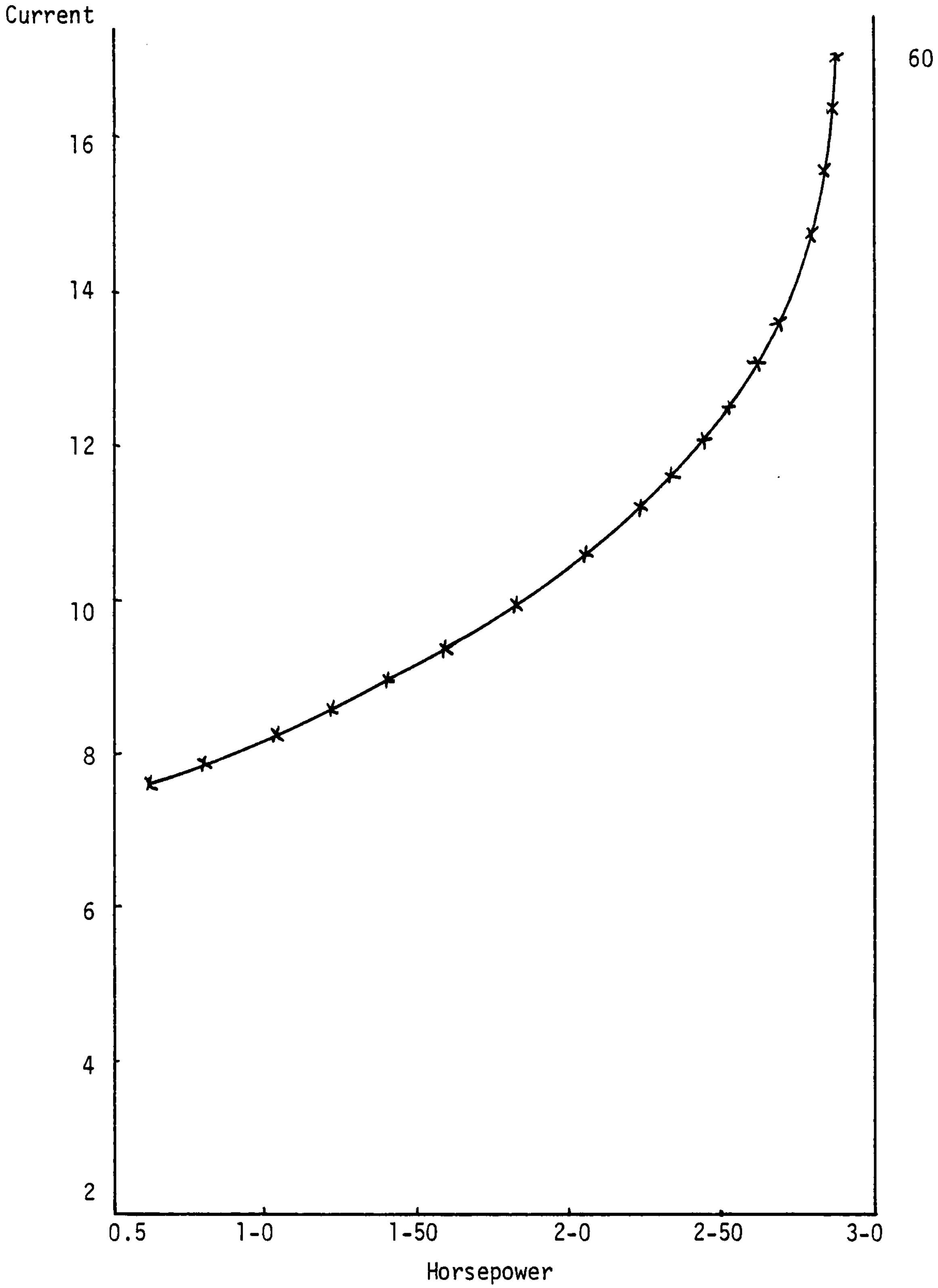

Figure 4-20. Calculated results; current vs horsepower, with R_X=0.75 ohm.

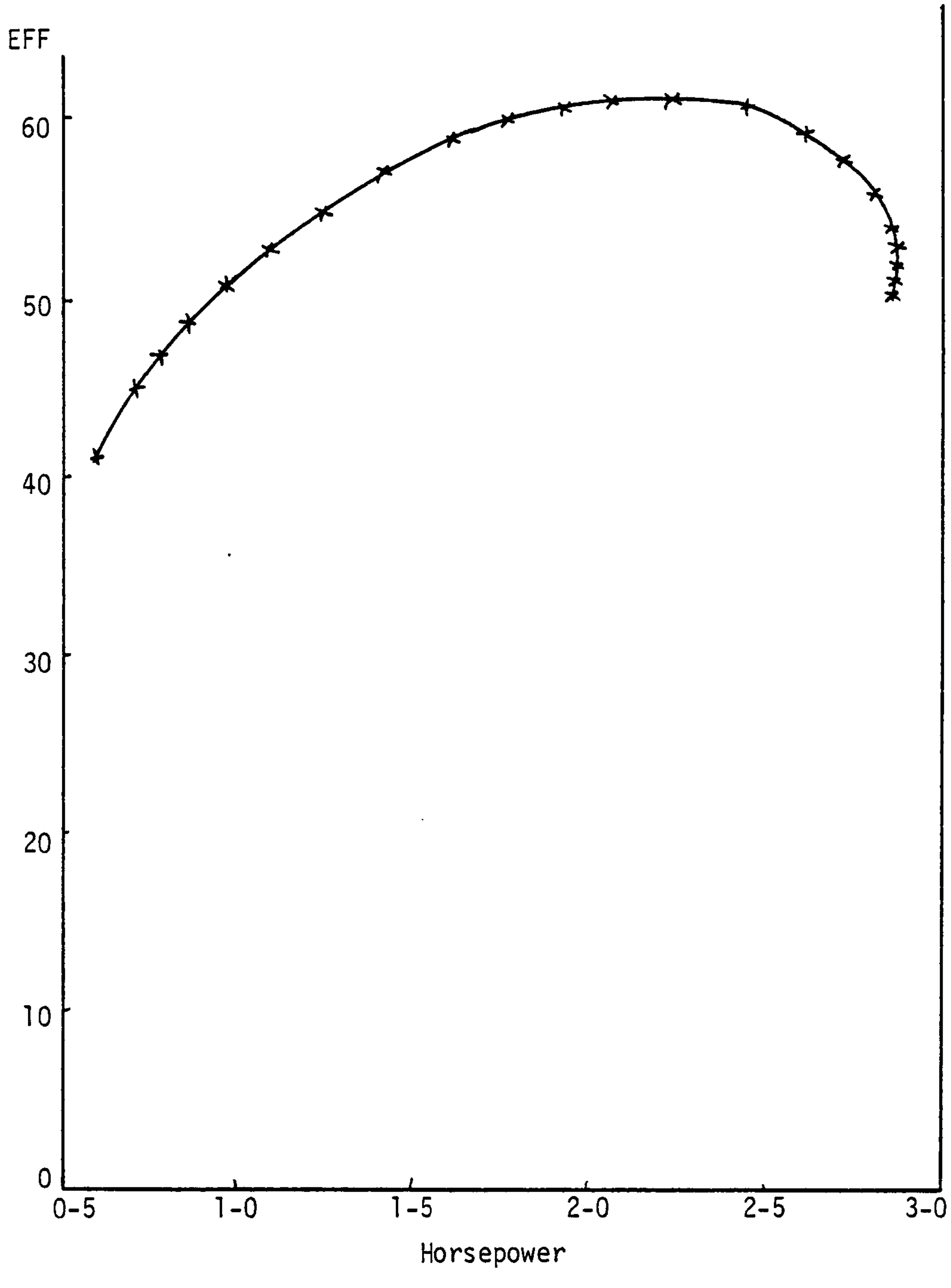

Figure 4-21. Calculated results; efficiency vs horsepower, with R_X=0.75 ohm.

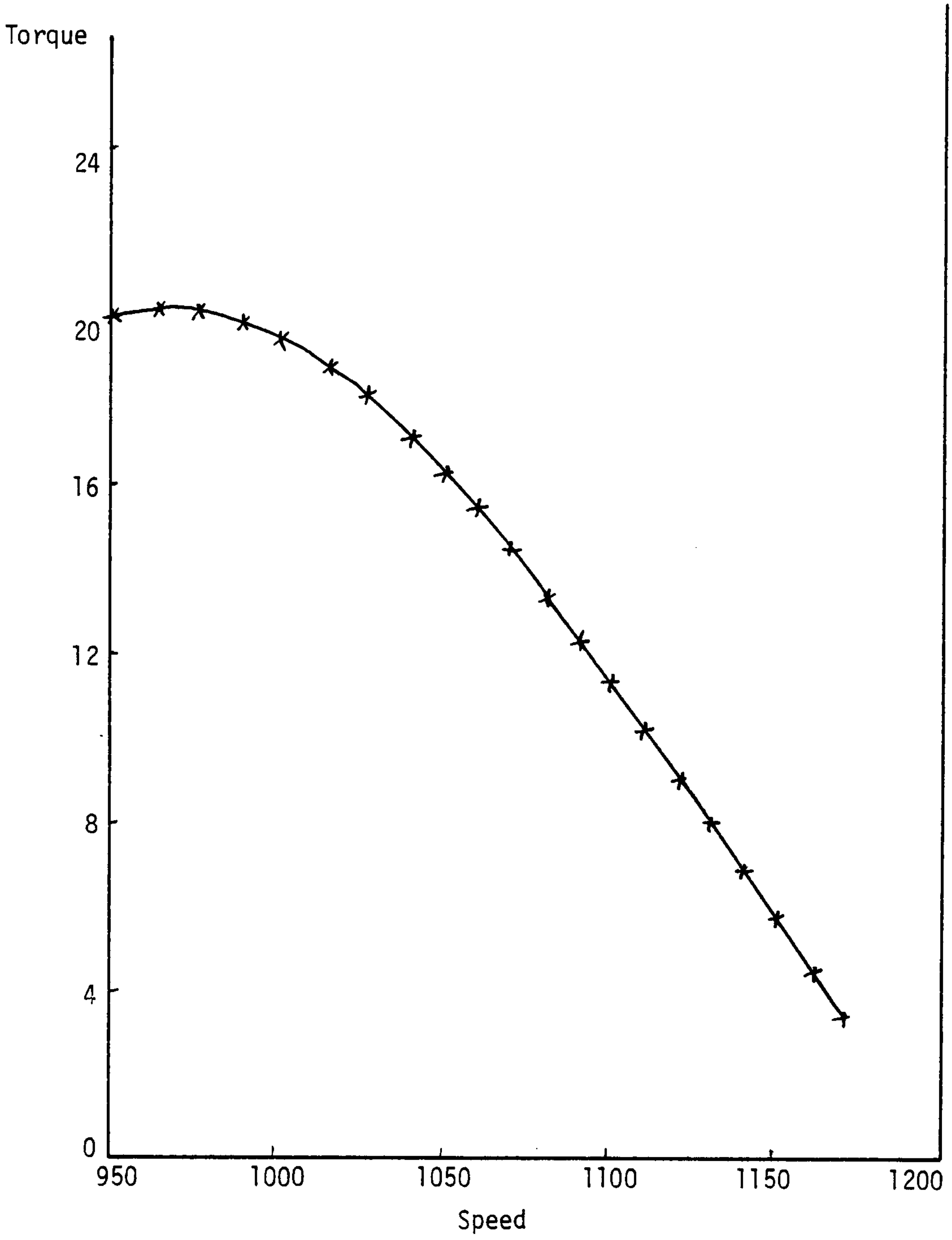

Figure 4-22. Calculated results; torque vs speed, with R_X=1.0 ohm.

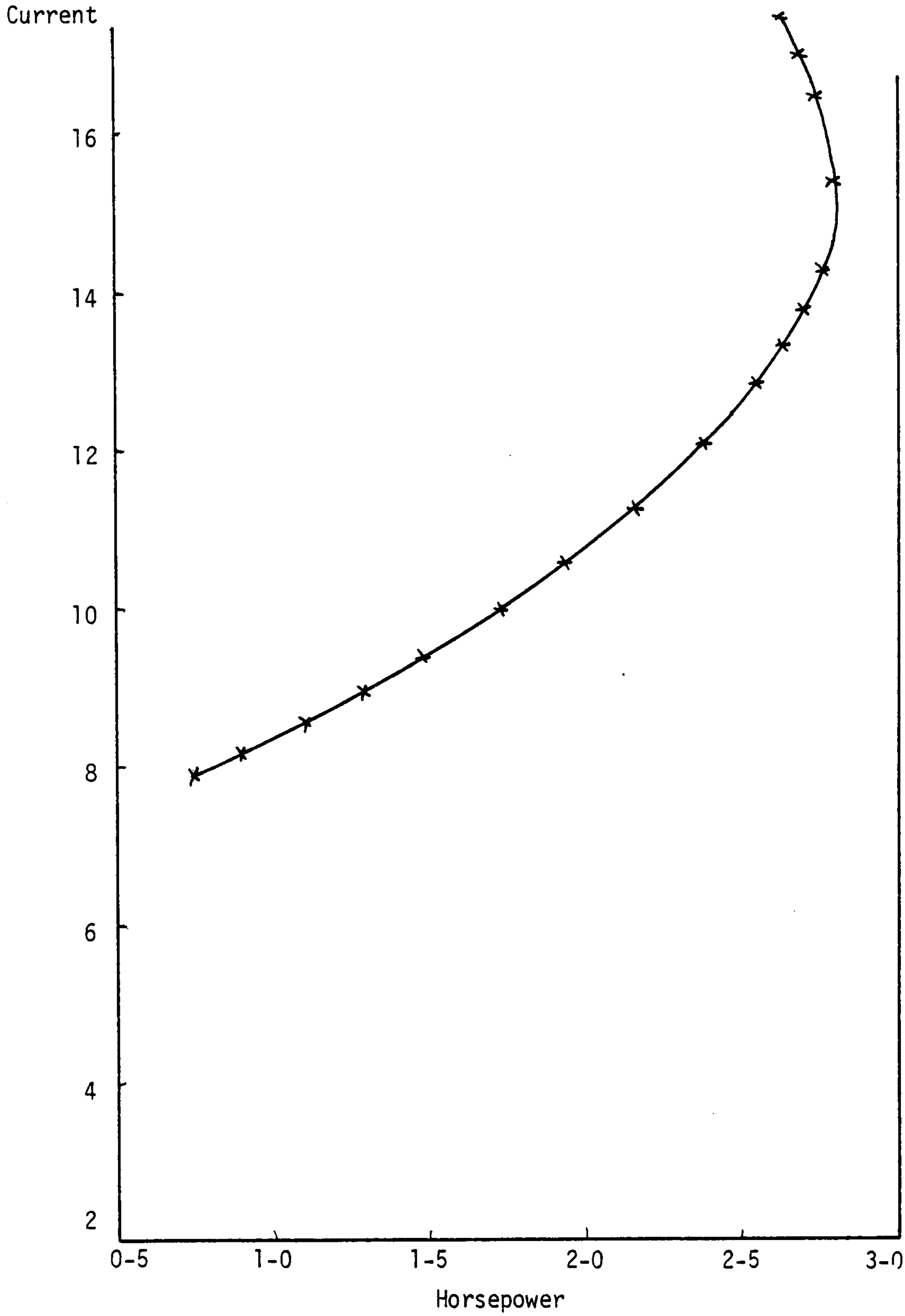

Figure 4-23. Calculated results; current vs horsepower, with R_X=1.0 ohm.

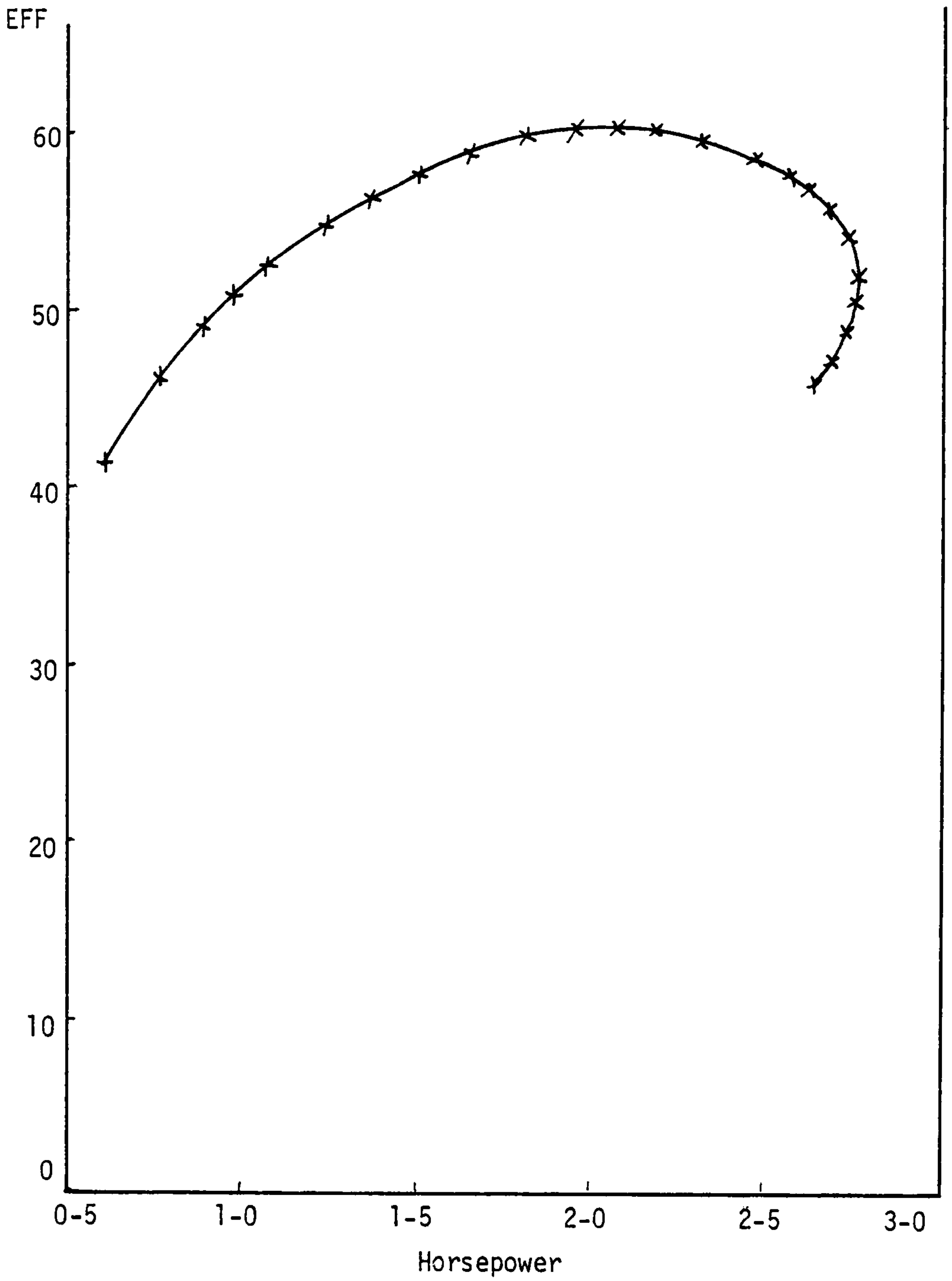

Figure 4-24. Calculated results; efficiency vs horsepower, with R_X=1.0 ohm.

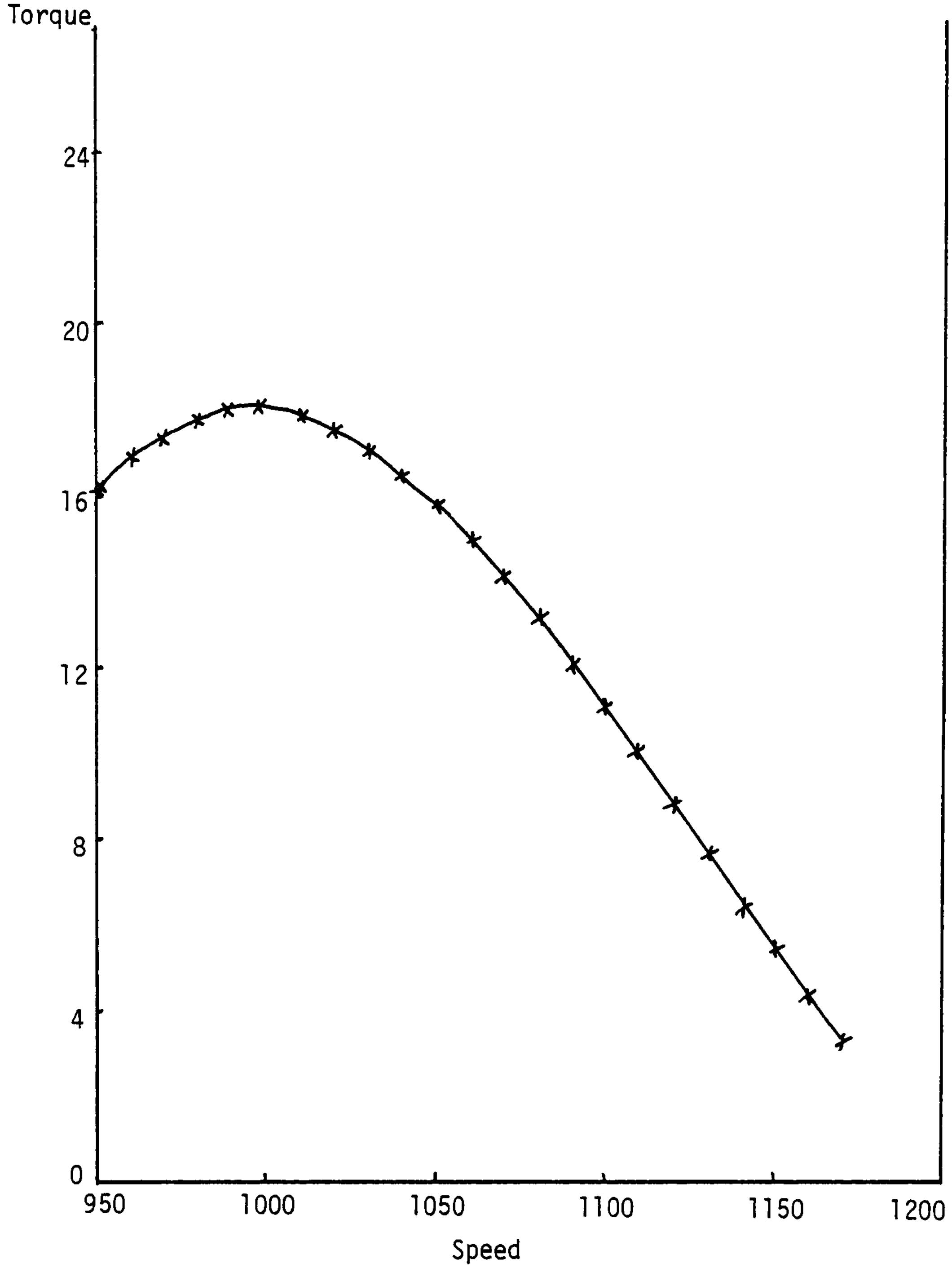

Figure 4-25. Calculated results; torque vs speed, with R_X=1.50 ohms.

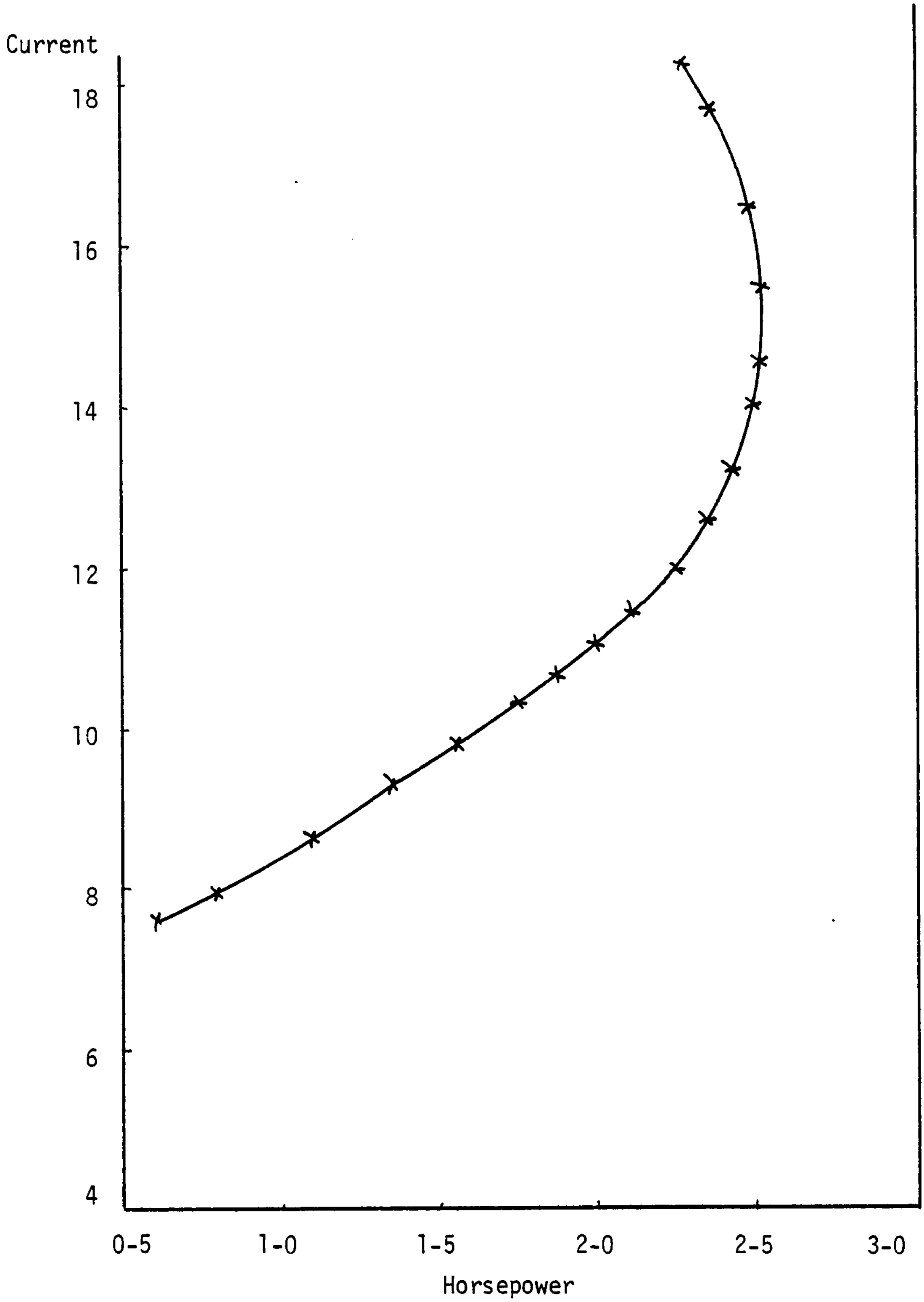

Figure 4-26. Calculated results; current vs horsepower, with R_X=1.50 ohms.

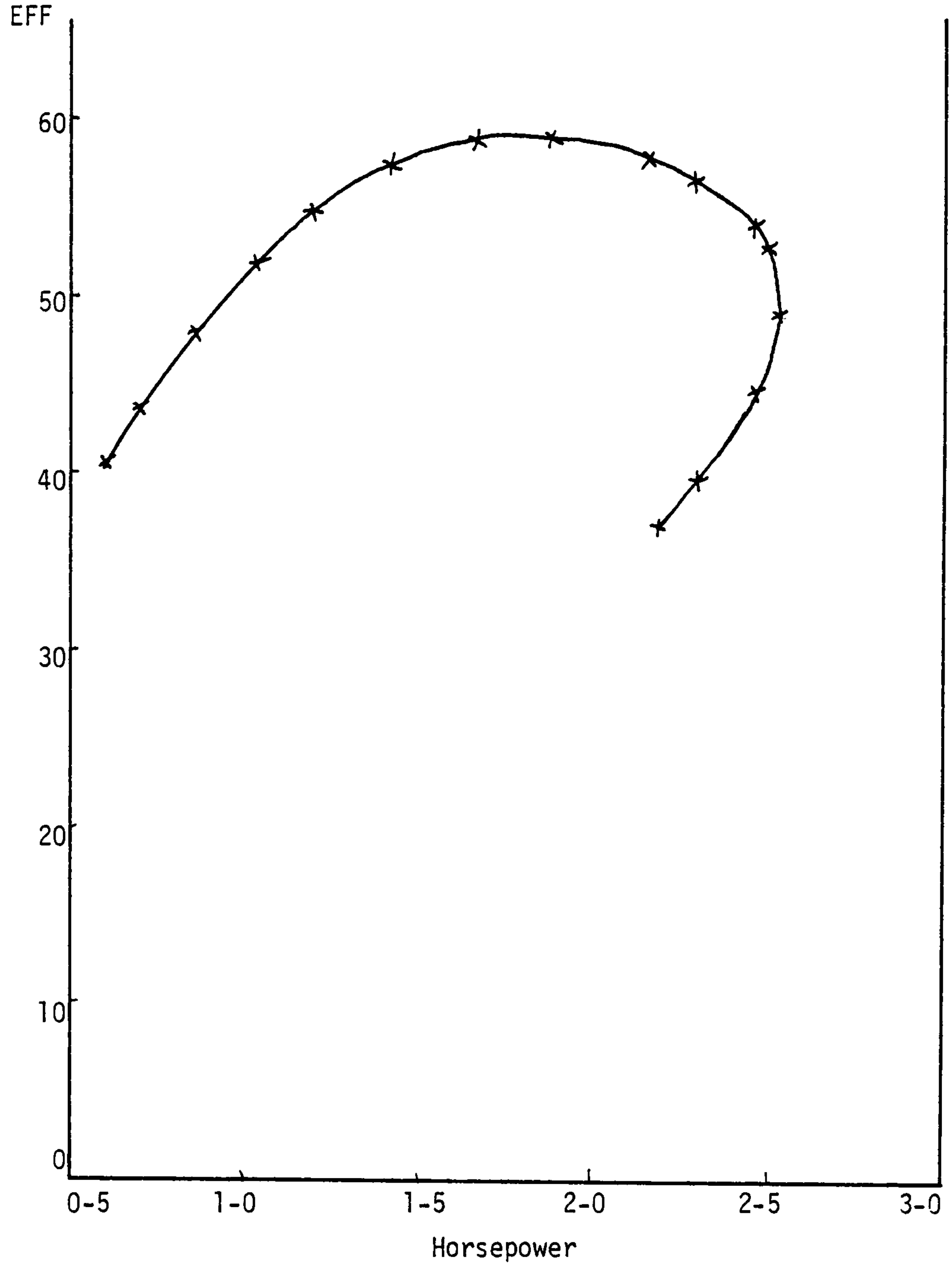

Figure 4-27. Calculated results; efficiency vs horsepower, with R_X=1.50 ohms.

This was illustrated in the speed torque curves, with different values of inserted resistor, as shown in Figure 4-1, 4-4, 4-7, 4-10, 4-13, 4-16, 4-19, 4-22 and 4-25, which were different from the typical speed-torque curves. It is obvious that in the ordinary course of events, the machines cannot possibly rotate at the same speed as the stator field, i.e. at synchronous speed, which would give $S = 0$, since no E.M.F.s would be generated and no currents could circulate in the rotor; hence no torque would be developed. In other words, slip being essential to the production of torque, the induction machine must run at a speed slightly below that of the stator field. For full-load torque, the speeds diminish with increasing values of added resistor (slip increases).

The lower motor efficiency, shown in the curves for measured and calculated results, suggests modifying the machines under test or replacing them with better quality of reasonable operating efficiency and torque. For ultimate realization the composite machines would be using an induction machine with two isolated sets of stator windings and a common cage rotor, or having two different machines with better parameters instead of the identical machines. Since the analysis of performance can be carried out using the developed steady state equivalent circuit in Chapter III, parameter optimization could be easily done.

CHAPTER V

CONCLUSIONS

A method has been proposed whereby the speed control with the twin stator induction motor arrangement can be accomplished by dissipating the slip power extracted from the rotor by induction to the stator windings through an external variable resistor in the stator circuits. The machine configuration required to implement this consists essentially of two polyphase induction machines having their shafts coupled and their rotor circuits interconnected, with one set of stator windings fed from a balanced polyphase power supply voltages and the other set of the stator windings connected directly to the external polyphase variable resistance. The test once was performed with no external resistor added; in other words the second stator short circuited, the configuration is that of the familiar concatenation connection of two slip ring induction machines. However, this thesis is concerned with the behavior of the pair of machines when the second stator is connected to the external variable resistance. The measured performance characteristics showed that the device runs at a speed controlled by varying the external resistance. However, this method resulted in a poor motor efficiency which suggests that a better quality machine, having lower winding resistances than the machine under test could be built and hence a practical machine of reasonable operating efficiency and torque could be achieved. Ultimate realization would be an induction motor with two isolated sets of stator windings and a common cage rotor.

Since the measured and calculated results are good, then the equivalent circuit approach is valid for the performance analysis. There is no reason to believe that the two identical machines used in the tests produced an efficient combination. Since the analysis of performance can be carried out using the steady state equivalent circuit derived in Chapter III, parameter optimization could be easily done.

This work has shown by analysis and test that it is possible to combine the ruggedness of the squirrel cage induction motor with the versatility of the wound rotor machine. Such a combination could be a great benefit to industries using a large number of variable speed drives.

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REFERENCES

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VITA

The author was born in Cairo, Egypt, on November 9, 1931. He attended elementary and primary schools in Cairo. He was graduated from high school in 1949.

He entered the Faculty of Engineering, The University of Heliopolis (Ein Shams) in Cairo, Egypt; in July 1954 he received his Bachelor of Science degree in Electrical Power Engineering.

From July 1954 to July 1956 he was employed by the Ministry of Public Works, Electrical and Mechanical Administration, as an electrical Maintenance Engineer in a fossil plant.

From July 1956 to March 1968 he worked for the Ministry of Housing and Public Utilities--Cairo Municipality as a supervision engineer, responsible for technical planning, developing, designing and constructing electrical projects. Taking advantage of working in Cairo, the Capital, he joined the Evening School of Languages located in Cairo. Now he speaks seven languages.

In April 1968 he was assigned to an overseas position in Kuwait at the Persian Gulf until November 1969 as a technical expert for the Ministry of Water and Electricity Electrical Projects.

In November 1969, he immigrated to the United States of America. In December 1969 he went to Boston, Massachusetts where he joined Stone and Webster Corporation as an Electrical Engineer and the evening school of Engineering at Northeastern University, for the

Master's degree in electrical Engineering. He also attended some educational courses sponsored by IEEE about Nuclear Plant Design and power plant protection and control.

In June 1971 he was employed by Bechtel Power Corporation where he worked until November 1976. He had different positions with Bechtel Corporation in connection with Nuclear Plant in construction as start up and liasion engineer in Plymouth Massachusetts (Pilgrim Nuclear Plant), Maryland (Calvert Cliffs Nuclear Plant), Connecticut (Millstone Nuclear Plant), and in Alabama (Joseph Farely Nuclear Plant). Also he had several technical positions in the design office in Gaithersburg, Maryland.

On May 7, 1976 (the Bicentennial Year) he became an American Citizen in Baltimore, Maryland.

In November 1976, he joined the Tennessee Valley Authority where he presently works as an electrical engineer.

In March 1977, he started his graduate studies. In March 1979 and in March 1980, he attended a lighting course sponsored by The University of Tennessee.

He is a registered professional engineer in the State of Tennessee.