PRINCE

Theory and Performance of a High Frequency Converter

Electrical Engineering

B. S.

1912
THEORY AND PERFORMANCE
OF A HIGH FREQUENCY CONVERTER

BY

DAVID CHANDLER PRINCE

THESIS
FOR THE
DEGREE OF BACHELOR OF SCIENCE
IN
ELECTRICAL ENGINEERING

COLLEGE OF ENGINEERING
UNIVERSITY OF ILLINOIS

1912
UNIVERSITY OF ILLINOIS

May 28, 1932

THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

DAVID CHANDLER PRINCE

ENTITLED THEORY AND PERFORMANCE

OF A HIGH FREQUENCY CONVERTER

IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF BACHELOR OF SCIENCE IN ELECTRICAL ENGINEERING

W. J. Schaller
Instructor in Charge

APPROVED: Eleftherg
HEAD OF DEPARTMENT OF ELECTRICAL ENGINEERING.
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General Electric High Frequency Converter.
(Magneto for speed indication attached.)
Theory and Performance of a High Frequency Converter.

I Introduction.

The new high frequency converter introduced by the General Electric Company operates by virtue of the fringing and tufting caused by the armature teeth as they pass across the field poles.

Embedded in the direct current field pole faces of an ordinary two pole motor there is a winding which has a pitch equal to the tooth pitch of the armature. As the latter revolves, alternate zones of a greater or lesser flux density succeed each other across the face of the pole. These lines of force cut the embedded high frequency winding inducing an E.M.F. which has a frequency equal to the product of armature teeth and revolutions per second, that is, equal to the slot frequency of the machine.

In order that this scheme may work effectively the pole shoe must be laminated, the air gap rather small and the tooth density low. This last requirement is the most important since the difference in reluctance between the path through the armature teeth and the path through the slot is entirely responsible for the electromotive force induced.

If the air gap were not small, the spread of flux from the teeth would practically neutralize the difference in reluctance between tooth and slot. The flux density in the field pole shoe varies at high frequency when the machine is in operation so that this shoe must be laminated in order to prevent excessive eddy current and hysteresis loss. Also the effect of any eddy currents would be to obstruct the
lines of force and prevent their penetrating a sufficient distance into the pole iron.

II General Theory and Development of the E.M.F. Formula.

In order to discuss the operation of this alternator quantitatively, it is necessary to make a number of approximations, the accuracy of which is rather problematical. The amount of tufting from the armature teeth must be estimated, while the damping action of the eddy currents and hysteresis action in the pole tips can only be guessed at.

Let the magneto motive force of the field be \( H' \). Then, referring to Fig.1., the density of the flux at \( b \) due to lines traveling from \( b \) to \( a \) will be

\[
\frac{H'}{ab} = \frac{H'}{\sqrt{h^2 + (5h)^2}}
\]

The density due to lines traveling from \( b \) to \( c \) will be

\[
\frac{H'}{ac} = \frac{H'}{h + d}
\]

Of course some flux will leave the iron at points between \( a \) and \( c \); on the other hand, most of the flux from \( a \) will tend to go straight across the gap to the iron of the pole shoe; so that, by considering only the lines from \( a \) and \( c \) a fair approximation should be obtained. Then the total density at \( b \) is

\[
\frac{H'}{\sqrt{h^2 + (5h)^2}} + \frac{H'}{h + d}
\]

The density over the tooth face will be

\[
\frac{H'}{h}
\]

and the field will have some somewhat the appearance of Fig.2. The E.M.F. wave produced by conductors cutting such a field is shown by the same figure. At any one time half of the
Fig. 2.

a) Flux Distribution.

b) E.M.F. Wave.
conductors are lying in the uniform field over the tooth faces. These conductors are, instantaneously, producing no E.M.F., as shown by the curve opposite this position. Midway between these conductors is the other set whose E.M.F. is shown by the red line on Fig. 2. The terminal voltage is the sum of these two. As the curve of flux density can have no square corners, the resulting E.M.F. wave should be nearly a sine wave.

The density over the tooth face is:
\[ \frac{\mathcal{E}}{h} = M \]

The minimum density at point 4, Fig. 2, is
\[ \frac{\mathcal{E}}{\sqrt{h^2 + (S^2)}} + \frac{h}{h + d} = 0 \]

Then the mean change of density which induces the E.M.F. is
\[ M - O \]

Let \( L \) be the length of the armature iron parallel to the shaft. The flux in the area \( e \), is
\[ e_x L M \]

That in \( e_2 \) is
\[ e_2 x L x \frac{M+O}{2} \]

The induced E.M.F. per conductor is
\[ E = \frac{2.2 \times 10^8 \times e \times L}{2} \left[ M - \frac{M+O}{2} \right] \]

Or, if \( N \) is the total number of active conductors which is equal to the total number of turns, the voltage for the whole winding is
\[ E = \frac{2.2 \times 10^8 \times N \times e \times L}{2} \left[ M - O \right] \]

The E.M.F. of the machine is now accounted for in terms of values which are readily found.
In the above formula the symbols represent:

- 2.22 the conversion factor between average and effective values.
- \( N \) the total number of turns on the machine.
- \( e \) the peripheral length of the stator tooth face.
- \( f \) the slot frequency i.e. R.P.S. x Teeth.
- \( L \) the iron length parallel to the shaft.

\[
M = \frac{H'}{h} = \frac{4\pi N_f I_f}{10h}
\]

where \( N_f I_f \) is the field ampere turns per pole.

\[
O = H' \left( \frac{1}{h^2 + (\frac{h}{2})^2} \frac{1}{h + d} \right)
\]

\[
H' = \frac{4\pi N_f I_f}{10}
\]

The parenthesis is defined above.

\[
\frac{M - O}{2} \text{ the mean flux variation}
\]

\[
\frac{E}{h} \text{ the total E.M.F. induced.}
\]

Let us now apply the formula to the case in hand and find whether or not the approximation is sufficiently close to be useful.

Net iron length

\( L \)

3.25"

Width of stator tooth

\( e \)

.15"

Width of armature tooth

\( s \)

.36"

Depth of armature slot

\( d \)

.65"

Field turns per pole

\( N_f \)

2750

High frequency turns per pole

\( N \)

36

Frequency

\( f \)

2000

Air gap

\( h \)

.037"

\[
\frac{M - O}{2} = \frac{4\pi N_f I_f}{2 \times 10} \left[ \frac{1}{h} - \left( \frac{1}{h^2 + (\frac{h}{2})^2} + \frac{1}{h + d} \right) \right]
\]

\[
= \frac{I_f \times 2750 \times 4\pi}{2 \times 10 \times 1.54} \left( \frac{1}{.037} - \frac{1}{.18} - \frac{1}{.687} \right)
\]

\[
E = \frac{2.22 \times 2000 \times 7.2 \times 2.75 \times 4\pi \times 20 \times 15 \times 3.25 \times 2.5}{2 \times 10 \times 10^8} = 130 I_f
\]
III Saturation Coefficient.

The curve from this equation is obviously a straight line, however, it follows the experimental E.M.F. curve as far as the knee of the latter. The bend in the experimental curve is, of course, due to saturation of the iron which has not been taken into account in the preceding derivation at all. It is a very simple matter to introduce a correction term in the form of a "saturation coefficient" which will cause the derived curve to follow the experimental curve over the entire working range of the machine with considerable accuracy. This saturation factor is derived from the direct current saturation curve for the machine operated as a generator as follows:— Taking the D.C. saturation curve of the machine as a measure of the saturation, the air gap density is to the density for no saturation as the ordinate of a point on the curve is to the ordinate of the corresponding point on a line tangent to the saturation curve through the origin; that is, $OA/OB$ (Fig. 3.) x density, considering no saturation, is equal to the density with saturation taken into account. Again $\frac{M-O}{2}$ will be found to vary with the same factor so that the induced E.M.F. $E$ varies as this factor squared or as $(OA/OB)^2$. Applying this factor gives a curve for $E$ which follows very closely the experimental curve of the machine. The final formula for the open circuit voltage is $E = 130 K^2 I_f$ where $K = OA/OB$ for the value of field current used. The D.C. saturation curve and the derived and experimental A.C. saturation curves are shown in Figs. 3-4.
IV E.M.F. Due to Armature Current.

It might seem at first thought that the armature current would directly effect the E.M.F. induced in the high frequency windings. A little consideration, however, will serve to show that this is not the case. A movement of the brush contact from one commutator bar to another might be expected to displace the armature reaction over a small angle and thus induce an E.M.F. in a stationary winding cut by the reaction flux. This effect may exist but is negligible for two reasons. The highest magnetomotive force of armature reaction is opposite the space between field poles. The conductors on the machine used do not lie in such a flux. Commutation with wide carbon brushes almost entirely eliminates any tendency toward oscillation of the armature field.

V Effect of Direct Current Armature Reaction on E.M.F.

The ways in which the direct current armature reaction might affect the high frequency E.M.F. are two. Distortion of the field flux might cause saturation of one pole tip, thus reducing the flux and hence the induced voltage. The back ampere turns of the armature due to brush lead might reduce the total flux and so lower the voltage of the high frequency winding.

The total conductors in the machine tested were 320 lying in forty slots. As the winding pitch was eighteen slots, the conductors in four slots did not have any effect on the armature reaction. This makes the conductors available for armature reaction 288 or 144 turns. However, the conductors
lying in slots under the pole face, only, are available for sending flux through the pole tips. There are twelve slots under a pole giving ninety six turns to send this flux. With a current of twelve amperes we have 1152 ampere turns in this position. With normal field current there are 3300 field ampere turns so that the cross magnetizing ampere turns are 33% of the total. This effect is present at the extremities of the pole tips. It decreases to zero at the center of the pole face so that the average result is about 16% in change of ampere turns. As actually operated the brush lead is about five degrees so that the demagnetizing action due to twelve amperes current in the armature is 173 ampere turns or about 5% of the total ampere turns. Adding the cross magnetizing, demagnetizing and field ampere turns vectorially gives a total of 3330 ampere turns acting upon the pole shoes. This is in excess of the normal ampere turns by only 1%. In making the addition, the demagnetizing ampere turns were subtracted directly from the normal field while the cross turns were added at right angles. Actual test data shows a variation of about this amount, at normal saturation, in the induced voltage, as shown in Fig. 6. Probably the averaging of the cross magnetizing action across the pole gives too low a result but the whole effect of the armature reaction is too small to warrant a more careful calculation.
VI Effect of Alternating Current Armature Reaction on Induced E.M.F.

Since there are twenty four slots across the face of one pole shoe, there are twenty four poles of alternate sign produced by the high frequency currents. The resultant of all the magnitomotive forces set up by these currents in the direction of the main field M.M.F. is zero or, at most, a very small alternating force which will have zero effect upon the main flux. For this reason there can be no alternating current armature reaction in the true sense of the word. The result of the high frequency currents is merely to produce screening, that is, they tend to prevent a rapid change of flux across the pole face. This action can best be dealt with by considering it as a leakage reactance. The leakage lines around the conductors, superimposed upon the main field of variable density produce a resultant field of more uniform density. The E.M.F. produced by the cutting of this field by the A.C. conductors is equivalent to the full E.M.F., considering no current, minus an E.M.F. of self induction produced by the leakage lines around the conductors. Under test the self inductive reactance, as found by passing alternating current through the windings and measuring the resistance and impedance drops, and the synchronous impedance, as obtained by a short circuit test, came out almost the same. This method of considering the reaction, then seems entirely justifiable. The regulation of the machine can be completely calculated as for a transmission line having the same resistance and reactance. The effect of leading and lagging currents, also, can be foretold.
VII Enumeration of Tests Run on Machine.

It did not seem practicable to separate the phenomena of the machine while operating it as a rotary; therefore, it was run as a generator to determine the various constants. In order to get the normal frequency of 2000 cycles, a speed of 3000 R.P.M. was required. To indicate the speed continuously during test a small magneto was coupled to the rotary shaft and the magneto current then led to a frequency meter. In this way the frequency of rotation could be read at all times.

Tests were run with the rotary belt driven to determine:
   a) The direct current saturation curve.
   b) The alternating current saturation curve.
   c) The synchronous impedance.
   d) The effect of armature current alone in producing E.M.F.
   e) The effect of direct current armature reaction on high frequency voltage.

Tests were run with the machine stationary to determine:
   f) The high frequency winding resistance.
   g) The high frequency winding impedance.

Great difficulty was experienced in running the rotary as a generator because of the high rotative speeds. Tests a, b, c, and d were finally run off at normal frequency by taping the pulley with friction tape and using the highest practicable belt tension. Test e could not be run at normal frequency because the load on the D.C. side proved too heavy for the belt friction.
VIII Index to Test Data and Curves.

Data for saturation curves— page 13.

Direct current saturation curve, Fig. 3.— 14.

Alternating current saturation curves,
  experimental and derived, Fig. 4.— 15.

Data for Synchronous impedance test.
  
  D.C. armature reaction test
  
  A.C. resistance and impedance— 16.

Synchronous impedance curve —— 17.

Armature reaction curves— 18.

Oscillograms of wave form of E.M.F.— 21.
### Saturation Curve Data.

<table>
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\( I_f \) is the field current in the D.C. saturation test.

\( E_{DC} \) is the E.M.F. from the D.C. saturation test.

\( E'_f \) is the E.M.F. found by interpolating from the curve between \( I_f \) and \( E_{DC} \).

\( E' \) is the E.M.F. found by interpolating from the tangent to the curve through the origin, Fig. 3.

\( K \) is equal to \( \frac{E'_f}{E_{DC}} \) or \( CA/CB \), Fig. 3.

\( I''_f \) and \( E''_{AC} \) are the coordinates of the experimental A.C. saturation curve.

\( I_f \) and \( E'_{AC} \) are the coordinates of the derived A.C. saturation curve.
Fig. 3. Direct Current Saturation Curve
Fig. 4.
Alternating Current Saturation Curve

- Curve plotted from experiment.
- Curve plotted from formula.

Field Amperes
Experimental Data.

### Synchronous Impedance

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### Direct Current Armature Reaction

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### Resistance and Impedance at 60 Cycles

Machine Stationary.

### Direct Current in Winding

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| Mean    | .0623   | Mean    | .0745   |
Fig. 5.
Short Circuitor Synchronous Impedance Test
Fig. 6.
Effect of Armature Reaction on High Frequency Voltage
# IX Winding Specifications

## Field Windings
- **Size of Wire**: 28.5 mils bare
- **Turns per Coil**: 2750
- **Resistance per Coil at 25°C**: 67.75 ohms

## Direct Current Armature
- **Size of Conductor**: .091 D.C.C.
- **Number of Slots**: 40
- **Conductors per Slot**: 8
- **Number of Coils**: 80
- **Turns per Coil**: 2
- **Number of Commutator Segments**: 20
- **Winding Pitch**: 18

## High Frequency Alternating Current Winding
- **Size of Conductor**: .1x.1 in.
- **Number of Slots per Pole**: 24
- **Conductors per Slot**: 3
- **Type of Winding**: Wave
- **Total Turns**: 72
- **Turns per Pole**: 36
Stamping Details of Armature and Pole Tip.

Pole Shoe.
24 slots per pole.

Armature Stamping.
40 slots.
Oscillogram of E.M.F. Wave.

Normal Frequency, 2000 Cycles.

Quarter Frequency, 500 Cycles.