THE OPERATING CHARACHTERISTICS OF A SYNCHRONOUS MOTOR AND THEIR RELATION TO STABILITY

A THESIS

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by Ralph L. Simenson

Approved:

PREFACE

This thesis is a report on the present stage of an interest in the operation of synchronous machinery, an interest which originated while the author was working in the test department of the Westinghouse Electric and Manufacturing Company.

In the preliminary work for this study an apparent gap was noticed by the author, between the scope of text book information and that of current magazine articles. Wide reading was resorted to in an attempt to fill in the space between.

The authors in the periodicals had one common failing, that of declaring their articles to be presented in as non-technical a form as possible, and to be clarified and simplified over preceeding discussions. That same claim is made for this one, and since the scope of the experimentation carried out does not warrant a mathematical analysis of the problems involved, the author has resorted to discussion and explanation of conditions that arose during his experiments in the hope that his thoughts and experiences may be of value in forearming any who might wish to delve further into the characteristics of synchronous machinery, or one of the many closely allied subjects.

Acknowledgement is hereby made to Professors W.A. Murray, C.W. Hoilman, and B.M. Widener for their ready suggestions, and their willingness to help whenever called upon for advice or guidance.

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PART I

Introduction;

Under the present system of widespread holdings and operation by public utilities there is a growing practice of interconnection of power systems, interchange of energy, and long distance transmission of a cheap source of power. Accompanying this developement there is wide current interest and study being applied to the problem of system stability. In any such widespread system, powered almost universally by synchronous generators, continuity of service depends upon continuous operation, which means maintaining the synchronism of the component units. The stability of this system is , like the strength of the proverbial chain, dependent for its maximum capacity upon the continuous operation of its most unstable unit. It is natural, then, that the method of analysis should begin with a scrutinizing study of the individual machines.

Synchronous generators transform the mechanical energy of huge steam boilers while rotating at the dizzy speed of 3600 revolutions a minute. Other huge water wheels catch the tumbling water from mountain streams to turn other alternators at less than a hundred revolutions a minute, yet the two machines tied together through a transmission network, will supply the same frequency of electrical energy to a common load. Their electrical speed will be the same and the most minute change in the speed of one, will be instantly accompanied by a proportional change in the other.

The problems involved concerning the design and selection of individual machines have been actively aired in technical publications. Men in close daily contact with the work in manufacturing and operating companies have published their views, discussed the results of their observations and tests, and have developed theories far beyond the scope of text book content. The best source of this literature is almost confined to the quarterly and annual "Transactions of The American Institute of Electrical Engineers". It contains the papers presented at conventions of the A. I. E. E. and also reviews of the good articles which appear from other sources.

RECENT INVESTIGATIONS

The most recent contribution to the field is the work of Professor Charles F. Dalziel, published in the March issue of "Electrical Engineering". In his article on "Static Power Limits of Synchronous Machines" he describes the results obtained through three years of experimentation on University of California laboratory equipment by graduate students and N. Y. A. helpers under his direction.

A SIMPLE APPROACH

The problem is greatly simplified and provides a common method of attack due to the adaptability of any system of networks to be considered as a single source and sink combination. All units supplying power to the system can be combined and considered as an equivalent unit, the total power of which is dissipated within the system. Loads or any parts of the system in which power is dissipated can also be combined into an equivalent load. Thus the problem is resolved into consideration of a single motor driven by a single generator, and lends itself to a comparatively simple analysis.

Dalziel experimented with a single motor generator combination, derived equations for maximum power transfer through the connecting lines, and applied those equations to three of California's long transmission lines. The stability limits he found compared favorably with the observations made in operating practice.

PROGRESSIVE DEVELOPEMENT

Since Hobart and Punga introduced a method of calculating the changing tooth reactances in 1904, there have been several other independently variable reactances segregated for consideration, and some of these split again into component parts.

Blondel presented a theory of two reaction analysis of synchronous machinery at about the same time, in which he divides the constants of the machine into two components. One component acting in absolute synchronism with the direct current excited field poles, either strengthening or detracting from their effect, may be designated as a direct axis component; the other, with a cross magnetizing or field distorting effect is differentiated as a quadrature axis component.

Doherty came into the limelight in 1918 when he and Shirley printed an article on "Reactance of Synchronous Machines and its Applications", in which he considers the changes in tooth tip reactance during the cycle and seems to be paving the way for the distinguishing characteristics between the salient pole and round rotor theories.

In 1926 Doherty and Nickel started a series of four articles giving an extension of Blondel's two reaction theory and using it in a study of torque angle characteristics under transient conditions. They introduced new definitions of armature leakage reactance and armature reaction reactance which have been adopted and are in present use.

Again in 1930, Doherty,with Pierce, gets into the effect of"Armature Circuit Resistance". This subject is also treated that year by C. F. Wagner, and applied to hunting phenomena in synchronous machines.

P. L. Alger,in February 1928, presented a method, "The Calculation of the Reactance of Synchronous Machines"; and it was nicely paralleled by Park and Robertson at the same time, who gave definitions and methods of test for determining direct and quadrature axis reactances. This work was extended in 1931 by the text of a paper by L. A. Kilgore, accompanied by test procedures of Sherwin H. Wright.

1929 started with a practical application when the Southeastern Power and Light Company made extensive tests on their transmission system during a period of light load, to determine the power limit of a troublesome line section. With the help and advice of engineers from the General Electric Company, they adjusted the loads to within five per cent of the calculated limiting values, then while their system was deliberately thrown out of synchronism, took oscillograph readings of the power transfer before the line breakers were allowed to function. Definite power limits were discovered, and no complaints were made of disturbances noticed by their customers.

R. H. Park, in July 1929, followed the work in the "Two Reaction Theory of Synchronous Machines" by presenting an extension of the work of Blondell, Dreyfus, and Doherty and Nickel. In his analytic work he shows that the total power output of a motor is equal to the mechanical power transferred across the air gap, less the rotor losses. He also works out the torque angle relations of a small machine connected to an infinite bus.

More work considering the torque involved came out in October 1929, when Penney gave a discussion of tests conducted by Theodore Williamson in measuring the torque produced by single phase short circuits. In his procedure, the fault was almost always applied at the moment when the terminal voltage was zero in order to obtain the worst possible condition that would occur under service conditions.

At the Massachusetts Institute of Technology the developement of a machine for solving difficult and intricate differential equations made possible a number of studies which had hitherto been neglected because of the tedious routine work and uncertainty of results obtained by a point by point solution of the equations. Known as the'Integraph' in 1931, it was used by Lyon and Edgarton to study "Transient Torque Angle Characteristics of Synchronous Machines", and after further developements into the 'Differential Analyzer' it was used by Professor Bush and three associated in their work on "Synchronous Motor Pulling Into Step Phenomena".

Lyon and Edgarton threw much light on the mechanical oscillations following the application of an abrupt shaft load. They solved the differential equations involving an equilibrium between rotor inertia, electromagnetic torque developed at any point in the oscillations, and the shaft torque caused by load and friction; and were able to show the effects of each.

The history of the problem is true to the fashion of the age when in 1933 a lady engineer steps up to make a contribution. Edith Clark and R. G. Lorraine developed a cut and try method of determining, "Power Limits of Snchronous Machines". Their procedure approximated a value of power transfer, then checked the stability of the system, repeating this approximation until some value was found which exceeded the stability limit. It might prove to be a lengthy and discouraging problem in a complex system, and their method has been superseded by the work of Dalziel.

As articles come and go, time segregates the sound principles for future use. The problem is a complex one and will command interest for many years to come. It is interesting to note the dependency of advance in the analysis of synchronous machinery upon the parallel developement of induction motors, switching facilities, relays, transmission lines, and other equipment and its theory. The most practical results have been coming from those manufacturing companies and operating companies who have the facilities to make tests on existing systems and large size or actual service equipment, while colleges and laboratories have been adding their share through contributions to the development of the theories involved. Throughout the work, frequent references are made to the analytic work of Steinmtz and the methods of Heaviside, and Wagner and Evans.

SUMMARY OF THE PROBLEM

To review the conditions being studied, assume a system of two synchronous machines connected to each other through an electrical circuit. If there is any transfer of energy from one machine to the other, then there is an electrical angle between the two machines. Furthermore, if one has a knowledge of, or the equipment to measure the resistances and reactances involved in the system, he can make an analytic study to determine its characteristics and limitations.

The electrical angle is a flexible tie between the power source and the load. An increase of load on the machine acting as a motor tends to slow it down, thereby increasing the angle and allowing a greater transfer of energy to take place, within the power limit of the system, of course. Too great a load will increase the angle beyond its capacity to cause an increase in current, and the motor will lose synchronism.

Sudden or shock loads have an inertia effect, and require more power to come into the system than one gradually applied. The electrical angle is the buffer that absorbs this shock effect. Upon demand it increases to more than the steady state value required, and like a coil spring, it oscillates about its steady state value until equilibrium is established between the reacting forces. A shock may throw the system out of synchronism if the angle is already near the power limit, even though the additional load could be carried if applied gradually.

Absolute power limits are determined through a study of steady state conditions, Then, as most loads encountered in service are applied with some degree of suddenness, the practical power limit is that value of steady state load that will allow the transient increase of any reasonable increment of increase in the load, without exceeding the limit of stability.

The magnitude of oscillations depends upon the reactances, rotor resistance, and rotor inertia of the machines. Hunting may be naturally prevalent in a poorly designed, or poorly selected unit, and this will tend to accentuate the oscillations when they start. Hunting is dependent upon the induction motor characteristics of the machine.

This is a brief picture of the conditions and factors involved in the system, and the problem is to become familiar with them, their effects, and their relations to each other.

PART II.

PURPOSE

The purpose in this thesis, is to learn as much as possible about the problems of synchronous motor action and the importance of their characteristics in regard to stability of operation. Three sources of information were used; a review of library reference material, discussion of the problems involved with other interested and informed persons, and experimental work in the laboratory with a synchronous motor that was reputed to be unstable in its operation.

LABORATORY EQUIPMENT

The equipment available for experimental work in the electric laboratory was a pair of Westinghouse motor generator sets, which were identical in size and design. Each set consisted of a 15 KVA, 220 Volt, 1200 RPM synchronous motor, direct coupled to a 15 H.P., 115 Volt type SK compound wound direct current motor.

The synchronous motors were of the laboratory type, with stator windings brought out to a connection board in six sections for various winding combinations of one, two, or three phase, star or delta, operation. The machines were built for use with interchangeable rotors, the synchronous rotor used being a salient pole rotor, but with a very small air gap, and heavily provided with a squirrel cage winding for damper bars.

The direct current motors were used shunt wound as a prime mover for a synchronous alternator, and cumulatively compounded as a generator when providing a variable load for a synchronous motor.

PRELIMINARY WORK

Tests were made on both A.C. machines to determine resistances of their windings, saturation curves, losses, efficiencies, speed torque curves, and starting power requirements. Resistances and losses were also determined for the D.C. machines in order to convert their loads to values of torque on the shaft of the synchronous machine.

Further work was planned to determine as many of the machine constants as possible, to study the power transfer during the loss of synchronism in the system, and to study the changes in the angular relation between the axis of the supply voltage and that of the motor under changing load conditions.

PROCEDURE FOLLOWED

First, V curve characteristics were taken of one motor driven from the laboratory 60 cycle circuit. During this test the stability of the motor seemed to well exceed its reputation. The unstable characteristics did express themselves, however, and a limit of stability was measured for several values of lagging power factor.

Next, oscillograph pictures were made of the supply voltage, with the intention of using it later to measure reactances and the power transfer between machines at the critical maximum load point and during loss of synchronism. However, due to the complexity of control, indistinct curves obtained, and difficulty of calibration, all future use of the oscillograph had to be abandoned.

Another set of V curve characteristics was then made using one machine as a power source to run the other as a motor. Finally torque-angle measurements were taken under variable loads and an attempt made to correlate the findings into the regular V.curve characteristics. A more detailed account of the separate tests follows in the subsequent discussion.

V CURVES, POWER FROM INFINITE BUS]ALMOST]

Machine No. 2, connected in series star, and operated from the 220 Volt laboratory circuit was run for V curve characteristics at five values of load, the load being adjusted by the output of the D.C. generator. Full load was selected as that point at which the motor drew the name plate current rating when operating at 80 per cent lagging power factor. The curves obtained are shown in Fig. 1.

In the no load curve, the actual load on the machine consists of windage and friction of the set, or a requirement of about two foot pounds of torque on the shaft. Conventional readings were taken, with the field excitation varying from minus 2 amperes and up to 23. Unity power factor occurred at 5.8 amperes. Several other features are worthy of mention.

At zero excitation there is sufficient residual magnetism in the field poles to bring the rotor into step and maintain synchronous speed. Unity power factor and minimum current comes at 5.8 amperes, but minimum A.C. power input is obtained at 7.2 field amperes. This can be explained as follows: at any point of underexcitation or lagging power factor, the reactive alternating current flowing supplies magnetization to the field core, so that the alternating current must supply at least a part of the iron losses of the machine. As the power supplied by the D.C. field is increased, the iron losses supplied by the A.C. circuit become smaller. Between 5.8 and 7.2 amperes of field excitation the rate of decrease of iron losses exceeds the rate of increase of the copper losses due to increasing current, with the net result that the A.C. power input drops off. At higher values of field excitation, the reactive current drawn from the line is leading, with the effect of demagnetizing the field core and balancing up the additional power expended in the field circuit. This would mean that the D.C. field supplies at least a part of the magnetism for the magnetic circuit of the A.C. part of the machine, and is undoubtedly a unique condition in electrical machinery. This is one point on which no reference material has been found, and a full explanation of the power transfer involved may afford some exhaustive study and research in the future.

With the field excitation at 23.2 amperes the line current had reached two and one fourth times its full load value, and the power factor which had fallen to six per cent had begun to rise again. At this point heating was noticeable and the condition was maintained just long enough to take meter readings. The increasing power factor shows a change of relation between the rate of increase of the copper and iron losses with the rate of increase of line current. This is to be expected since the losses are increasing with the square and the 1.6 power of the line current, which itself is almost a straight

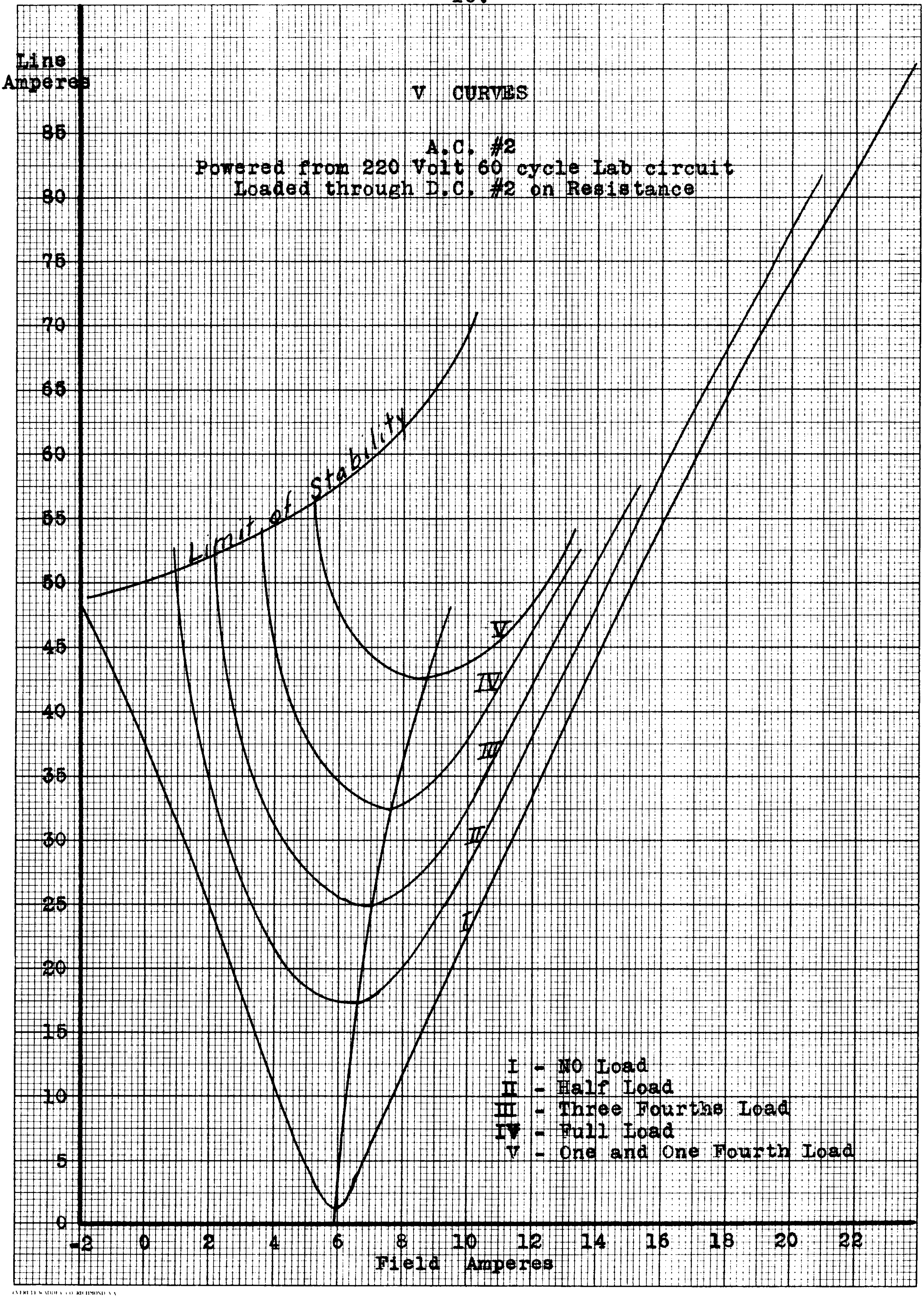

Line Amperes
V CURVES
A.C. #2
Powered from 220 Volt 60 cycle Lab circuit
Loaded through D.C. #2 on Resistance
Limit of Stability
V
IV
III
II
I
I - NO Load
II - Half Load
III - Three Fourths Load
IV - Full Load
V - One and One Fourth Load
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
-2
0
2
4
6
8
10
12
14
16
18
20
22
Field Amperes

Fig. 1

line relationship.

At zero amperes when the field excitation is reversed and excited to a negative value the rotor is extremely sensitive to control, but occasionally the line current will increase along an extension of the no load V curve until it exceeds the limit of stability, pulls out of step, lets the rotor slip one pole position, and resumes its place at the equivalent positive value of field excitation on the curve.

The no load V curve marks a boundary between motor and generator action of the machine, all that area within the V representing conditions of motor operation. With facilities to drive the motor at very slight changes of power input it would be possible and of interest to study the characteristics during the transition through an area representing motor losses, and into an area representing power generation.

Other curves taken at half load, three fourths, full, and one and one fourth load respectively were read from as high a value of field excitation as heating of the windings allowed, down to that value which just allowed the machine to pull out of synchronism. The lower values are plotted on the curve as the limit of stability.

The method used to set critical load conditions was to reduce the field excitation one step at a time until synchronism was broken. Then the field excitation was quickly increased simultaneously with cutting down the motor load by reducing the field of the D.C. generator. Generally the motor had maintained sufficient speed through its induction motor characteristics to allow it to pull back into synchronism. It was then necessary to reset the load before reducing the field excitation to almost the critical point for a reading.

Practice in this operation proved very beneficial in later tests, especially in determining torque angle characteristics during which the motor was operating on the critical limit most of the time, and pulled out of synchronism quite frequently. When the motor pulls out it slows down considerably, depending upon the amount of load it is carrying. The heating that takes place in the damper windings is a function of the change in speed from 1200 revolutions a minute, and as they are designed for starting service, which is but momentary, due caution must be exercised to prevent their overheating.

Evidences of instability that asserted themselves in this part of the test were the habits of the machine to pull out of step when on the underexcited part of the curve. This is to be expected at some point, however, and the results show that the line current was over 125 per cent of the rated full line current at all points where synchronism was lost. It also carried 125 per cent of the full power load well enough, although between fairly narrow limits of field excitation.

V CURVES, POWER FROM SIMILAR MACHINE

The next test carried on was essentially the same, but with a change of the power supply. Several difficulties arose due to this change.

Instead of drawing power from a fairly constant voltage bus direct from the voltage regulator, machine No. 1 was driven as an alternator by its direct current motor, which was in turn supplied from one of the laboratory direct current plants. The use of this machine, having the same faults, regulation, and susceptibility to system changes, tended to accentuate any oscillations or hunting that arose. It introduced the necessity for controlling the supply voltage and frequency for the motor being tested, each of which was hard to maintain with any degree af accuracy.

The frequency was indicated by a connection to the 60 cycle laboratory circuit through synchronizing lights and the power transfer was assumed to be negligible. As a safety precaution, a switch was installed in the direct current motor circuit, to be operated from any point on the test setup by means of a drawstring.

When the motor pulled out of step in this system a double reaction would take place. The motor lost speed while the alternator gained speed; but due to the high regulation of the alternator, its voltage would drop considerably, allowing the motor still less power to carry its load. The motor would practically come to a halt, and whine and vibrate noisily. Heating of the rotor windings was terrific during a stall, and the only safe method of recovering stable operation was to shut down the entire system and start over.

In the curves obtained there is quite a distinct difference in characteristics, attributable to the change of constants in the power supply. See Fig. 2. First there is an increase of excitation current throughout the whole set of curves. During the no load run, with the field excitation set at 5.8 amperes to correspond to the unity power factor setting of the other set, the alternator voltage which gave unity power factor was far too low, reading about 180 Volts. In raising to normal voltage, the field excitation of both machines had to be increased to maintain the power factor.

The method used in setting for successive readings

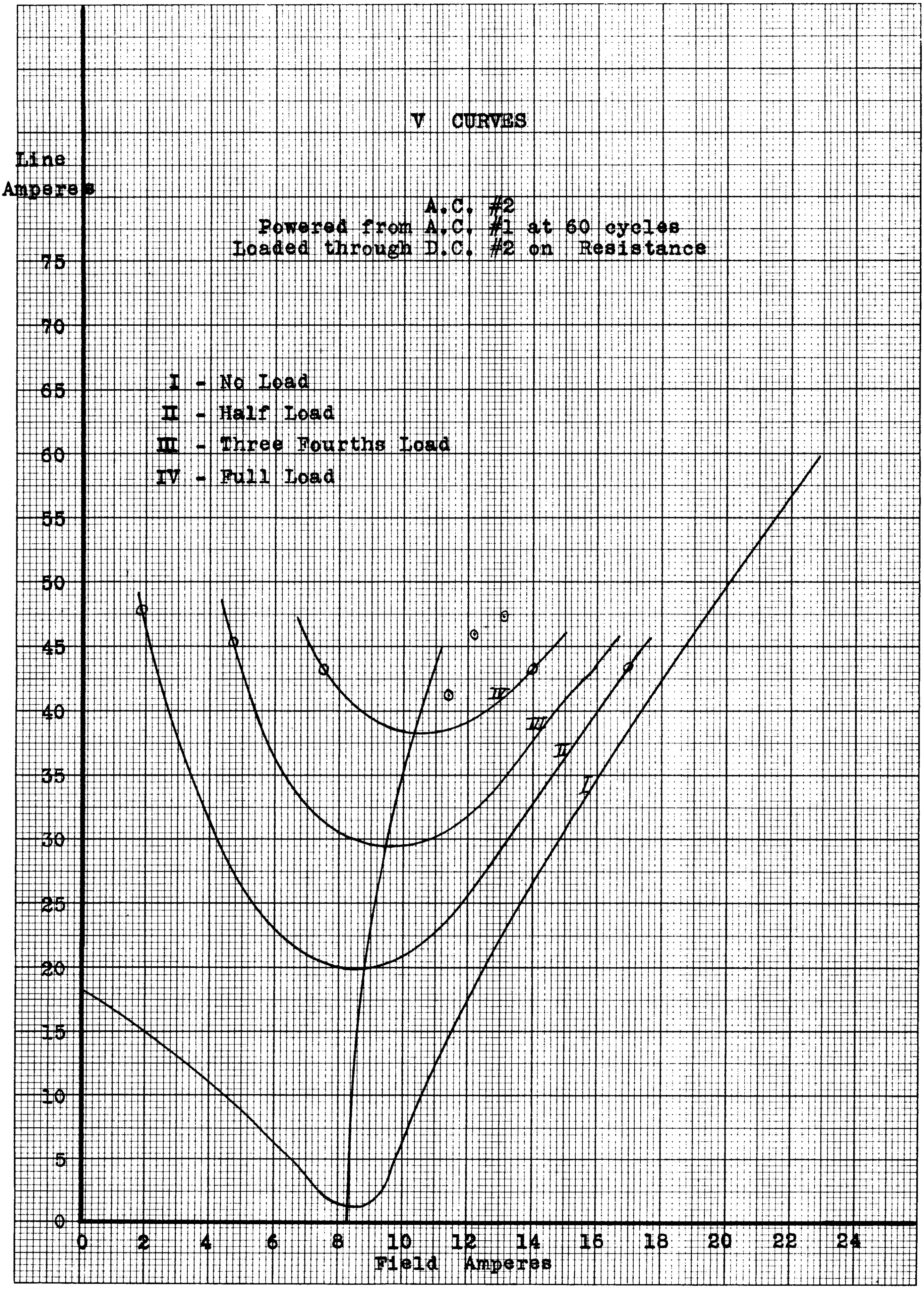

V CURVES
A.C. #2
Powered from A.C. #1 at 60 cycles
Loaded through D.C. #2 on Resistance
I - No Load
II - Half Load
III - Three Fourths Load
IV - Full Load
Line Amperes
Field Amperes
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
0
2
4
6
8
10
12
14
16
18
20
22
24
I
II
III
IV

Fig. 2

was to adjust the motor field excitation to a new value, then change the alternator voltage, simultaneously trying to keep the frequency constant. Speed changes with small variations in load were slight, but difficult to correct for, and demanded a great deal of attention. The use of synchronising lamps proved a ready indicator of speed variation, and were a big advantage over the laboratory tachometers.

The general shape of the no load curve is the same as in the first test, but comparison on a basis of motor field excitation is not desirable because of the large differences in line current and unsimilarity in this respect. For instance, at zero excitation, the current was only 18.5 amperes as compared with 37 on the other power source. Minimum power input was again obtained slightly above the point of unity power factor. The curve was carried up until the reactive current in the motor supplied the full magnetizing current of the other machine, and the D.C. field current of the alternator was almost zero.

The half load, three fourths load, and full load curves have similar changes conforming themselves to the no load curve. The limit of stability on the lagging side is lower than before, and the system also loses synchronous speed when the motor is overexcited on this test. This is due more to the alternator pulling ahead of its load than from the motor pulling out behind. Of course it has the same effect, but is much harder to check, once started, and force back into stable operation. This limit, plotted on the curve sheet, shows a narrow margin of excitation under which the motor can be ex pected to carry a given power load.

One point was obtained at one and one fourth load, but the position was too unstable to get any kind of a curve, To obtain higher values an approach was made from all sides. The field excitation was predetermined, set, the speed held constant, and the load gradually increased until synchronism was lost. It was tried with the load rheostat set and the speed increased from a low value up toward 1200 RPM, but never reached; and it was attempted by overexciting both fields, setting the load and speed, then reducing the excitation to get normal voltage. Then synchronism was usually lost at about 240 Volts.

V CURVE COMPARISON

A **stable** source of voltage shows a decided advantage over a similar machine source. At the high point obtained in the first test, the load could be carried satisfactorily with any value of field excitation from 6 to 12 amperes. Some variation in stability occurs because of the same inertia characteristics of the similar rotor. Hunting is accentuated, and there is always a double angle between the axis of the machines. When connected on a large system, the angle between the axis of the system and the machine terminal voltage is inversely proportional to the capacity of the system, and usually negligible.

The differences in operating characteristics on the two sources of power can be explained as due to the differences in system constants of resistance and reactance. In any system the current that flows is due to the difference between generated e.m.f. and the induced back e.m.f. in the motor. In a system with a low impedance (the ideal system, known as an infinite bus, has no impedance and can be approximated by a large system for a small load) the voltage that makes the current flow can be measured as the impedance drop of the motor, while in one with a high impedance, that voltage is the impedance drop of the entire system. For that reason the current flowing will not necessarily be the same for one value of back e.m.f. of the motor when connected to two different systems.

CONCLUSIONS

The final result of this study of V Curves demonstrates the need for determining the constants of machines and system parts. It ties in very nicely with the theory of studying system stability by reducing the whole system to an equivalent motor generator set.

It also disproves any grounds for the reputation of instability the machine had acquired, as it has shown that the motor will carry its rated load if properly excited. A knowledge of V curve characteristics is all that is needed for an operator to maintain satisfactory operation; and any loss of synchronism is due to carelessness, improper field excitation, or unintentional overloading of the machine by the operator. True, the machine does not have overload capacity, but a knowledge of this characteristic should be supplied when the unit is first purchased and applied to a certain job.

TORQUE AND ANGLE MEASUREMENTS

The remainder of the experimental work was done on one motor, in measuring static and dynamic power limits. Power was drawn from the 60 cycle laboratory circuit in order to facilitate adjustment, eliminate speed changes, and increase the load range.

The change of angle was measured by means of a makeshift stroboscopic arrangement. A circular disk ruled off into twelve sectors, alternately colored black and white, mounted on one end of the motor shaft, was covered by a pasteboard box which excluded most of the light, but which was punctured by enough peek holes to provide observation. The neon bulb illuminating the disk operating on a 110/6 Volt peak wave potential transformer, was excited by connecting to one line wire and to the neutral point of the motor, giving 127 volts on the high side of the transformer. A protractor mounted close to the rotating disk provided a standard on which to fix the reference axis and to measure the angle of shift of the rotor.

One source of error was introduced by the distance between the protractor and the rotating disk. To minimize this error in reading the protractor a line of sight was determined, and measurements made with the eye in the same position each time. The distance once set was not changed.

Since the machine under observation is a six pole machine, three cycles of electrical energy are generated during one revolution of the rotor, or 360 electrical degrees has as its mechanical equivalent 120 degrees, bearing the ratio of 3:1 as measured on the protractor. Hence any measurements made by sight, or in any manner on the mechanical side, are subject to magnification of error, and must be considered only as relative values. Mechanical measurement would be more accurate and applicable to a two pole, 3600 RPM machine.

LOW VOLTAGE TRIAL

The first curves taken were at half voltage to get an indication of the results to be expected, to become familiar with the procedure of handling, and to minimize the heating and liability of damage to the equipment. They were made in conjunction with a set of speed torque curves, so readings were taken with the field shorted through several values of resistance, and then with amounts of field excitation.

The static power limit is the limit of the machine when excited with a value of field current to give unity power factor at a given load, while the dynamic power limit is the limit when the field excitation is changed to maintain unity power factor. In varying the field currents, they were adjusted to give these values.

Readings were taken of power input to the motor, output of the D.C. generator, and the stroboscope angle. To the D.C. output was added the D.C. machine losses and the sum converted to torque in foot pounds, output of the synchronous motor. The results are represented in curves of the angle of rotor lag plotted against the shaft torque, Fig. 3.

From the curves it is easily seen that the angle of rotor shift is an inverse function of the strength of excitation. The weaker the field, the greater the angle of shift, between limits of zero and dynamic values of field current. Below the knee of the dynamic durve,

TORQUE ANGLE CURVES

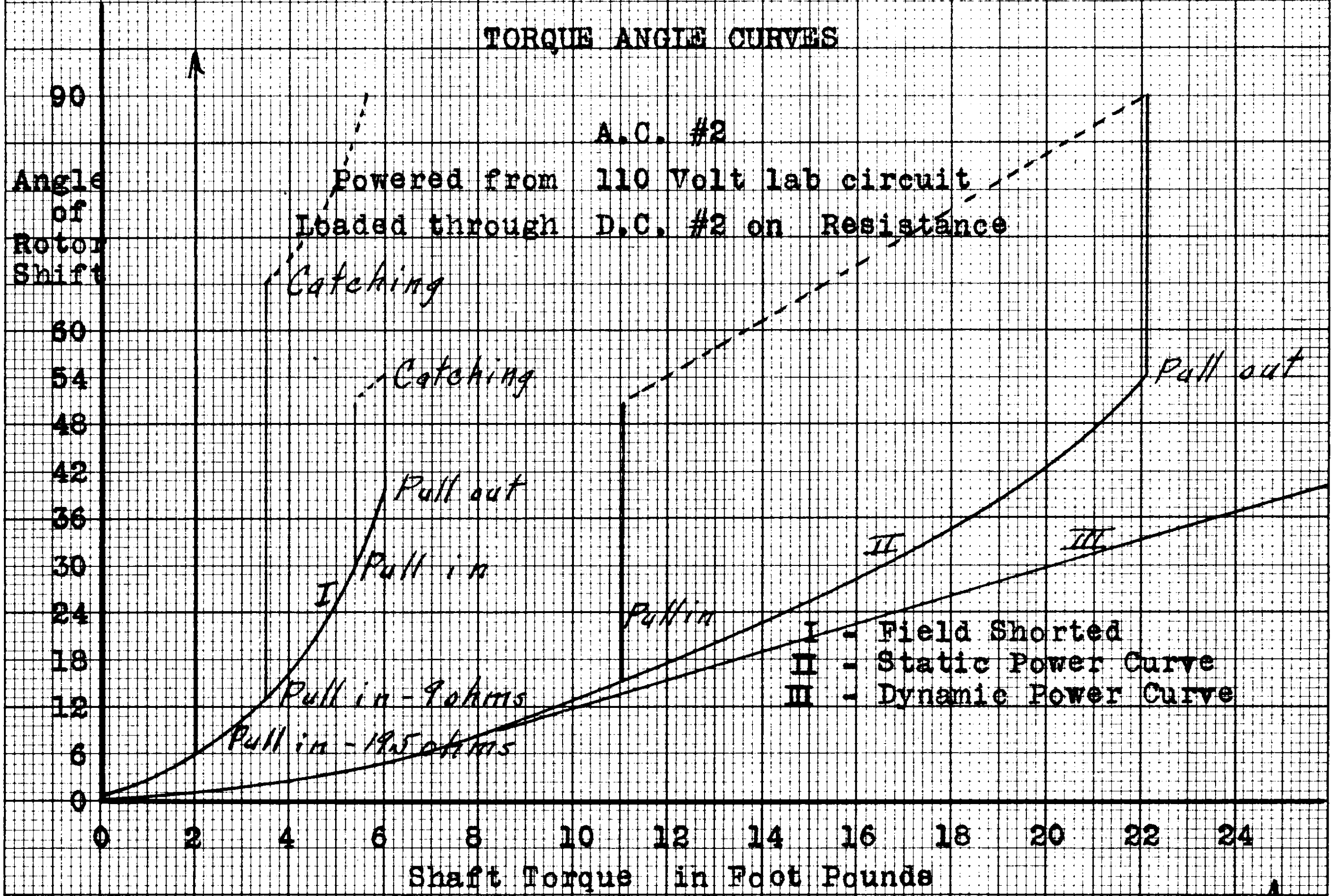


Fig. 3

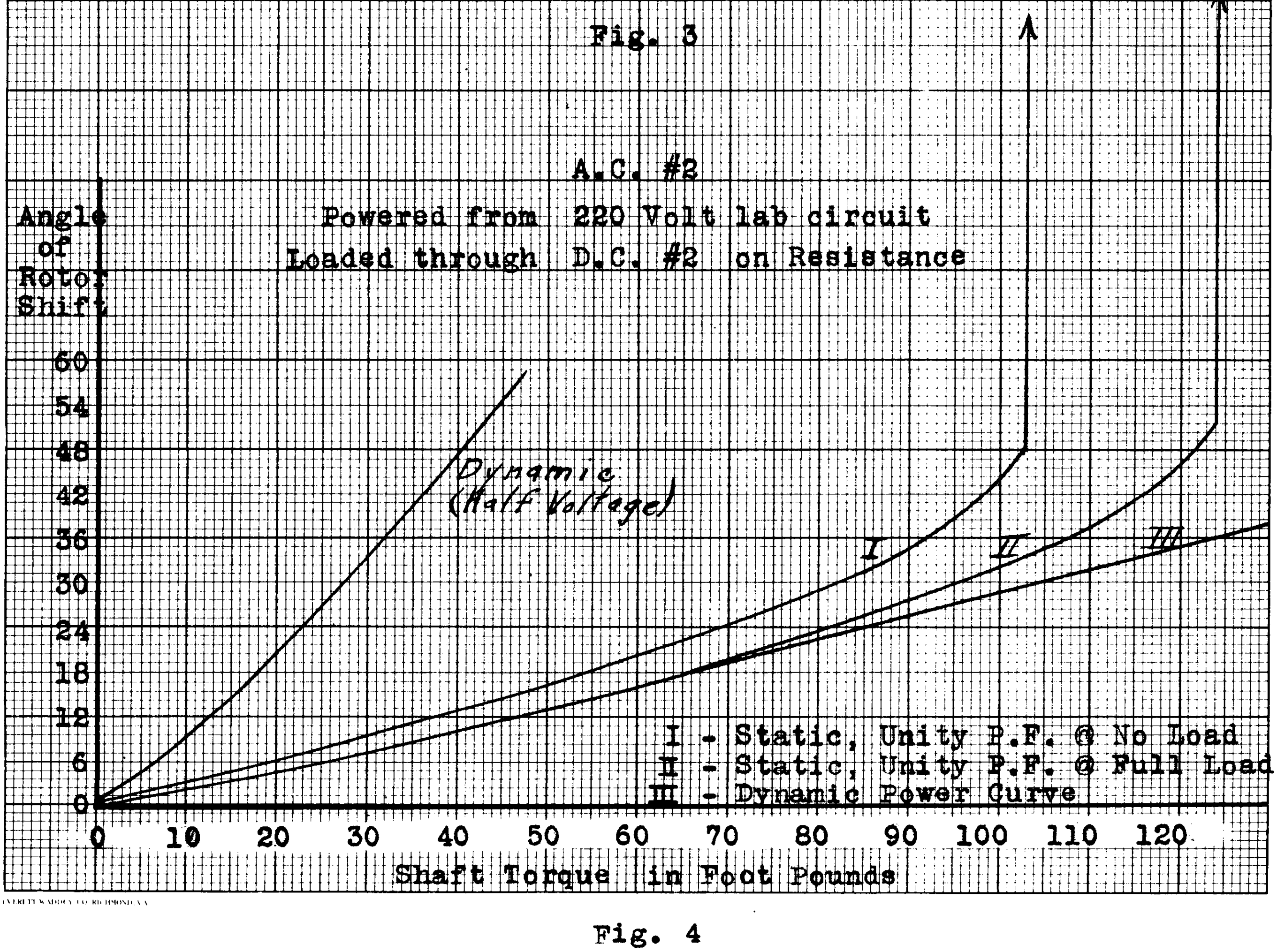


Fig. 4

over excitation has no appreciable effect, while above the knee it reduces the angle from the dynamic value to a line along an extension of the lower part of the curve.

Lyon and Edgarton give the expression:-

$$\frac{E_1' (V)}{X_s} \sin \theta$$

for the synchronous characteristic of any given torque where E_1' is the excitation voltage, V is the terminal voltage, X_s is the synchronous reactance, and θ is the angle between applied terminal potential and the induced e.m.f. of the machine. Their total solution of the torque results in similar curves.

The inclusion of field resistance affects stability by the changing of the machines induction motor characteristics, and shows up in the treatment of transient loads. It does not affect the total limit of load carried by the motor when the load is gradually applied, but does act during the time the rotor is shifting its angular position or when the motor is running at other than synchronous speed. Thus it may be a limiting factor in the consideration of a load suddenly applied. It also reduces the load which can be pulled back into step.

For instance, in Fig. 3 the pull out torque is 6.2 foot pounds. Field resistance alone is 3 ohms. With the field shorted direct, the pull in torque is 5.6 foot pounds. With a total of 9 ohms resistance in the field circuit the load pulled into step is only 3.54 foot pounds, and a total of 19.5 ohms in the field circuit is the maximum field resistance with which the motor will pull back into synchronism with torque requirements merely being enough to overcome inertia, friction, and windage losses, or about two foot pounds.

THE THESIS IS NOT ALL WORK

This setup provides a fascinating experiment to watch in observing the action of the motor through the stroboscope rather than through the electrical instruments. A typical case is that which gives the static power limit at 110 Volts operation. The field is excited at 3.2 amperes, giving unity power factor at no load. As the load is increased, the rotor gradually turns backwards with respect to its axis, equal increments causing slightly increasing increments of shift, up to 54 electrical degrees. Sudden increments set up oscillations in the rotor, and it rocks back and forth seeking a position of equilibrium for the new load. These are readily discernable by the stroboscope at this value of voltage and excitation, and can be followed, measured and counted. with ease.

As the rotor approaches the critical angle, these oscillations are more pronounced, their magnitude is greater, and more time is required to settle into a condition of equilibrium. In order to operate on the critical point, very fine adjustments must be made in the load. Accidental overloads can be forced back into synchronism by quickly overexciting the motor field, if control rheostats for the field and load are placed at the point of observation for the stroboscope.

At the critical point synchronism may be lost by very slight changes in the system. Kicking the motor pulley causing a momentary change in friction load, variations of supply voltage exciting either the motor or the D.C. generator, or a slight drop of voltage in the A.C. power supply will cause the unbalance. In responding to these changes, the rotor angle will slowly start to increase, gaining rapidity until well over 90 electrical degrees from its original axis, at which point its action becomes too rapid to be followed through by eye.

At this setting, however, the motor maintains a speed of about 1180 RPM and variations in the speed during each revolution can be noticed at the stroboscope. Three times during each revolution of slip the rotor passes through a portion of the magnetic field in which it would be in stable operation. While it is going through this field it speeds up momentarily, almost catching up to synchronous speed; but not having enough synchronizing power with which to reach and maintain synchronous speed, it gradually moves into an opposite field and is decelerated again. The angle at which highest speed is reached is just 90 electrical degrees from the reference axis.

With a reduction of load the angle of the catching position is reduced until at 50 per cent of the pull out torque, the motor is operating near a critical pull in point. It is running there at a very low value of slip, and there is a definite catching of synchronous speed at about 50 electrical degrees. This catching position allows the accelerating force to operate on the rotor for a longer period of time than the decelerating force acts, and finally a state of equilibrium is reached between the synchronizing torque, the inertia of the rotor, and the load. The rotor reaches synchronous speed at the catching position, 48 electrical degrees behind its original axis, holds it momentarily, then speeds up still more until it decreases the angle to the position of synchronised static equilibrium for that load, 15 degrees. There the rotor oscillates back and forth as though it had just experienced a slight change in normal operation, and continues to run in stable synchronous operation.

RATED VOLTAGE TEST

Torque angle characteristics were measured again using the same motor running from the 220 Volt line. The same readings were taken using two values of static field excitation to give unity power factor at no load and at full load, and one reading with the dynamic excitation current. During this test it was found quite easy to estimate the relative stability of the machine from a reading of the angle. When synchronism was lost, though, action was too fast to follow, and heating of the rotor prevented experimental determination of the pull in torque and angle measurement. The curves were extended up to the static power limits, but the dynamic power limit was not reached.

RESULTS OBTAINED

This experiment on low voltage, is a slow motion demonstration of the forces and action of a machine under service conditions, and affords an excellent opportunity for observation.

During the out of synchronism operation, all of the meters are swinging back and forth with the speed changes of the rotor, and at small values of slip, they seemed to indicate the changes of power transfer through the slip cycle. Some readings were taken of the maximum and minimum readings of the meters in an attempt to approximate the amounts of power exerted at the extreme points, but no satisfactory results were obtained. Perhaps the most significant readings were those of the D.C. generator loading down the motor, as its voltage would indicate the maximum and minimum speed. However oscillograph readings would have to be made to secure any fine degree of accuracy, and even that would provide a complicated method of point by point solution.

The curves show no advantage in stability for over excitation of the motor, but they do emphasize a smaller capacity for underexcitation. This accentuates the value of a knowledge of the motor characteristics by the operator for satisfactory service operation.

PART III

SUGGESTIONS FOR FUTURE WORK

This study has delved into a broad subject, one in which there are many phases, any one of which is large enough to justify its choice as a subject for thesis material. In a field so broad it is difficult to select a definite goal to be achieved, but there are many that can be worked toward and reached through the combined efforts of many workers. Knowledge can be attained in two ways, by self experience, and through the experience of others, and those who can profit by the experience of others are off to a flying start.

Throughout this work there have been several questions come to mind in which there has been no information available, and which would provide an interesting problem for future experiment. Some of these are wholly theoretical, some practical, but only a few are such that they would be conveniently adapted to laboratory work. Difficulties and equipment limitations arise in the laboratory that should be considered in the selection of problems, and against which forewarning and preparedness can save much time and effort.

One question which has been raised for future study is that of the exact conditions prevailing when the motor is running at no load and between the conditions of minimum current input and minimum power input. Consideration should be given to the relative power supplied by the D.C. field circuit and its changes with the changes in that of the A.C. supply. Also the amount of energy stored in the magnetic field.

A study of the area outside the no load V curve involving the graphical representation of the transition from motor to generator action could be made if it is possible to make fine adjustments in the power delivered from a prime mover, and accurate power measurements.

In the final experiment performed, the author was impressed with the ease of judging relative stability of the machine by measuring the variation of the angle of rotor shift with respect to the axis of the supply voltage. He here suggests the possible value to a large alternator of some built in exploring coil or induced voltage indicating device that could be used for control or alarm purposes when the angle becomes near the stability limit.

The method used in measuring the rotor angle was subject to large error. One mechanical degree being equivalent to three electrical degrees, any error in reading the mechanical value is magnified. The stroboscope readings are subject to variations in voltage, too, and it is often desirable to measure the rotor position when no voltage is being generated. The development of a more accurate means of measurement would increase the value of this study, and would undoubtedly find other applications.

The angles measured were plotted into the V curves but not enough readings were taken to show any definite trends of torque angle changes at low power factors. A study of this would prove interesting, and with several workers the tests could easily be made simultaneously.

DIFFICULTIES AND EQUIPMENT LIMITATIONS

High voltage regulation of both direct and alternating current sources were encountered. Heavy cables were used throughout the test setup to minimize this as much as possible. In using another machine for A.C. supply, the regulation was much worse, and the frequency could not be held constant. In this case the stability of the machine is also reduced, and the load capacity is limited.

Another feature in operating four machines in a system, the overall efficiency is about 63 per cent. To transfer power through the system taxes the capacity of the first unit excessively to obtain near rated load on the third or fourth machine.

With regard to the D.C. power supply, regulation can be partly compensated for by using one plant for field excitation or steady loads, and another for variable loads. Brush contact of the D.C. motors and of the supply plants should be frequently checked to insure use of the maximum capacity of the machine.

Motor speed can be controlled only as accurately as the speed measuring device. Synchronising lamps as used in this experiment, are easy to use, but only adaptable when 60 cycle current is being generated at the proper voltage.

It was found impossible to load back through the D.C. plants because of their series field windings. Heavy D.C. loads must be expended on resistance grids.

Accurate determination of losses in all machines used should allow a means of checking power input against power output readings under all conditions. Such accuracy is difficult to obtain and entails considerable preliminary work, but upon it depends the accuracy of the final results.

Oscillograph measurements are necessary to record transient values and for measuring reactances of a machine. To be of value and oscillograph should be handy, accurate, and easy to control. The three element oscillograph tried was found to be unsuitable. It was difficult to adjust, gave indistinct curves from two of its elements, and was inconsistent. A cathode ray oscillograph will not give a permanent record needed for measuring transient currents.

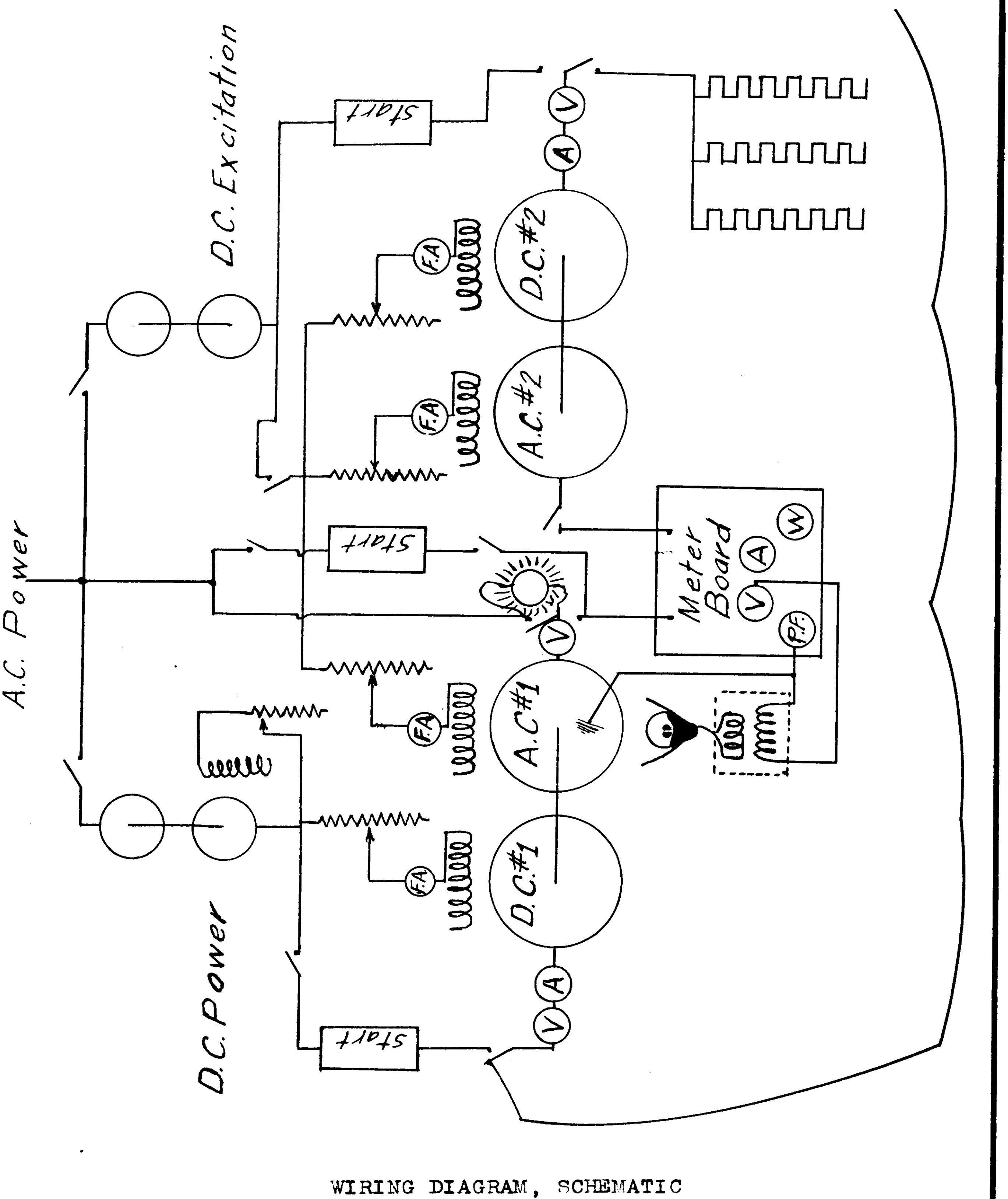
TIME LIMITATIONS

Experimenting of this nature entails the use of a great deal of laboratory equipment and ties up meters, cables, supply plants, switches, and rheostats that are needed in other parts of the laboratory during regular classes. Assembly, connecting, and becoming familiar with the test equipment requires more time than many of the actual tests to be made, and without careful planning and preparation, all of the time available may be spent without having an opportunity to see the test through.

Calculations made and curves checked in the lab. will save time of checking errors later, and several tests run using the same connecting cables, meters, etc. will have the same line and meter losses, and will give comparitive results without correction.

Fig. 5 shows a schematic diagram of the wiring diagram used, and gives some indication of the amount of equipment involved in the performance of this experimental work. Most of the experiments were run during the holidays, and between the Winter Quarter examinations and the organization of Spring Quarter laboratory classes, during which periods the equipment could be left assembled for two weeks at a time.

Finally, this type of work is more than a one man job. For a greater return of information from the time and effort expended, two or three students should be working together, assisting each other in consultation,



WIRING DIAGRAM, SCHEMATIC

Illustrating amount of equipment used

Fig. 5

discussion of reference material, thrashing out of the problems involved, and checking each other on the accuracy of their methods used. Also it would greatly simplify the conduct of tests in the laboratory; and there are times, especially during overload runs, when it is almost essential to have two or three operators to maintain control of the setup! Cooperation will prevent waste of time and power, and will insure the safety of students and equipment.

FINAL CONCLUSIONS

In review, the author is struck with a feeling of the relative insignificance of his findings. Other sources of information seem to have a wealth of ideas, a scope far beyond the present investigation, and a variety of means to approach the subject. Upon further consideration, however, and a realization of the comparative expenditures of time, energy, and thought given to the subject, much familiarity has been gained with the general problem, with the factors involved, and their relative importance. Some interesting experiments have been watched, and the groundwork has been laid for more. In this light, the original purpose has been accomplished.

The differences in V curve characteristics and

stability as dependent upon the source of power demonstrates the need for a knowledge of the system constants, and prove that the motor in question is not unstable within its rated values of current, voltage, and load. Characteristic curves have been drawn and are available for reference by anyone who is to operate the motor. Suggestions have been made to be incorporated into laboratory experiment procedure. And the way is open for a continuation of this study from the point at which this one
has just been
finished.

- - -

APPENDIX

LABORATORY DATA AND RESULTS

Equipment used: 2 motor generator sets

Westinghouse A.C. Generator
15 KVA
220 Volt
39.4 Ampere
80% P.F.
3 phase
60 cycle
1200 RPM
Exciting Amps. 12.8
Exciting Volts 125

Machine No. 1
S028C580
Serial 4548391

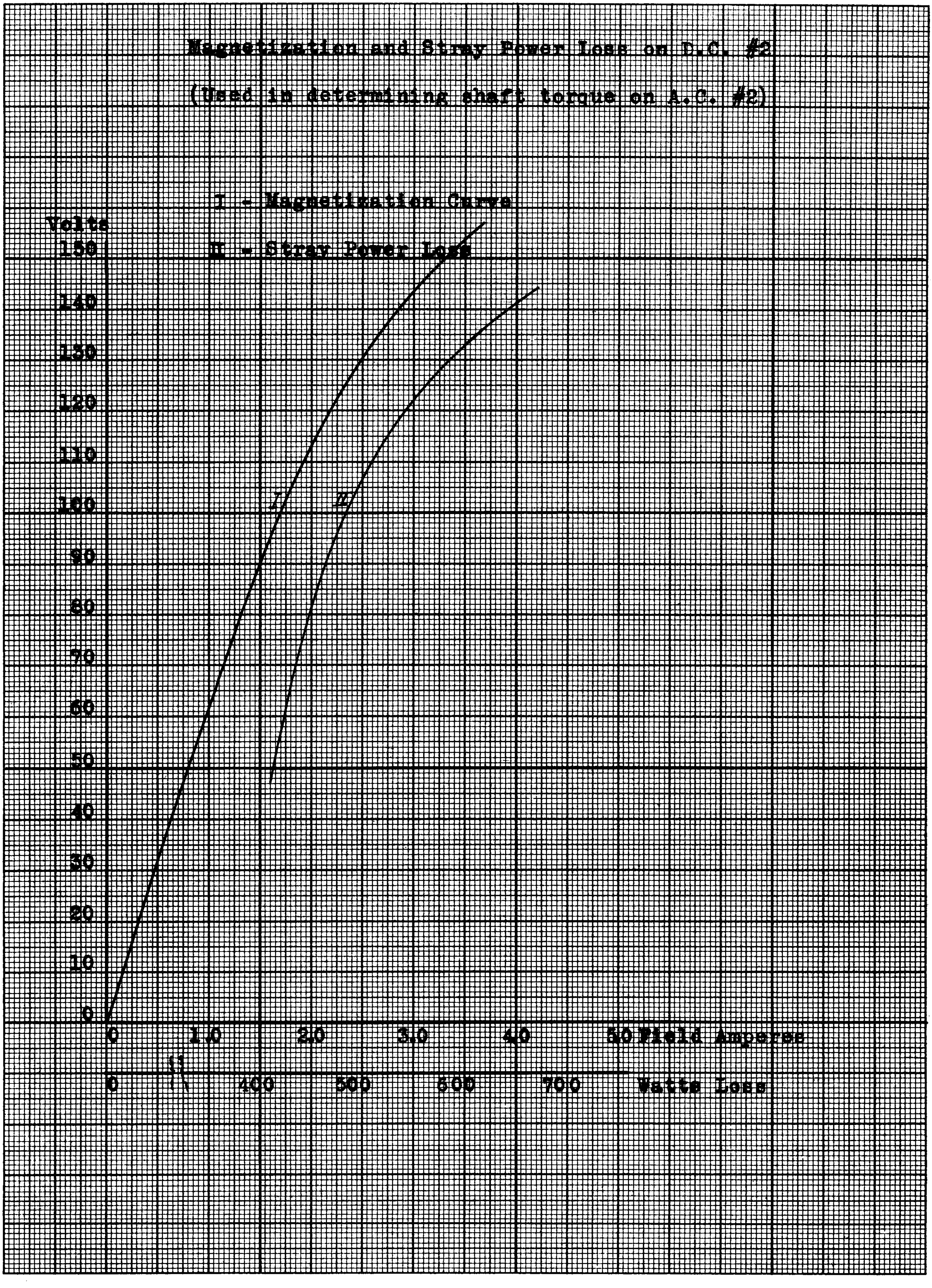
Machine No. 2
S028C856
Serial 4549224

Westinghouse D.C. Motor
Type SK
Frame 83
15 H.P.
115 Volt
113 Ampere
1200 RPM
Style 399564

Machine No. 1
Serial 4548389

Machine No. 2
Serial 4549222

Source of D.C. power Plant No. 1
Source of D.C. field excitation Plant No. 4

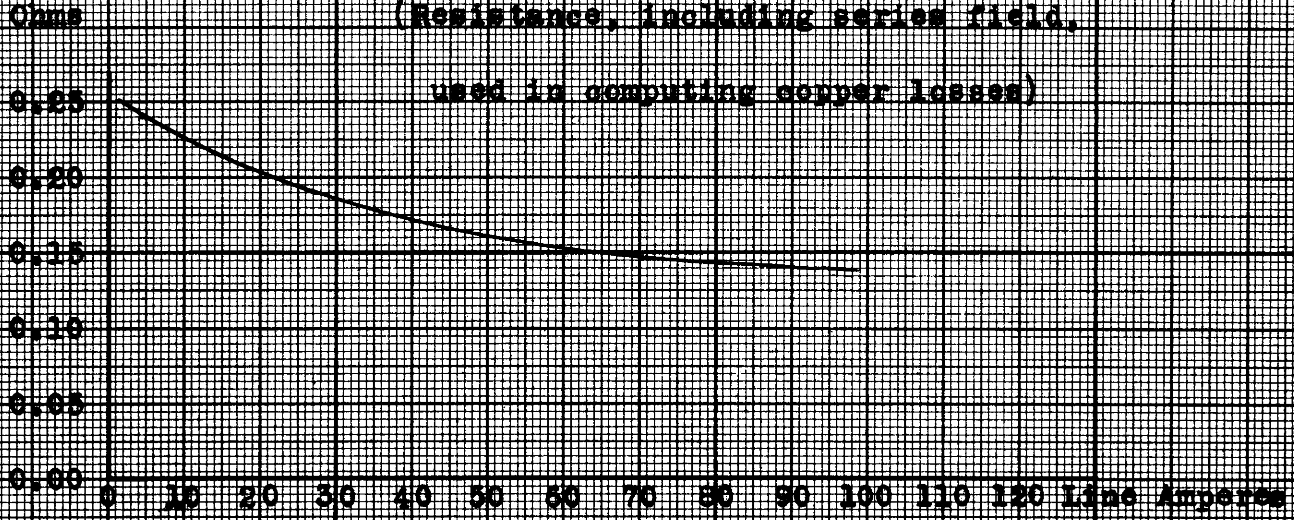


Magnetization and Stray Power Loss on D.C. #2

(Used in determining shaft torque on A.C. #2)

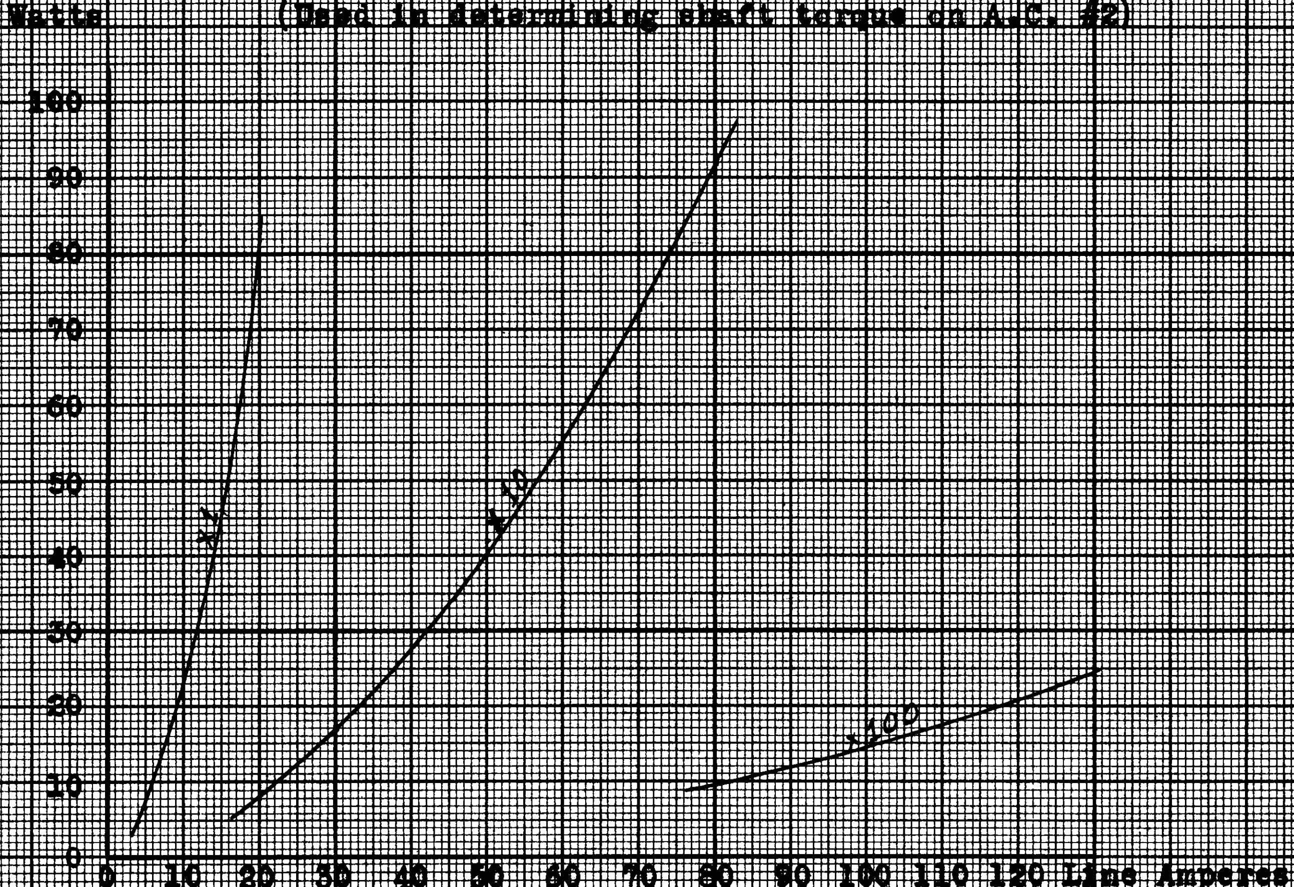
Armature Resistance Curve, D.C. #2

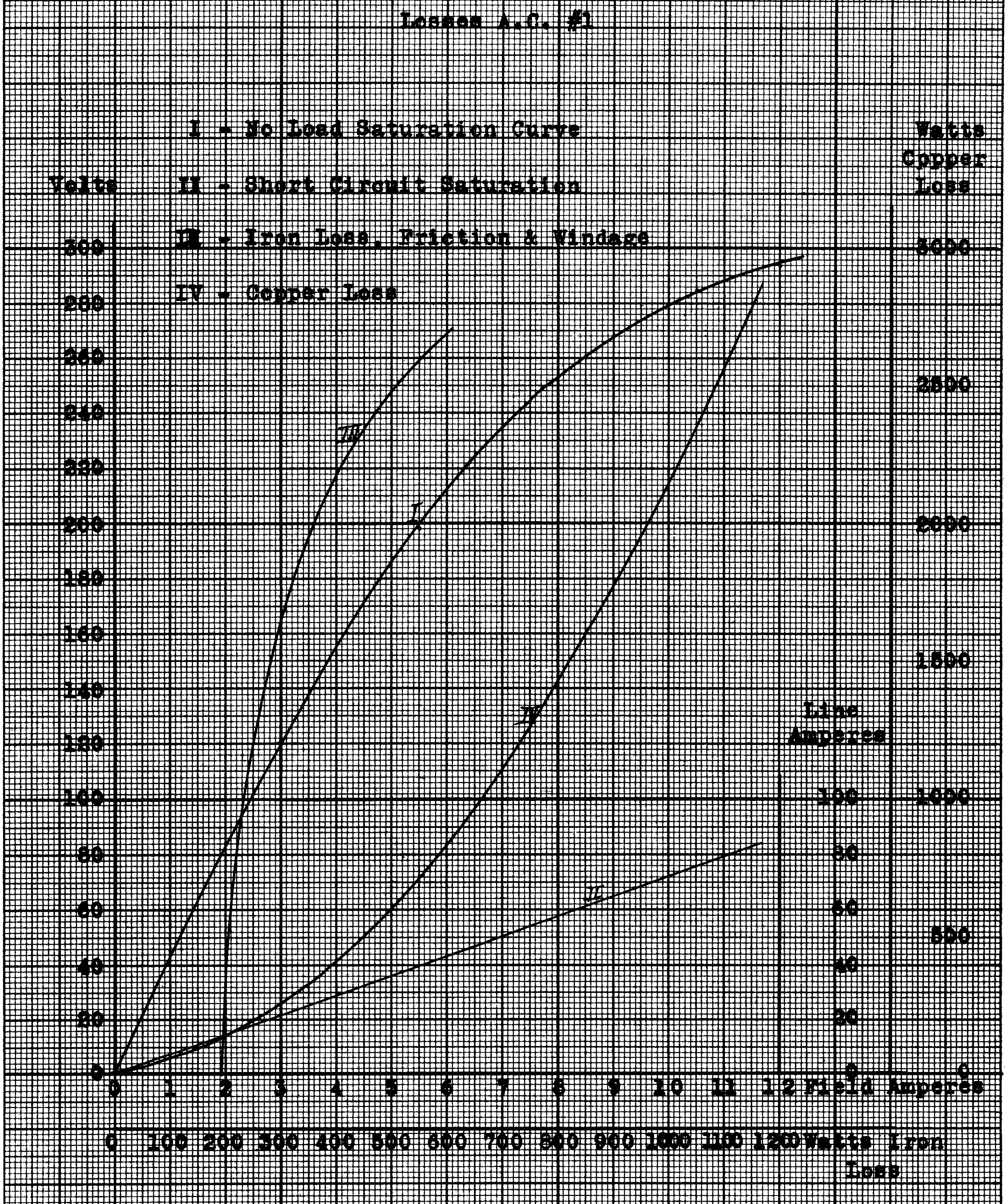
(Resistance, including series field, used in computing copper losses)



D.C. #2 Copper Losses

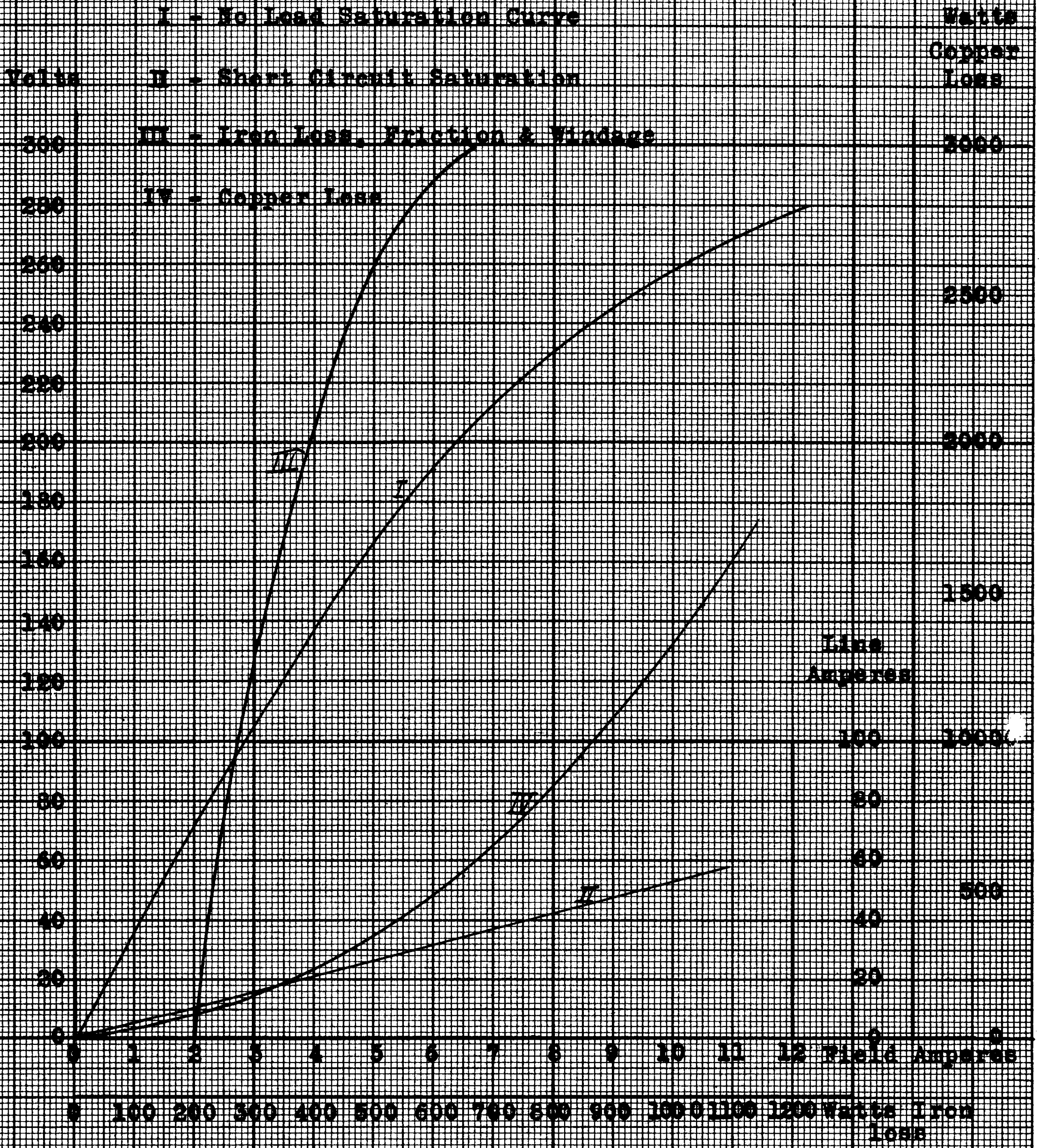
(Used in determining shaft torque on A.C. #2)





Measured resistance, per phase	0.112	ohms	
Effective resistance " "	0.165	ohms	
Synchronous impedance " "	2.56	ohms	@ 7.5 F.A.
Synchronous reactance " "	1.96	ohms	@ 7.5 F.A.

Losses A.C. #2



Measured resistance, per phase 0.103 ohms
Effective resistance " " 0.152 ohms
Synchronous impedance " " 3.25 ohms @ 7.5 F.A.
Synchronous reactance " " 2.87 ohms @ 7.5 F.A.

No load curve V CURVES

A.C. #2 Powered from 220 Volt 60 cycle lab circuit
Loaded through D.C. #2 on Resistance.

Volts	Amps	Watts	F.A.	P.F.	D.C. load	
228.	48.	1700	- 2.	.09	Volts	0
228.5	37.	1500	0.	.10	Amps.	0
229.	26.6	1160	1.6	.11	F.A.	0
230.	21.6	1000	2.3	.115	Watts	0
230.	15.7	860	3.3	.138	%load	0
230	6.5	880	4.7	.34		
230	2.4	680	5.5	.71		
230	1.5	600	5.8	1.00		
231	3.9	480	6.5	.31		
231	7.85	320	7.2	.10		
231.5	21.0	700	9.5	.083		
233.	32.7	840	11.7	.064		
232	39.6	1160	13.0	.073		
233	41.9	1160	13.5	.069		
234	63.8	2080	17.8	.081		
234	88.0	3520	23.2	.10		

Pulled out below - 2.0 amps. field excitation

V CURVES

A.C. #2 Powered from 220 Volt 60 cycle lab circuit
Loaded through D.C. #2 on Resistance.

Half load curve.

Volts	Amps.	Watts	F.A.	P.F.	D.C.load	
226	51.1	8200	.85	.41	Volts	100
227	39.6	7630	1.6	.49	Amps.	57.2
226	32.3	7480	2.5	.588	F.A.	1.53
228	21.2	7100	4.2	.85	Watts	5720.
228	17.3	6950	6.0	1.00	%load	50.
230	25.0	6870	9.1	.75		
230	33.2	7270	10.9	.56		
231	42.2	7430	12.7	.44		
232	64.4	8550	17.1	.33		
232	86.8	----	22.0	----		

Pulled out below .85 amps field excitation

V CURVES

A.C. #2 Powered from 220 volt 60 cycle lab circuit
Loaded through D.C. #2 on Resistance.

Three fourths load curve.

Volts	Amps.	Watts	F.A.	P.F.	D.C. load	
226	53.3	11400	2.1	.54	Volts	100
227	48.2	10850	2.25	.565	Amps.	84.4
228	39.1	10550	2.95	.67	F.A.	1.47
228	34.6	10480	3.5	.755	Watts	8440
229	28.0	10410	4.7	.93	%load	75
229	24.9	10100	6.3	1.00		
230	28.5	10400	8.6	.91		
230	38.8	10500	11.2	.675		
230	57.4	11000	15.2	.48		

Pulled out below 2.1 amps. field excitation

V CURVES

A.C. #2 Powered from 220 volt 60 cycle lab circuit
Loaded through D.C. #2 on Resistance.

Full load curve.

Volts	Amps.	Watts	F.A.	P.F.	D.C.load
227	53.3	14300	3.6	.67	Volts 126
227	44.8	14100	4.0	.75	Amps. 89.5
228	37.7	13550	5.0	.90	F.A. 2.3
229	33.5	13300	6.4	.99	Watts 11280
229	32.8	13250	7.4	1.00	% load 100
229	35.7	13400	9.3	.94	
231	54.2	14100	14.1	.65	

Pulled out below 3.6 amps. field excitation

One and one fourth load curve.

Volts	Amps.	Watts	F.A.	P.F.	D.C.load
226	56.8	----	5.1	---	Volts 129
224	50.4	17300	5.7	.875	Amps. 109
226	42.3	16750	7.45	1.00	F.A. 2.36
226	43.1	16750	8.75	.98	Watts 14080
226	49.6	17100	12.0	.88	% load 125

Pulled out below 5.1 amps. field excitation

LIMIT OF STABILITY

A.C. #2 Powered from 220 Volt 60 cycle lab circuit
Loaded through D.C. #2 on Resistance.

Amps.	F.A.	% load
56.0	0.0	3.5 (Friction)
51.1	0.85	50.0
60.0	1.5	64
53.3	2.1	75
54.	2.85	87
53.3	3.6	100
54.	4.9	119
56.8	5.1	125
54.4	6.0	137
62.	8.15	164
71.4	9.25	188

Maximum load obtained at given setting of field exc.

V CURVES

A.C. #2 Powered from A.C. #1 at 60 cycles.
Loaded through D.C. #2 on Resistance.

No load curve.

F.A.'	Volts	Amps.	Watts	F.A."	D.C. load	
20.1	228	18.1	1240	0.0	Volts	0
8.7	230	4.8	760	6.7	Amps.	0
7.9	230	2.1	610	7.5	F.A.	0
7.1	228	1.4	560	8.0	Watts	0
6.5	230	1.5	440	9.0	%load	0
5.1	230	8.8	320	10.0		
4.6	230	15.9	640	11.5		
3.2	232	48.0	2560	19.5		

V CURVES

A.C. #2 Powered from A.C. #1 at 60 cycles,
Loaded through D.C. #2 on Resistance.

Half load curve.

F.A.'	Volts	AMPS.	Watts	F.A."	D.C.load	
18.6	234	47.6	9050	1.7	Volts	123
17.8	232	45.3	9270	2.2	Amps.	54
16.6	233	39.9	8430	2.7	F.A.	2.28
14.7	234	33.7	8570	3.7	Watts	6640
13.	234	27.1	8200	5.0	% load	60
10.5	234	20.9	8320	7.0		
9.5	233	20.0	8330	8.0		
7.5	234	21.0	8330	10.3		
5.5	234	28.8	8620	13.0		
4.0	234	36.8	8900	15.2		
3.3	233	43.4	9000	16.9		

V CURVES

A.C. #2 Powered from A.C. #1 at 60 cycles,
Loaded through D.C. #2 on Resistance.

three fourths load curve.

F.A.'	Volts	Amps.	Watts	F.A."	D.C.load	
17.2	232	45.3	13000	4.5	Volts	129
14.0	230	35.2	12700	6.2	Amps.	78.5
11.8	233	30.2	12400	8.0	F.A.	2.45
10.5	234	30.0	12700	9.0	Watts	10100
9.0	234	30.0	12500	10.8	% load	90
7.5	234	33.2	12500	12.5		
6.0	233	40.3	11900	14.8		
6.2	234	40.7	12700	15.2		

Full load curve.

F.A.'	Volts	Amps.	Watts	F.A."	D.C.Load	
15.0	232	43.3	16300	7.5	Volts	131
13.0	233	39.7	16200	9.0	Amps.	99.2
9.5	234	40.5	16600	12.7	F.A.	2.5
10.9	232	38.5	16200	11.0	Watts	13000
8.5	232	43.6	16300	14.0	% load	115

V CURVES

A.C. #2 Powered from A.C. #1 at 60 cycles.
Loaded through D.C. #2 on Resistance.

Points taken for maximum load

F.A.'	Volts	Amps.	Watts	F.A."	% load
10.2	233	41.2	17100	11.4	115
11.6	233	46.0	19000	12.2	125
11.1	234	47.4	19400	13.1	130

TORQUE ANGLE CURVES

A.C. #2 Powered from 110 Volt 60 cycle lab circuit
Loaded through D.C. #2 on Resistance.

Field leads shorted. Field Resistance, 3 ohms.

Volts	Amps.	Watts	F.A.	Torque [illegible]	Angle deg.	
113.5	17.5	540	0	2.0	6	
113.0	18.1	901	0	3.2	12	
113.5	18.7	930	0	3.8	12	
113.8	19.3	1060	0	4.4	18	
114.5	20.2	1170	0	4.9	24	
114.0	21.4	1320	0	5.5	30	Pulls in
114.0	22.8	1400	0	6.0	36	
114.0	23.3	1760	0	5.9	42	Pulls out

Increase in D.C. load until pull out from 42 degrees. Catching action at 54 degrees. Reduction in load brings catching action back to 51 degrees, from which motor pulls in and runs at 30 degrees.

TORQUE ANGLE CURVES

A.C. #2 Powered from 110 Volt 60 cycle lab circuit,
Loaded through D.C. #2 on Resistance.

Field shorted with 6 ohms resistance in circuit.

Volts	Amps.	Watts	F.A."	Torque lb.ft..	Angle deg.
113.5	17.5	540	0	2.0	6
114.8	18.3	870	0	3.54	12
114.5	19.0	1040	0	4.35	18
114.5	19.8	1180	0	5.0	24
114.5	21.0	1300	0	5.45	30
114.5	22.1	1390	0	5.9	36
Increase to pullout point at				6.0	39
Decrease to catching at				3.6	66
Pull in point at				3.54	12

Static power curve, unity power factor at no load.

114.0	2.6	480	3.2	2.0	0	
113.5	3.3	650	3.2	3.3	3	
114.2	6.15	1210	3.2	7.0	6	
113.5	9.98	2090	3.2	11.05	15	Pulls in
113.5	12.1	2400	3.2	13.0	21	
113.0	20.3	3680	3.2	19.3	39	
112.5	25.2	4210	3.2	21.5	51	
112.5	28.8	4360	3.2	22.1	54	Pulls out

Reduction in load brings catching action 51 degrees, from which motor pulls in and runs at 15.

TORQUE ANGLE CURVES

A.C. #2 Powered from 110 Volt 60 cycle lab circuit,
Loaded through D.C. #2 on Resistance.

Dynamic Power curve, Field adjusted for unity P.F.

Volts	Amps.	Watts	F.A."	Torque lb.ft.	Angle deg.
114.0	2.3	470	3.2	2	0
113.0	17.0	3500	4.3	18.4	27
112.0	26.1	5190	5.6	27.8	33
111.0	31.4	6280	6.3	32.5	39
111.0	37.7	6520	7.2	38.8	42
110.5	43.4	8480	8.0	43.0	48
110.5	43.9	8640	8.9	44.1	48
110.0	50.4	9940	9.7	50.0	51
109.5	65.2	12840	12.5	62.5	57
107.7	85.3	16400	15.9	73.8	63

Test limited by line current in A.C. #2.

TORQUE ANLGE CURVES

A.C. #2 Powered from 220 Volt 60 cycle lab circuit,
Loaded through D.C. #2 on Resistance.

Static power curve, unity power factor at no load.

Volts	Amps.	Watts	F.A."	Torque lb.ft..	Angle deg.
233.0	1.6	610	5.6	2.0	0
229.0	9.6	4080	5.6	24.0	9
229.0	20.9	8860	5.6	55.0	18
228.0	32.5	13040	5.6	70.5	24
226.0	43.5	16680	5.6	88.6	33
224.0	56.7	19600	5.6	103.0	48 Pulls out.

Static power curve, unity power factor at full load.

233.0	8.6	360	7.5	2.0	0
232.0	14.7	4460	7.5	24.0	6
230.0	23.2	9140	7.5	56.6	15
228.5	31.7	12720	7.5	70.5	21
227.0	39.4	16120	7.5	88.6	27
225.0	47.3	19200	7.5	103.0	33
222.5	64.8	23100	7.5	124.0	51 Pulls out.

TORQUE ANGLE CURVES

A.C. #2 Powered from 220 Volts 60 cycle lab circuit,
Loaded through D.C. #2 on Resistance.

Dynamic power curve, Field adjusted for unity P.F.

Volts	Amps.	Watts	F.A."	Torque lb.ft.	Angle deg.
233.0	1.6	610	5.6	2.0	0
232.0	9.5	3900	5.8	24.0	6
229.0	20.7	8460	5.9	56.6	15
228.5	31.3	13040	6.8	70.5	21
227.0	39.4	16120	7.5	88.6	27
226.0	46.8	19200	7.8	103.0	30
225.5	56.0	22800	9.2	124.0	36
223.0	63.2	25700	10.2	140.0	42

Test limited by heating of the motor. No indication of instability at last set of conditions.

Full load torque on motor shaft, 76.5 pound feet.

SYNOPSIS OF LITERATURE REVIEWED

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