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THE DETERMINATION OF ALTERNATOR CHARACTERISTICS.

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The exacting requirements now to be met in regard to the performance of A. C. machinery and the expense of duplicating in the testing room all the conditions of future operations,make proper indirect methods for the determination of the characteristics of A. C. apparatus of great value.

In the following discussion, the e.m.f. induction and current relations under different conditions as to load and power factor in the armatures of several types of A. C. generators will be considered both theoretically and experimentally, and indirect methods for obtaining the regulation of a particular machine developed and applied to those of other types.

For convenience of reference the following divisions have been made:

Armature reaction and armature reactance.

Tests of an inductor alternator.

Alternator regulation, indirect methods for determination.

Application to inductor machine.

Application to other types.

ARMATURE REACTION AND ARMATURE REACTANCE.

Consider the no-load induction distribution on an alternator of the type shown in Fig. 1, structural details of which are given in Fig. 5. During the rotation of the inductor the armature induction pulsates between a maximum and minimum value, but is constant in direction. When an inductor lug is exactly

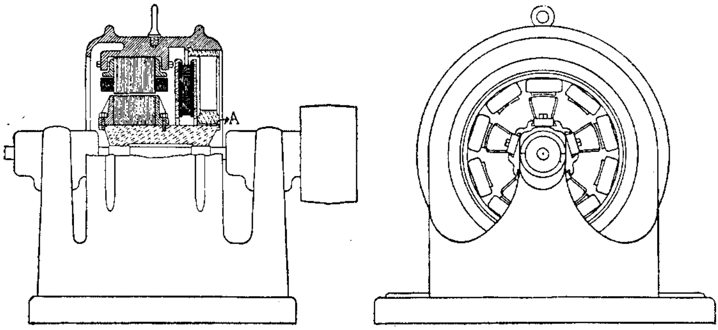

FIG 1.

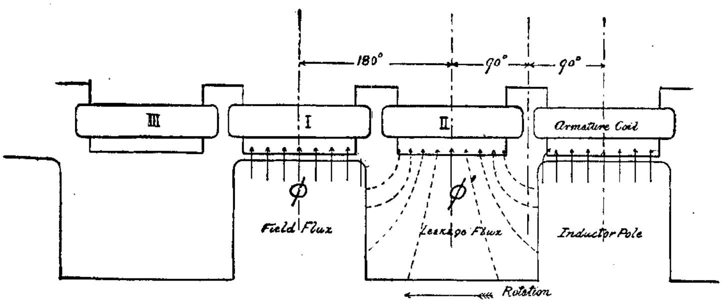

FIG. 2.

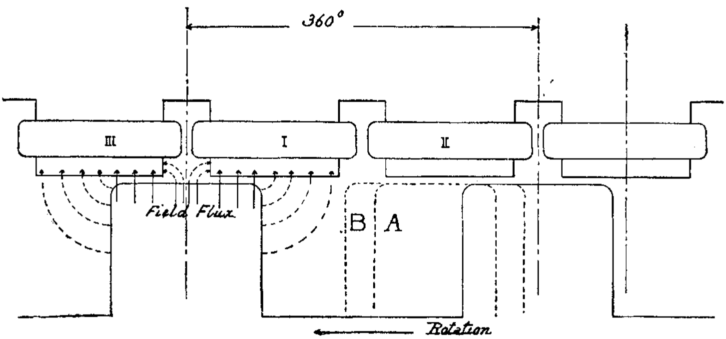

FIG 3.

opposite an armature coil (see Fig. 2), the induction through that coil is a maximum, but as the lug recedes from it, the induction diminishes to a minimum, until the lug stands opposite the adjacent coil. The minimum induction is a leakage flux and the e.m.f. of the machine is diminished in proportion to the ratio of this minimum induction to its maximum value. This leakage flux should, therefore, be as small as possible.

The average e.m.f. induced in any armature coil is the difference between the flux φ, shown in Fig. 2, which passes through that coil when covered by an inductor lug, and the flux φ', when

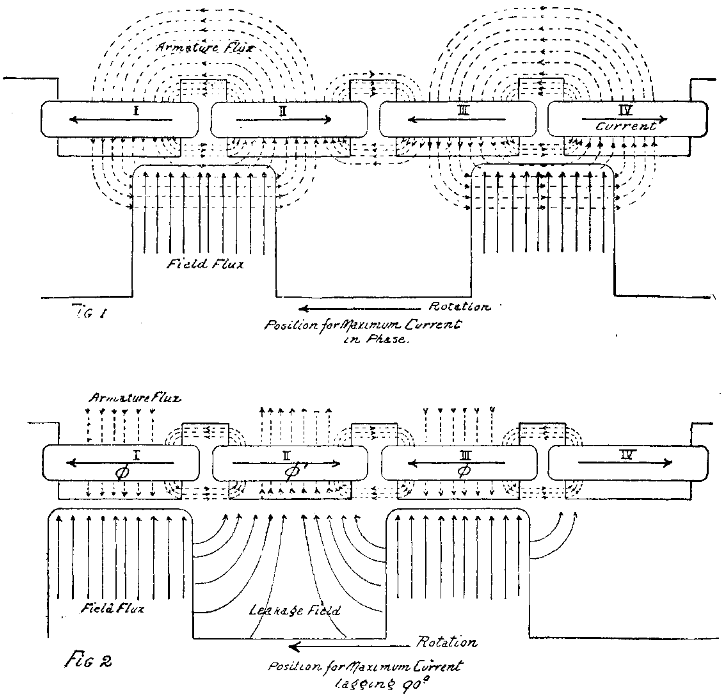

FIG. 4.

the coil is midway between these two adjacent lugs, divided by the time of half a period, that is:

$$\varepsilon_{\text{average}} = (\varphi - \varphi') \div (T/2)$$

Fig. 3 will be referred to later.

When the armature carries a current, the effective magnetic flux is the resultant of the m.m.f. of the field and of the armature ampere turns. If the armature current lags by 90° the field and armature m.m.f.'s will exactly oppose each other, as shown in Diagram 2, Fig. 4.

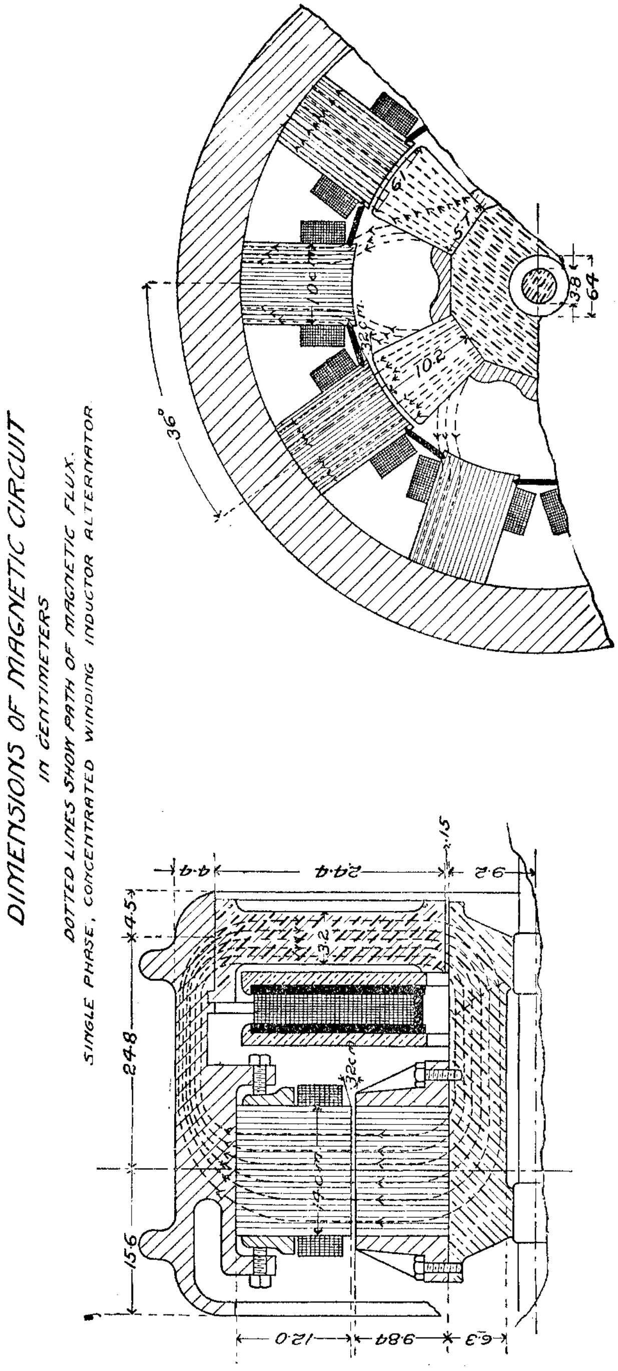
DIMENSIONS OF MAGNETIC CIRCUIT
IN CENTIMETERS
DOTTED LINES SHOW PATH OF MAGNETIC FLUX.
SINGLE PHASE, CONCENTRATED WINDING INDUCTOR ALTERNATOR
36°
6.1
5.7
10 cm
.32 cm.
10.2
3.8
6.4
4.4
24.4
.15
9.2
4.5
3.2
24.8
.32 cm
15.6
12.0
9.84
6.3

FIG. 5.

If n and i are respectively the number of turns and amperes in field coils, and N and I the number of turns and the effective current in one armature coil, the resultant m.m.f. of field and armature will be:

$$(n\,i - N\,I\sqrt{2}) \text{ for coil 1.}$$

and

$$(n\,i + N\,I\sqrt{2}) \text{ for coil 2.}$$

As seen, the m.m.f.'s of coils 1 and 3 directly oppose the field m.m.f., diminish the maximum induction, while the action of coil 2 is to increase the leakage flux.

Both of these actions diminish the induced e.m.f. The reluctance of the path of the coils is, however, very different; the magnetic circuit of coil 1 is that of the machine, and varies with the saturation of the machine circuit, while the magnetic circuit of coil 2 is made up largely of air, and the flux through it is proportional to the armature current.

The m.m.f. due to this quadrature current, in addition to diminishing the effective armature flux, will generate lines of force encircling the armature coils, but not passing through the main magnetic circuit of the machine. This cross-magnetizing effect is, however, small in the concentrated winding type of alternator with quadrature current.

With in-phase current the case, however, is different. The diminution of effective flux (see position of inductor lug, Fig. 3), unless the machine is highly saturated, is negligible, for the m.m.f. of coils 1, and 2 (see Diagram 1, Fig. 4) tends only to set up a cross flux increasing the induction of the leading tip of the inductor lug and diminishing the induction through the trailing tip, producing a change in the distribution of magnetic flux and resultant wave form, but altering little the resultant induction or total e.m.f. generated. It is thus seen that the effect of the armature current in diminishing the total effective induction and varying its distribution depends on the phase relation of e.m.f. and current.

In considering the path presented to the armature flux at any angular position of the coils relatively to the inductor lugs, other than the particular ones just given, it will be seen that its reluctance periodically changes. As before stated, with the inductor lug opposite an armature coil (position A, Fig. 3), the reluctance of the magnetic of the armature coils is that of the machine, but after a small angular displacement of the inductor (position B,

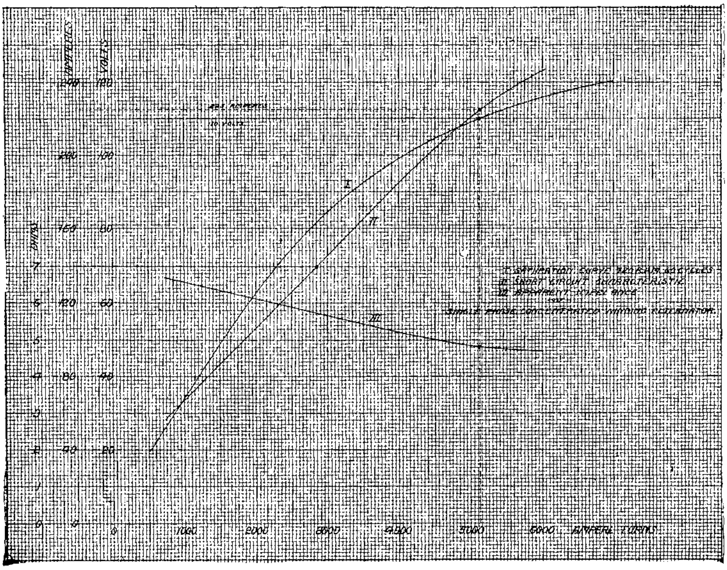
AMPERES
VOLTS
SHORT CIRCUIT CHARACTERISTIC
SINGLE PHASE CONCENTRATED WINDING ALTERNATOR.
I
II
III
AMPERE TURNS

Fig. 6.

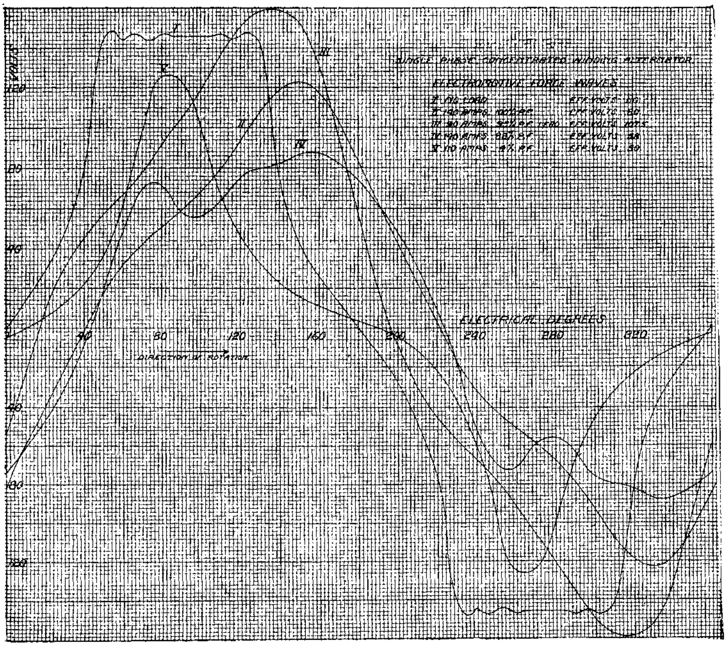
SINGLE PHASE CONCENTRATED WINDING ALTERNATOR.
ELECTROMOTIVE FORCE WAVES
ELECTRICAL DEGREES
DIRECTION OF ROTATION
VOLTS
40
80
120
160
200
240
280
320

Fig. 7.

Fig. 3), the reluctance is diminished, the flux due to armature current increasing and becoming a purely local one. This periodic fluctuation of the reluctance in the path of the induction set up by the armature m.m.f., as easily seen, may have a very marked effect on the regulation and wave form of machines of the type illustrated.

TEST OF AN INDUCTOR ALTERNATOR.

The machine is that illustrated in Fig. 1. The magnetic dimensions are given in Fig. 5. The armature consists of ten coils of 75 turns each, connected in parallel, the resistance cold equals .04 ohms. The excitation is effected by a single exciting coil, as seen, containing 1,710 turns. The normal output is 15.4 k.w.; voltage, 110; speed, 720 r.p.m.

The following tests were made:

Saturation curve, 60 cycles.

Short-circuit characteristic, 60 cycles.

Real induced e.m.f. waves, with different armature currents and different power factors, 3 amperes field excitation.

Current waves under different conditions.

Curves showing variation of induction due to armature current, for different positions of the inductor lug, 3 amperes field excitation.

From these were deduced curves of synchronous impedance, curves of induction distribution under different conditions of load, and curves, which for the present, we will call counter e.m.f. waves. Curve I, Fig. 6, is the saturation curve. Curve II is the short-circuit characteristic. Curve III is the synchronous impedance, calculated. Curve 1, Fig. 7, is the no-load or nominal induced e.m.f. wave. Curve II is the real induced e.m.f. wave for in-phase current of 140 amperes .The great variation in the induction distribution with the resultant change of wave form will be noticed. Curve III, Fig. 7, is the real induced e.m.f. wave for a leading current of 90 amperes, 95% power factor. Owing to the fact that with this particular power factor the armature current (Curve III, Fig. 8) is in step with the nominal induced e.m.f., the total effective induction has been but slightly altered in amount, as seen by Curve II, Fig. 9; its distribution, however, has been changed.

Curve IV, Fig. 7, is the real induced e.m.f. wave for 140 amperes, 88% power factor, lagging, and clearly shows the effect of diminishing power factor in bringing the real induced e.m.f. wave back in phase with the nominal induced e.m.f.

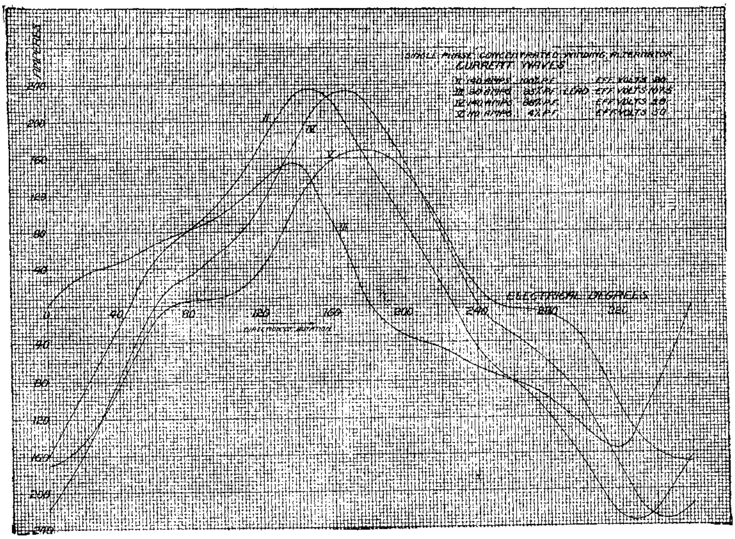
CURRENT WAVES
AMPERES
ELECTRICAL DEGREES
0
40
80
120
160
200
240
280
320

Fig. 8.

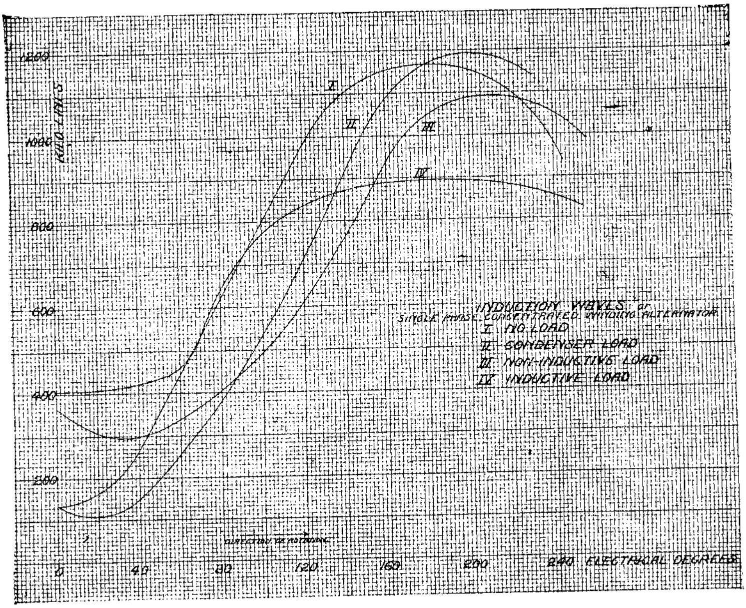
INDUCTION WAVES OF
SINGLE PHASE CONCENTRATED WINDING ALTERNATOR
I NO LOAD
II CONDENSER LOAD
III NON-INDUCTIVE LOAD
IV INDUCTIVE LOAD
KILO-LINES
1200
1000
800
600
400
200
0
40
80
120
160
200
240 ELECTRICAL DEGREES

Fig. 9.

Curve V is the real induced e.m.f. wave for 110 amperes, 4% power factor, lagging. Here the e.m.f. wave, while greatly altered in extent and form, has returned almost exactly to, and in phase relation with, the nominal induced e.m.f., as, of course, would be expected. All the above e.m.f. waves were taken with a constant field excitation of three amperes and a speed of 720 r.p.m.

Curves II, III, IV and V, or curves of real induced e.m.f. waves under different conditions, were taken from a test coil of 75 turns, wrapped uniformly about an armature coil, and they equal the machine terminal e.m.f. waves plus the armature ohmic drop. For e.m.f. wave measurements a special contact maker was used, charging and discharging a condenser through a Weston voltmeter.

The tremendous change of wave form with character of load in this machine, will be noted to be far too much for successful commercial use, but for purposes of illustration the machine is an excellent one.

Curves II, III, IV and V, Fig. 8, are current waves corresponding to the e.m.f. waves II, III, IV and V, Fig. 7. The shift of current with the nature of load shows clearly the change of the armature m.m.f. from a cross-magnetizing to a demagnetizing effect, as the lag increases from zero to 90°.

Curves I, II, III, and IV, Fig. 9, show the variation of induction through one armature coil with different positions of inductor lug, for armature currents (Fig. 8) of zero amperes, 90 amperes, 95% power factor, leading; 140 amperes, 100 % power factor; and 110 amperes, 4% power factor, lagging. These curves were determined by integrating the areas of the real induced e.m.f. waves, Curves I, II, III and V, Fig. 7.

By Curve I it will be noticed that the maximum induction in one armature coil is slightly over 1,160,000 lines, representing a maximum induction per square centimetre of about 10,000 lines. The minimum induction, or leakage flux, occurring when the armature coil is midway between two adjacent inductor lugs, is 130,000 lines.

Curve II is the induction wave with 90 amperes armature current, 95% power factor, leading. This current, as before stated, being in step with the nominal induced e.m.f., the maximum and minimum values of the induction through any of the armature coils is but slightly altered by the armature current, but the shift of the induction wave, due to the cross-magnetizing effect of the armature m.m.f., is easily seen.

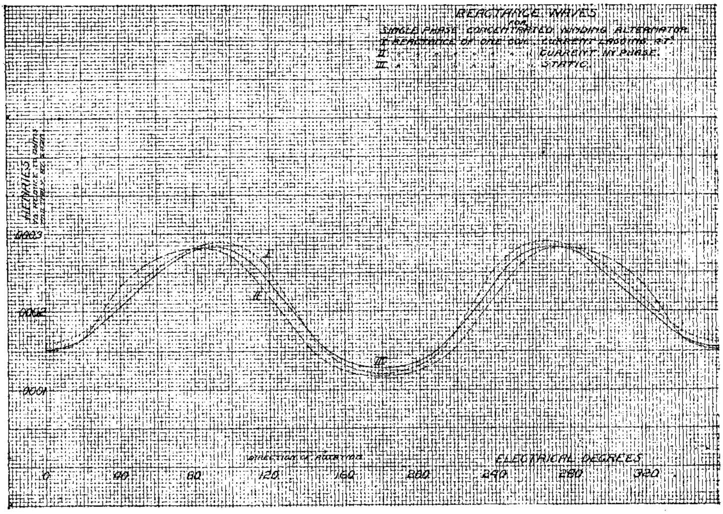
REACTANCE WAVES
FOR
SINGLE PHASE CONCENTRATED WINDING ALTERNATOR
II " " " " CURRENT IN PHASE.
III " " " " STATIC.
.0003
.0002
.0001
I
II
III
ELECTRICAL DEGREES
0
40
80
120
160
200
240
280
320

FIG. 10.

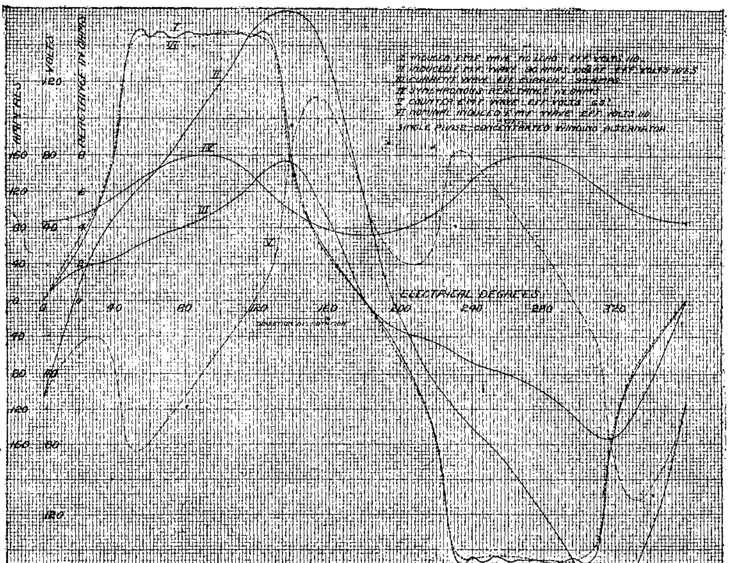
SINGLE PHASE CONCENTRATED WINDING ALTERNATOR
ELECTRICAL DEGREES
0
40
80
120
160
200
240
280
320
I
II
III
IV
V
VI

FIG. 11.

Curve III is the induction wave corresponding to a current of 140 amperes in step with the terminal voltage, but lagging behind the nominal induced e.m.f. by nearly 50°, due to the armature reactance. The demagnetizing effect of the armature current now becomes marked, the maximum induction being diminished and the leakage flux increased.

Curve IV is the induction wave for 110 amperes, lagging 85° behind the nominal induced e.m.f. This curve shows with great clearness the demagnetizing effect of wattless armature currents, and the virtual absence of any cross-magnetizing effect. The maximum no-load induction is reduced from 1,160,000 lines to approximately 900,000 lines, and the no-load leakage is increased from 130,000 to 400,000 lines.

The shape of the induction wave is altered, becoming flatter, and its maximum and minimum values are changed, but it has regained a practically in-phase angular relation to the no-load induction wave. The diminution of voltage with quadrature current is thus seen to be due almost entirely to armature reaction.

From the above induction waves and from the instantaneous values of armature current, given in Fig. 8, the total induction due to the armature m.m.f. diminution of field flux, increase of stray field and cross lines for different positions of the inductor, are readily found.

If π is the increase or decrease of induction through the coil for any position of the inductor above or below the induction when no armature current is flowing, and if π be divided by the instantaneous value of the current and by 10^8, the result will be the total inductance of the coil in henrys, and multiplying by the angular velocity and the number of turns in the armature coil, we have the instantaneous value of the total inductance of the coil in ohms. This includes both the effective armature reaction and armature reactance. In Fig. 10 are given Curves I and II of total armature reactance calculated as above. Curve I is for non-inductive external load. Curve II is for current in phase with the nominal induced e.m.f.

These curves of inductance or reactance were also experimentally determined as follows:

A search coil of 75 turns was wound over one of the armature coils and connected to a suitable ballistic galvanometer. The fields were excited by a current of three amperes; different direct currents were passed through the armature for different posi-

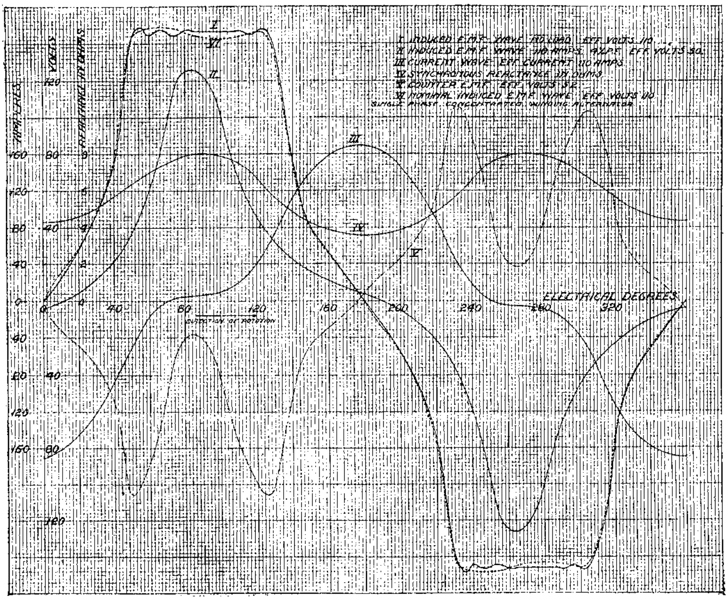
I INDUCED E.M.F. WAVE NO LOAD EFF. VOLTS 110
II INDUCED E.M.F. WAVE 110 AMPS. 92 P.F. EFF. VOLTS SO
III CURRENT WAVE EFF. CURRENT 110 AMPS.
IV SYNCHRONOUS REACTANCE IN OHMS
V COUNTER E.M.F. EFF. VOLTS 52
VI NOMINAL INDUCED E.M.F. WAVE EFF. VOLTS 110
SINGLE PHASE CONCENTRATED WINDING ALTERNATOR
AMPERES
VOLTS
REACTANCE IN OHMS
ELECTRICAL DEGREES
DIRECTION OF ROTATION

FIG. 12

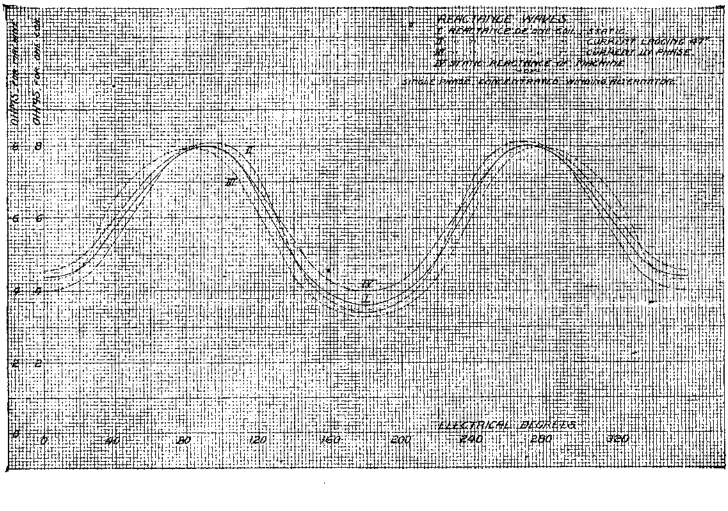
REACTANCE WAVES
I REACTANCE OF ONE COIL, STATIC
II CURRENT LAGGING 47°
III CURRENT IN PHASE
IV STATIC REACTANCE OF MACHINE
SINGLE PHASE CONCENTRATED WINDING ALTERNATOR
ELECTRICAL DEGREES

FIG. 13.

tions of the inductor lugs, and the throw of the galvanometer noted when the armature current was made or broken. Knowing the galvanometer constant, its readings indicated the total actual change in the number of lines threading the armature coils for different values of current and position of inductor.

Curve III, Fig. 10, gives the result in henrys when 100 amperes in the armature circuit was used, and is seen to correspond very closely to the values of reactance determined from the induction and current curves. A variation of armature current from a few amperes to 140 amperes gave virtually identical results.

The above curves of Fig. 10 show the variation of the total armature reactance for different positions of the inductor lug. The maximum reactance occurs when the inductor lug or pole is midway between two coils (2, Fig. 4); the minimum value when the inductor lugs are opposite armature coils (1, Fig. 4). The total armature reactance is thus seen to pulsate synchronously with the position of the inductor, maximum and minimum value occurring for inductor positions as above shown.

From the curves of total armature inductance with inductor position and armature current, the counter e.m.f., or e.m.f. which must be added to the real induced e.m.f. to give the nominal induced e.m.f., may be determined. Calling the counter e.m.f. at any instant, e, we have $\varepsilon = (d\,L\,i) \div (dt - 10^{-8}) = (1) \div (10^{-8})\,[(L\,d\,i) \div (dt) + (i\,d\,L) \div (dt)]$ volts. Where L is the instantaneous value of the total inductance per coil taken from Curve III, Fig. 10, and i the instantaneous value of the current in the coil, taken from current waves, Fig. 8.

The method is then simply to take the sum of any instantaneous value of L into the slope of the current wave corresponding to such value, and the instantaneous value of i corresponding to L into the slope of the inductance wave at the same time. This divided by 10^{-8} will give the instantaneous value of the counter e.m.f. of the coil. The process is a tedious one, but by plotting the curves to a large scale, quite accurate results may be obtained.

Applying the method to the case where the armature current is in phase with the nominal induced e.m.f., we have the results shown in Fig. 11. Curve I is the no-lead or nominal induced e.m.f. wave experimentally determined. Curve II is the real induced e.m.f. wave with 90 amperes and external power factor of 95% leading. Both these curves are the same as shown in

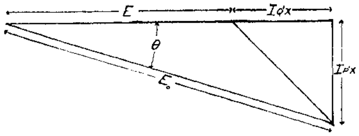

Fig. A.

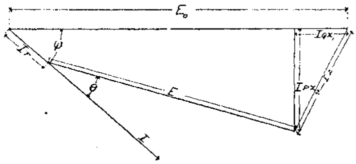

Fig. B.

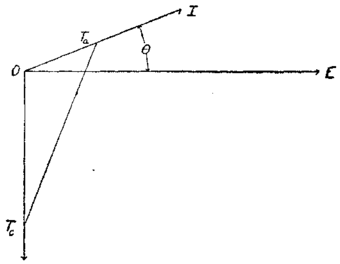

Fig. C.

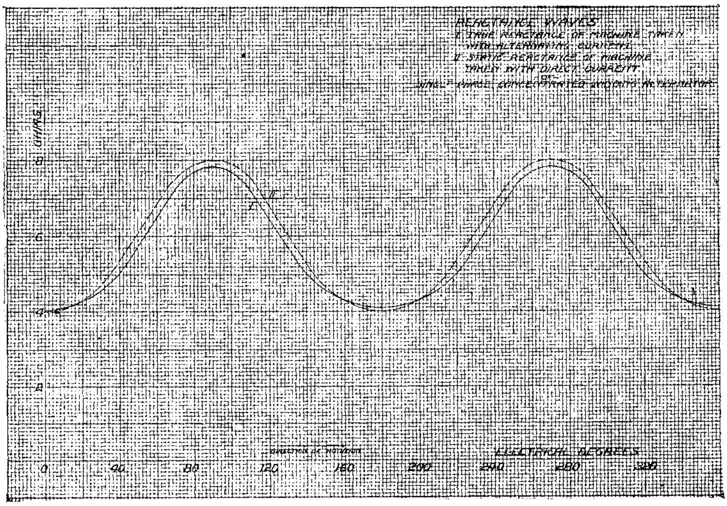

Fig. 14.

Fig. 7. Curve III is current wave, Curve IV the reactance wave and Curve V is the c.e.m.f. wave calculated from the equation as given above. Adding Curves V and II we have Curve VI, which should be identical with Curve I. Although not identical, the agreement between the two is extremely close.

If the equivalent sine wave or the c.e.m.f. wave is determined, it will be found to lag 90° behind the equivalent sine wave of the real induced e.m.f. wave. The effective value of the c.e.m.f. is 65 volts; the effective value of the nominal induced e.m.f. is 110 volts; and the effective value of the real induced e.m.f. is 107.5 volts, which together nearly form the right angled triangle that would be expected, as this c.e.m.f. is practically all due to the variation of induction set up by the cross-magnetizing currents of the armature. Dividing the effective value of the counter e.m.f. by the effective armature current, we have .722, a coefficient measuring the effect of cross-magnetization.

Applying the same method when the armature current lags by practically 90° behind the nominal induced e.m.f., we have the results given in Fig. 12. Curve I is as before the no-load or nominal e.m.f. wave. Curve II is the real induced e.m.f. with 110 amperes, lagging 85° from the nominal induced e.m.f. Curve III is the current wave; Curve IV the reactance wave; and Curve V the derived c.e.m.f. wave. Adding Curves II and V, as before, we have Curve VI, which again very closely corresponds to Curve I.

Determining the equivalent sine wave of the c.e.m.f., it will be seen to lag 90° behind the equivalent sine wave of current, but as the current lags practically 90° behind the nominal induced e.m.f., the c.e.m.f. wave is almost exactly in opposition to the nominal induced e.m.f., instead of being at 90° from it,as was the case with in-phase current. The effective value of the nominal induced e.m.f., is 110 volts; the effective value of the real induced e.m.f. is 50 volts; the effective value of the counter e.m.f. is 52 volts; this latter being virtually the difference between the first two. Dividing again the effective value of the counter e.m.f. by the armature current, we have .45, a coefficient now measuring the demagnetizing effect instead of the cross-magnetizing effect, as before.

It is thus seen that in this type of alternator, having a variable magnetic reluctance—and the statement is true for other types as well, as will be seen later—the e.m.f. vector representing the effective armature m.m.f., reaction and cross-magnetizing effect,

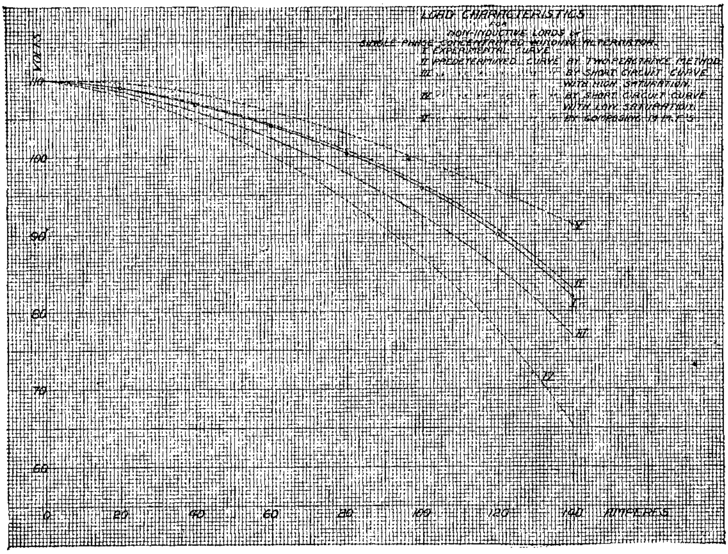
LOAD CHARACTERISTICS
FOR
NON-INDUCTIVE LOADS OF
SINGLE PHASE CONCENTRATED WINDING ALTERNATOR.
I EXPERIMENTAL CURVE
II PREDETERMINED CURVE BY TWO REACTANCE METHOD
III " " BY SHORT CIRCUIT CURVE
WITH HIGH SATURATION.
IV " " BY SHORT CIRCUIT CURVE
WITH LOW SATURATION.
V " " BY COMPOSING M.M.F.S.
VOLTS
110
100
90
80
70
60
0
20
40
60
80
100
120
140
AMPERES
I
II
III
IV
V

FIG. 15.

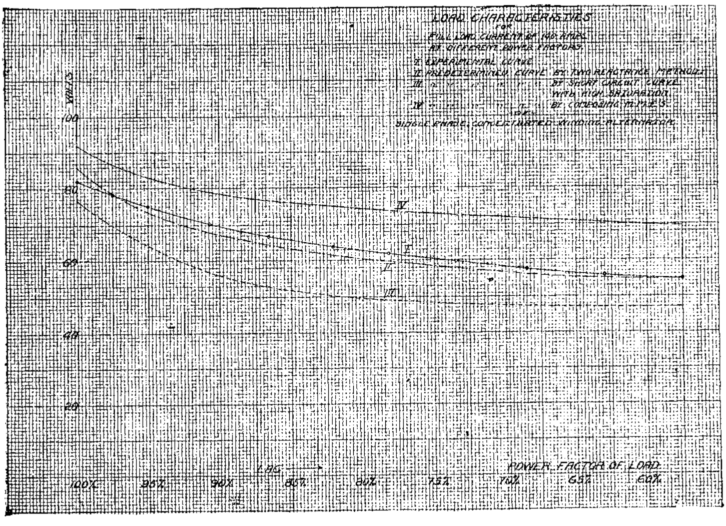
LOAD CHARACTERISTICS
FOR
FULL LOAD CURRENT OF 140 AMPS.
AT DIFFERENT POWER FACTORS.
I EXPERIMENTAL CURVE
II PREDETERMINED CURVE BY TWO REACTANCE METHOD
III " " BY SHORT CIRCUIT CURVE
WITH HIGH SATURATION.
IV " " BY COMPOSING M.M.F.S.
FOR
SINGLE PHASE CONCENTRATED WINDING ALTERNATOR.
VOLTS
100
80
60
40
20
LAG
POWER FACTOR OF LOAD.
100%
95%
90%
85%
80%
75%
70%
65%
60%
I
II
III
IV

FIG. 16.

varies not only in magnitude but in angular relation to the nominal induced e.m.f. from 90° to 180°, as the power factor of the total circuit varies from unity to zero.

In Fig. 13 are given in ohms the inductance curves I, II and III of Fig. 10, reduced from henrys, and an additional curve, IV, giving in ohms the total inductance of the machine for different positions of the inductor lugs, the 10 armature coils being all in parallel. It will be noted that the adjacent minimum values for this latter curve are the same, and equal to one-tenth of the mean of the adjacent unequal minimum values of reactance for one coil, as a little consideration will show should be the case.

Alternator Regulation, Indirect Methods for Determination.

The term " synchronous reactance " has been very generally used as combining the effect of armature reaction and the stray field due to the cross-magnetizing effect of the armature current, in the determination of alternator regulation; and, properly measured as the resultant of the demagnetizing and cross-magnetizing armature m.m.f., will give correct results. But, in general, it cannot be determined as a result of a single observation, as is ordinarily assumed.

Usually the synchronous reactance is determined from the short-circuited characteristic at low, or comparatively low, field excitations, the method of procedure being to short-circuit the armature through an ammeter and vary the exciting current until full load armature current is reached. The value thus obtained, however, will be incorrect for the following reasons: The field excitation being much below normal, the quadrature armature current will have a much greater proportional demagnetizing effect than when the field is fully excited; and further, in general, the field due to the cross-magnetizing effect of an equal in-phase armature current is greater than the diminution of field flux to the quadrature current. If the latter were equal in a particular machine, and the synchronous reactance were determined with normal field excitation and full load quadrature current, its use would lead to correct results. If the demagnetizing effect of a given quadrature current is not equal to the cross-magnetizing effect of an equal in-phase current, as in general it is not, one may be determined as a function of the other, as will be shown below. The demagnetizing effect of varying quadrature armature currents with full field excitation

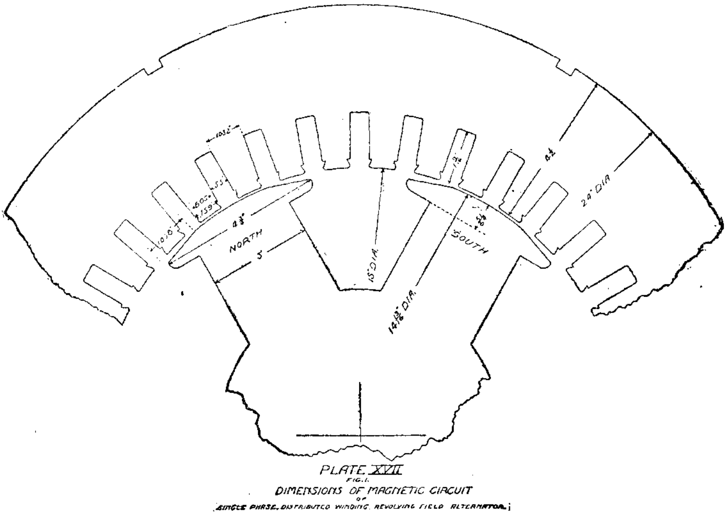

Fig. 17.

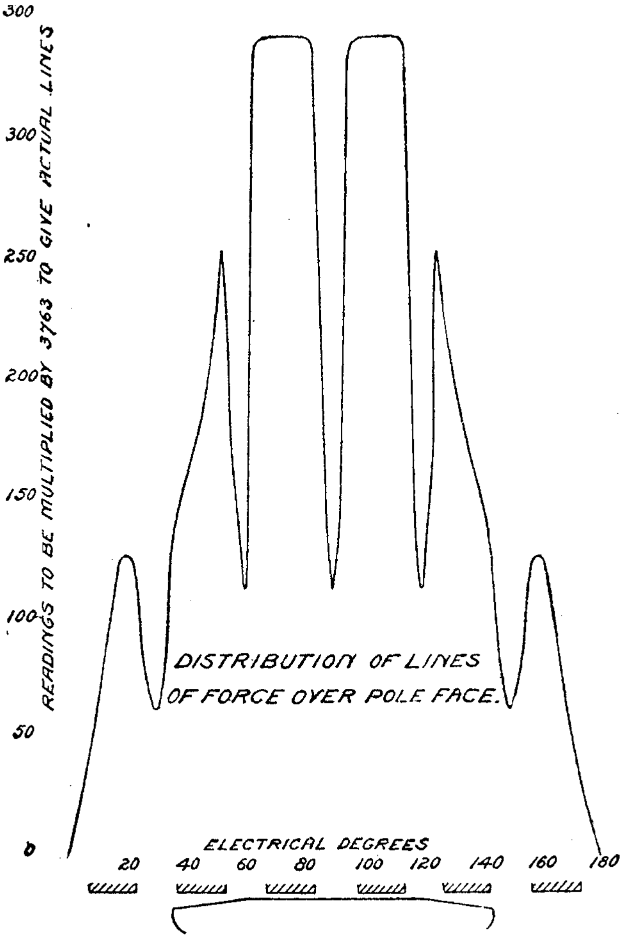

Fig. 17 b.

may be determined by working the alternator on a purely reactive load.

When the armature current lags behind the nominal induced e.m.f., by an angle between 0° and 90°, it may, of course, be regarded as made up of two components; the in-phase component, equal to the current multiplied by the cosine of the angle between the current and nominal induced e.m.f., and the quadrature component, equal to the current by the sine of the same angle.

Figure A. illustrates a method, which we will call the short-circuit characteristic method, used for the determination of alternator regulation. E is the terminal e.m.f., equal to the real induced e.m.f. when the armature ohmic drop is negligible. $I\,Q'\,x$ is taken as the component of the e.m.f. consumed by synchronous reactance corresponding to the demagnetizing effect of armature current. $I\,P'\,x$ is taken as the component of the e.m.f. consumed by synchronous reactance corresponding to the cross-magnetizing effect of armature current. x is the synchronous reactance determined from ordinary short-circuit characteristic with low field excitation; and P' and Q' are respectively the power factor and the inductance factor of the external load. From the diagram, we have:

$$E = \sqrt{E^2_0 - (IP'x)^2} - i\,Q'\,x$$

Applying this method to a given machine, it will generally be found to regulate better than the formula indicates, for the reason that the method of determining the magnetizing component of synchronous reactance gives too high a value for it. Other errors involved in the formula are the use of P', Q', as power and inductance factors of the load, instead of the power and inductance factors of the total circuit, armature and external load; and the assumption that the cross-magnetizing component of the synchronous reactance and demagnetizing component are equal.

Another approximate method, which we will call "composing m.m.f. method" (see *L'Endustrie Electrique*, December, 1899), is illustrated in Figure C. Referring to the figure, $O\,E$ is the real induced e.m.f.; $O\,I$, the current lagging by an angle θ behind the terminal volts. The armature ohmic drop is assumed to be negligible. On $O\,I$ is set off $O\,T_a$, the field m.m.f. necessary to overcome a quadrature current equal to I, determined from the

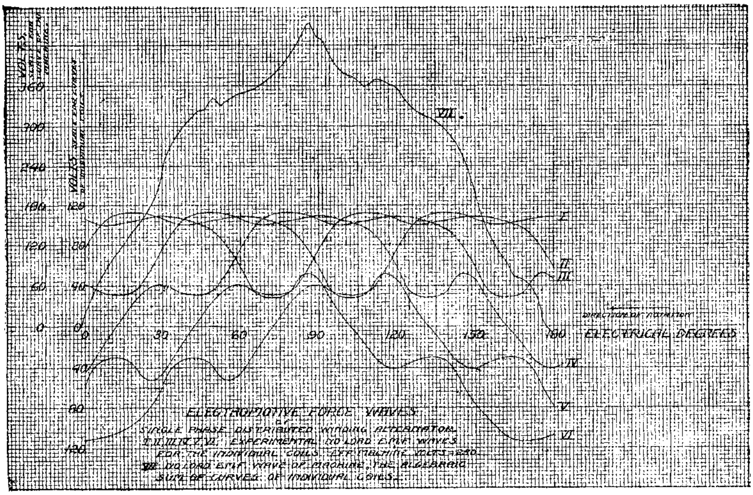
VOLTS
ELECTRICAL DEGREES
DIRECTION OF ROTATION
VII.
I
II
III
IV
V
VI
ELECTROMOTIVE FORCE WAVES
OF
SINGLE PHASE DISTRIBUTED WINDING ALTERNATOR.
I, II, III, IV, V, VI. EXPERIMENTAL NO LOAD E.M.F. WAVES
FOR THE INDIVIDUAL COILS. EFF. MACHINE VOLTS = 250.
VII. NO LOAD E.M.F. WAVE OF MACHINE, THE ALGEBRAIC
SUM OF CURVES OF INDIVIDUAL COILS.

FIG. 18.

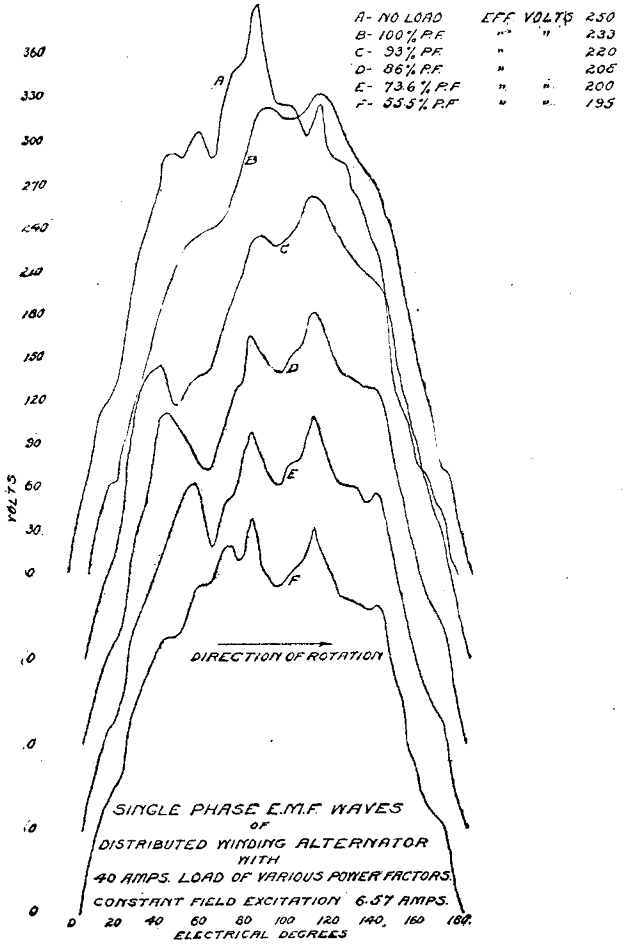
A- NO LOAD EFF. VOLTS 250
B- 100% P.F. " " 233
C- 93% P.F. " 220
D- 86% P.F. " 206
E- 73.6% P.F. " " 200
F- 55.5% P.F. " " 195
A
B
C
D
E
F
VOLTS
DIRECTION OF ROTATION
SINGLE PHASE E.M.F. WAVES
OF
DISTRIBUTED WINDING ALTERNATOR
WITH
40 AMPS. LOAD OF VARIOUS POWER FACTORS.
CONSTANT FIELD EXCITATION 6.57 AMPS.
0 20 40 60 80 100 120 140 160 180
ELECTRICAL DEGREES

FIG. 19.

short-circuit characteristic. From T_a is struck an arc with a radius equal to the field m.m.f. The distance to the point where this arc intersects a line drawn at right angles to $O\ E$ is taken as the effective m.m.f., producing the real induced e.m.f., E. Having $O\ T_c$ or the effective m.m.f. acting, E is determined from the saturation curve. As will be readily appreciated, the principal objections to this method are the assumption that the alternator works on a straight line characteristic, and the neglect of armature self-induction.

The following method, which we will call for convenience "the two reactance method," has been found to give accurate results when applied to a number of alternators of widely different types.

The demagnetizing effect of different quadrature currents is determined at full load field excitation, and not at an excitation just sufficient to circulate full load current through the armature on short-circuit, as is ordinarily done.

The armature, instead of being short-circuited, is operated at constant full load field excitation on a suitable variable reactance and the difference between the voltage given by the saturation curve and terminal voltage is noted. The voltage thus obtained divided by the current gives the value of the demagnetizing component of the synchronous reactance corresponding to normal conditions of machine operation. The cross-magnetizing effect for different in-phase currents is taken as equal to the demagnetizing component of the synchronous reactance multiplied by the ratio of the total inductance of the armature, with the inductor lugs in position shown in I, Fig. 3, to the inductance of the armature with the inductor lugs in the position shown in II, Fig. 3. The inductance is determined by passing through the armature, from external source, a suitable alternating current when the lugs are in the position just named, and the fields fully excited.

Curve I, Fig. 14, is a complete curve of armature reactance at 60 cycles with the inductor in the positions named and intermediate ones. The ratio of maximum to minimum values of this curve is the ratio referred to above.

Curve II, Fig. 14, is one obtained by the ballistic method, and is seen to agree quite closely with Curve I.

Using the values so obtained for the demagnetizing and cross-magnetizing components of synchronous reactance, the Figure B due to Blondel, properly expresses the relations of e.m.f. and currents in the armature of an alternator under full load condi-

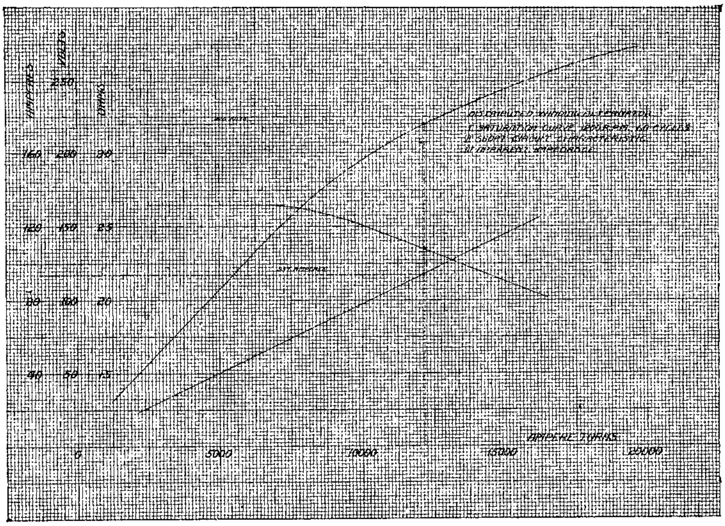
AMPERES
VOLTS
OHMS
250
160 200 30
120 150 25
80 100 20
40 50 15
0
5000
10000
15000
20000
AMPERE TURNS

FIG. 20.

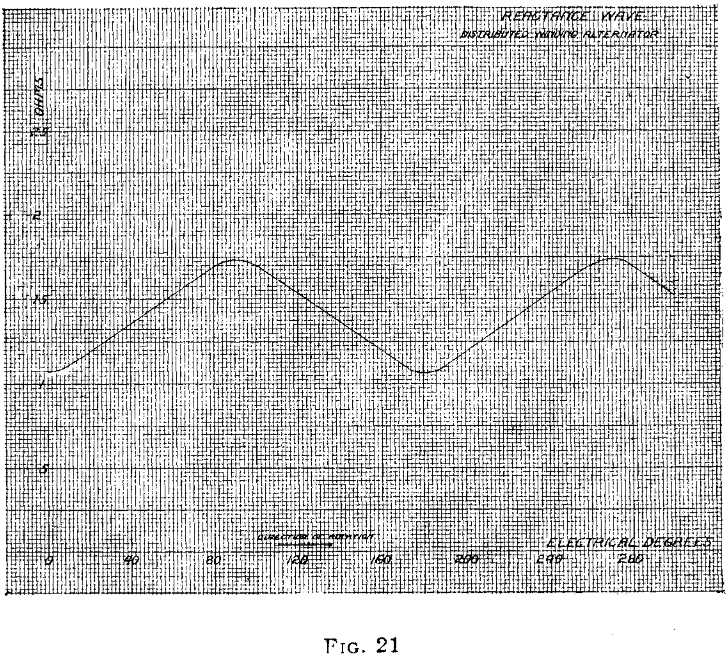
REACTANCE WAVE
DISTRIBUTED WINDING ALTERNATOR
OHMS
2
1.5
1
.5
ELECTRICAL DEGREES
0
40
80
120
160
200
240
280

FIG. 21

tions of operation. E_0 is the nominal induced e.m.f.; φ, the phase angle between the current and the nominal induced e.m.f.; θ, the phase angle between the current and the terminal voltage; X, the demagnetizing component of synchronous reactance; X_2, the cross-magnetizing component of synchronous reactance; P and Q, respectively, the power and inductance factors of the whole circuit; $I r$,the ohmic drop; and E, the terminal e.m.f.

Application to Inductor Alternator.

The different indirect methods for determining the variation of terminal voltage as a function of the armature current and the power factor of the external load for constant field excitation, stated above, have been applied to the 15.4 k.w. inductor alternator, shown in Figs. 1 and 5, and compared with directly observed results.

The saturation curve, short-circuit characteristic, and the curve of synchronous impedance for this alternator were given in Fig. 6. Curve I, Fig. 15, gives the actual observed load characteristic for non-inductive load at a constant field excitation of 3 amperes.

Curve II is a calculated curve by the two reactance method. It is seen to agree exceedingly well with the observed curve.

Curve III is the calculated curve by the short-circuit characteristic method, using the value of the synchronous reactance obtained with full field excitation, the short-circuited armature current being 225 amperes, or 85 amperes above the normal full load current.

Curve IV is a calculated curve by the short-circuit characteristic method, using the value of the synchronous reactance obtained with a field excitation just sufficient to circulate the full load current of 140 amperes through the armature.

Curve V is the calculated curve by composing m.m.f.'s.

It will be noted that while the terminal voltage by the short-circuit method, for a given armature current, is much less than the observed terminal volts, the agreement becomes much more close when the values of the synchronous reactance are obtained with high field excitation. The method of composing m.m.f.'s gives much too high a value for the terminal voltage, as will be expected.

In Fig. 16 are shown the results of the same methods applied to the case of constant armature current with variable external

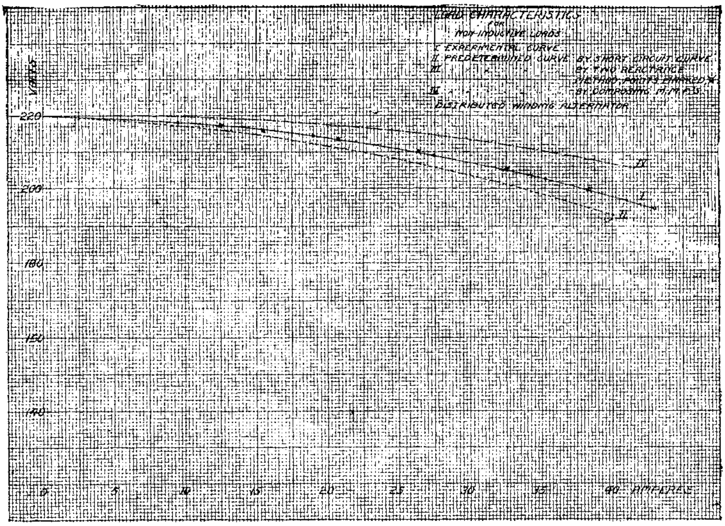
LOAD CHARACTERISTICS
FOR
NON-INDUCTIVE LOADS
I EXPERIMENTAL CURVE.
II PREDETERMINED CURVE BY SHORT CIRCUIT CURVE
BY TWO REACTANCE
METHOD, POINTS MARKED
BY COMPOUNDING M.M.F.S.
DISTRIBUTED WINDING ALTERNATOR
VOLTS
220
200
180
160
140
0
5
10
15
20
25
30
35
40 AMPERES
I
II
IV

FIG. 22

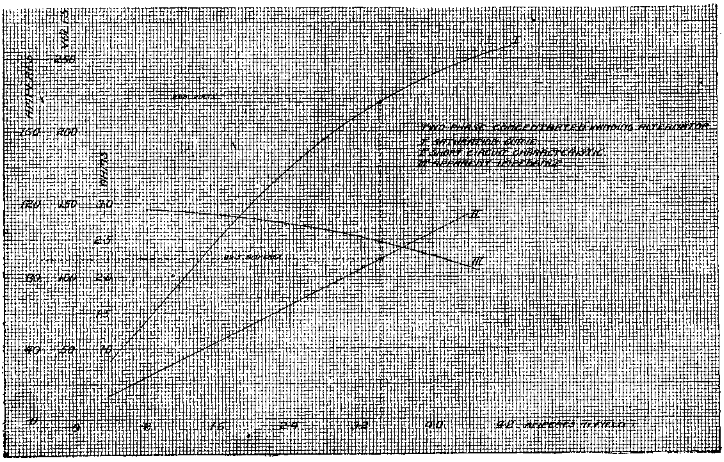
TWO PHASE CONCENTRATED WINDING ALTERNATOR
AMPERES
VOLTS
OHMS
250
200
150
100
50
3.0
2.5
2.0
1.5
1.0
150
120
90
60
0
8
16
24
32
40
48 AMPERES IN FIELD
I
II
III

FIG. 24.

power factor, as compared with the observed results.

Curve I gives the observed values of the terminal e.m.f., with power factor, for constant field current of 3 amperes and constant armature current of 140 amperes. Curve II is that calculated by the two reactance method; Curve III by the short-circuit characteristic with high field excitation; and Curve IV by composing m.m.f.'s.

Again, the two reactance method is seen to give accurate results, while the short-circuit characteristic method gives, as before, too small values, and the method of composing m.m.f.'s too large values of the terminal e.m.f.

Application to other Types.

A second machine upon which a number of tests were made was of the revolving field, distributed armature winding type, the magnetic circuit of which is shown in *a*, Fig. 17.

In addition to the load characteristics observed and determined by the different methods, tests were made of the induction distribution under the different conditions; the wave form of the terminal e.m.f. was analyzed into its component wave forms, due to the individual armature coils; and the conditions affecting the change of wave form with character of load were studied.

In *b*, Fig. 17, is given the no load induction distribution with the field magnet in the position shown, the fields being excited to give normal terminal voltage. This was obtained by means of a ballistic galvanometer and suitable exploring coils in the usual way. It will be noted that the larger part of the induction enters the armature through the teeth, as might have been expected, but about one-third of the induction, in the case of the teeth immediately opposite the pole, passes into the armature by way of a slot due to the high induction intensity in the teeth.

Curves I, II, III, IV, V and VI, Fig. 18, are the individual e.m.f. waves for each of six successive angularly displaced armature coils in series, when the machine is connected as a single phaser. Curve VII is obtained by taking the algebraic sum of the instantaneous values of the first six curves, and agrees very closely with the no-load observed e.m.f. wave, Curve IV, Fig. 19. These curves show most clearly the advantages of distributed windings as regards wave form, for while the e.m.f. from an individual coil, as Curve IV, is a very flat topped wave, and somewhat similar to the no load e.m.f. wave of the concentrated winding inductor alternator (Curve I, Fig. 7), the machine

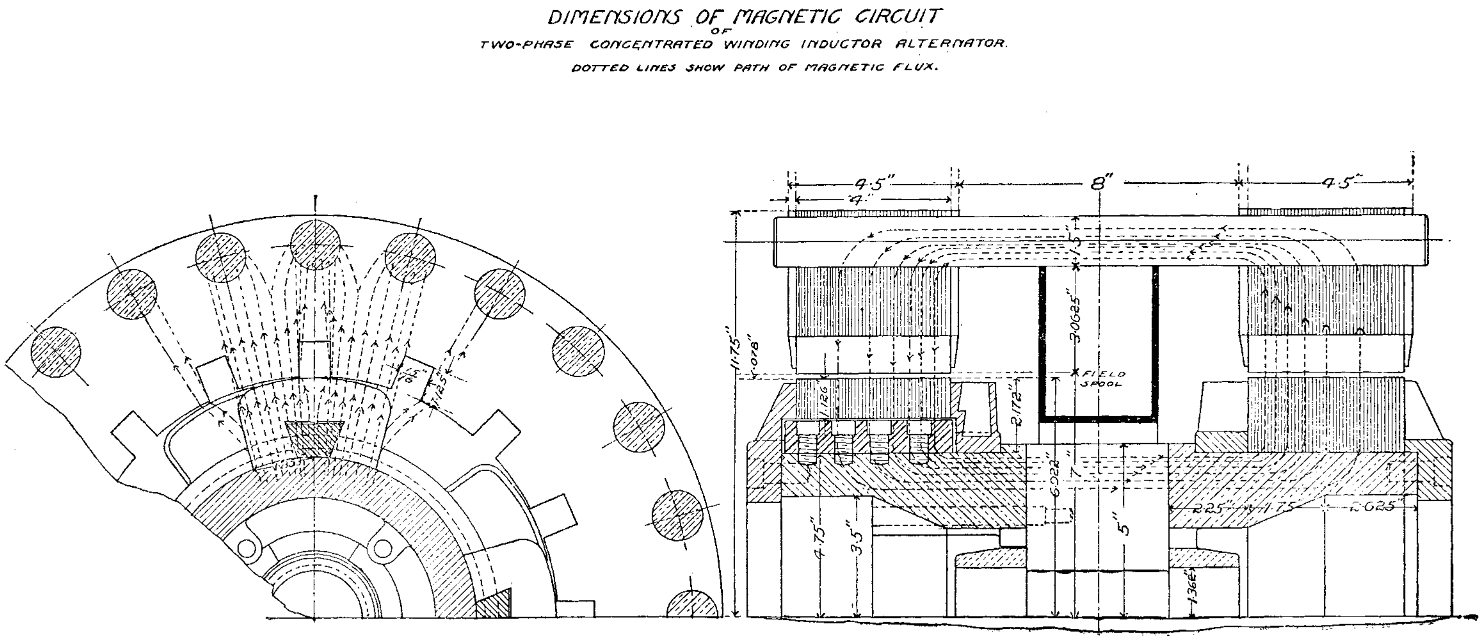
DIMENSIONS OF MAGNETIC CIRCUIT
OF
TWO-PHASE CONCENTRATED WINDING INDUCTOR ALTERNATOR.
DOTTED LINES SHOW PATH OF MAGNETIC FLUX.
4·5"
4"
8"
4·5"
11·75"
·078"
3·0625"
FIELD SPOOL
2·172"
1·126"
6·022"
7"
5"
4·75"
3·5"
2·25"
1·75"
2·625"
1·362"

FIG. 23.

e.m.f. wave, which is the resultant of six such waves displaced by 30°, is very nearly sinusoidal.

If a machine is desired which will give not only an extremely close approximation to a sine wave e.m.f. at no load, but also shall hold such wave form with changes of the load, the number of slots per phase per pole must be made as large as practicable, and the induction distribution such that the e.m.f. waves for the individual armature coils are also as near to sine waves as possible.

In Fig. 19 are given a series of e.m.f. waves with constant field excitation, a constant full load armature current of 40 amperes, and power factors varying from unity to .55. It is to be noted that while the wave form changes with the power factor, the change is by no means so great as in the case of the concentrated winding inductor type.

Curve I, Fig. 20, is the saturation curve of the machine shown in Fig. 17; Curve II, the short-circuit characteristic; and Curve III, the synchronous impedance calculated from Curves I and II. At 4.6 amperes exciting current, the impedance is 2.6 ohms, the effective resistance being .186 ohms, the reactance 2.31 ohms.

The complete reactance wave for this machine, obtained by sending through the armature an alternating current, the field poles being in different positions, is shown in Fig. 21. The ratio of maximum to minimum values of the reactance is seen to be 1.625. As the demagnetizing component of synchronous reactance from the short-circuit characteristic is 2.31 ohms, the cross-magnetizing component of the reactance is $2.31 \times 1.625 = 3.75$ ohms.

The three indirect methods for the determination of alternator regulation before discussed, were applied to this machine and compared with the experimental curve. The results are shown in Fig. 22. Curve I is the experimental or observed load characteristic for a non-inductive external load. Curve II is calculated by the short-circuit characteristic method, high field excitation. Curve III, determined by the two reactance method, is identical with the experimental curve, Curve IV, determined by composing m.m.f.'s. The correspondence between the observed and calculated value by the two reactance method is highly satisfactory.

The magnetic circuit of the third machine tested is shown in Fig. 23. The machine is a 10 k.w., 220-volt, 60-cycle, two-phase

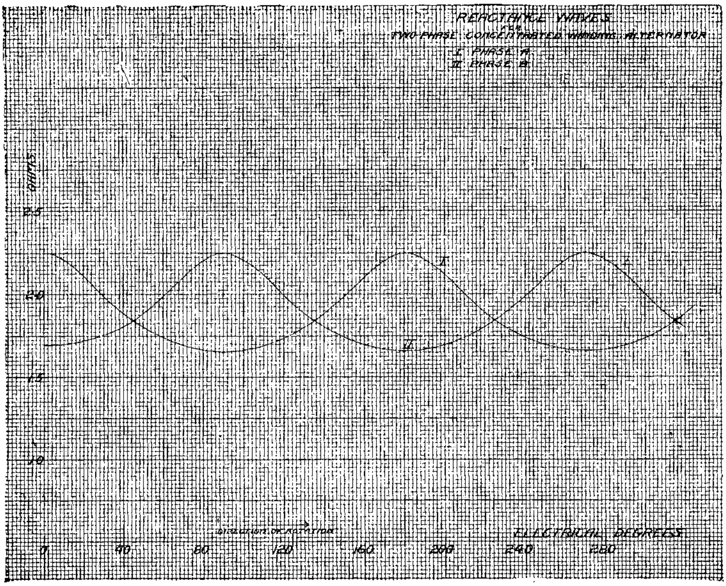
REACTANCE WAVES
TWO-PHASE CONCENTRATED WINDING ALTERNATOR
I PHASE A
II PHASE B
OHMS
2.5
2.0
1.5
1.0
ELECTRICAL DEGREES
0
40
80
120
160
200
240
280

Fig. 25.

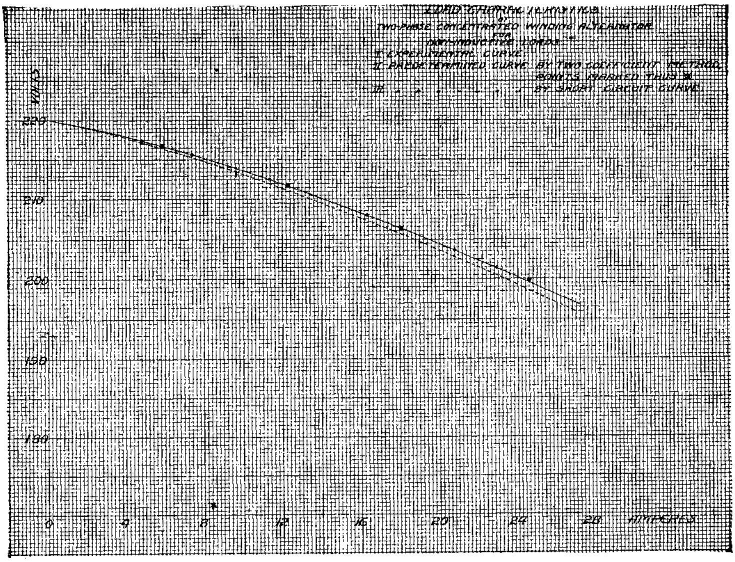
TWO-PHASE CONCENTRATED WINDING ALTERNATOR
I EXPERIMENTAL CURVE
BY SHORT CIRCUIT CURVE
VOLTS
220
210
200
190
180
0
4
8
12
16
20
24
28
AMPERES

Fig. 26.

inductor alternator of well-known type, having concentrated armature winding. Curve I, Fig. 24, is the saturation curve; Curve II, the short-circuit characteristic; and Curve III, the synchronous impedance.

At 3.4 amperes exciting current the synchronous impedance is 2.46 ohms, the effective resistance, as found by independent measurements, .588 ohms, and hence the demagnetizing component of the synchronous reactance at full load field excitation is 2.37 ohms. The ratio of the armature reactance with the inductors midway between two adjacent armature coils, to the armature reactance with the inductors opposite the armature coils, as obtained from reactance waves, Fig. 25, is 1.3. The cross-magnetizing component of the synchronous reactance is, therefore, $2.37 \times 1.3 = 3.1$ ohms.

Curve I, Fig. 26, is the observed external characteristic with non-inductive load. Curve II, the points of which are exactly on Curve I, is the load characteristic determined by the two reactance method. Curve III is determined by the short-circuit characteristic method with high field excitation, and since in this machine the stray field due to the cross-magnetizing turns is less than one-third greater than the field set up by the demagnetizing turns for equal current, it agrees fairly closely with the observed results.

My thanks are due to Prof. R. B. Owens, whose suggestions and assistance made possible the investigation, and to Mr. H. A. Burson, Demonstrator in Electrical Engineering, for much help, both in the drawing of the curves and in the calculations, and also to Messrs. Franklin, Maxwell and Jackson, graduates of 1902, for taking observations.

McGill University,
Montreal, Can.,
June 9, 1902,