THESIS

on

"The design, Construction, and Testing, of a Revolving Field, Three Phase Alternator".

Submitted to the Faculty
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Bachelor of Science

by

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INTRODUCTION

By way of preface, a few words may be said regarding the advantages of the revolving field type of machine.

The first in its favor and the chief reason for its existence, is that by passing the heavy armature current through permanent stationary contacts and only the small field current through sliding contacts, the brush loss is reduced to a negligible quantity. In this respect, there is a very desirable saving, both in cost of construction and operation.

The revolving field machine is also lighter and more compact, for the following reason. Other factors being equal, two machines of the same voltage must have the same diameter of air gap. In the A.T.B., the only material outside of the air gap is that composing the thin, wrought iron, magnetic circuit; and the light frame necessary to secure the armature. In the ordinary dynamo, however, the air gap diameter is increased by the length of a pole core and shoe, and by the thickness of a heavy cast iron or steel magnetic circuit. The saving in weight and space is evident.

Better field ventilation is also secured and the armature ventilation remains almost as good. This makes a cooler machine possible.
DESIGN.

I. SPECIFICATIONS.


II. ASSUMPTIONS.

Length of air gap - 1/8 inch.
Number of poles - 6.
This requires 1,200 R.P.M. to give a frequency of 60 cycles.

The peripheral velocity of the field is assumed from good practice to be 5,000 feet per minute.

Concentrated winding is chosen on account of its simplicity.

Cast steel is selected for the hub, magnet cores, and pole shoes, because its high permeability allows of smaller dimensions, thus giving more room for the magnet coils, slip-rings, etc.

The machine, being for laboratory use, will be excited from a 110 volt, direct current line, with a rheostat in the field circuit for voltage regulation.

III. CALCULATIONS.

(1) Diameter of field.

Diameter of field = 5,000/(1,200 x 3.1416) = 1.32 feet = 15.9 inches. Take 16" as field diameter.

(2) Dimensions of pole shoe and flux per pole.

By Steinmetz's Rule: L = B (K. V. A.)/d_f.
In this formula, \( L = \) length of armature parallel to shaft, \( B \) is an empirical factor, \( d_f \) is the diameter of the field in inches. \( B \) is taken as 4.

Substituting:

\[
L = \frac{4 \times 12}{16} = 3"
\]

Since this would entail too high a flux density in the field cores, \( L \) is increased to 4.5".

The pole pitch is equal to:

\[
\frac{16 \times 3.1416}{6} = 8.38"
\]

For convenience, the dimensions of the shoe are taken as 4.5" X 4.5" which gives an area of 20.25 Sq. in. Assume an air-gap density of 20,200. This is also the density on the face of the pole shoe.

Then the flux per pole:

\[
\phi = 20\frac{1}{3} \times 20,200 = 409,000 \text{ maxwells.}
\]

(3) Number of Inductors per phase and per slot.

Watts per phase is equal to:

\[
12,000/3 = 4,000.
\]

Volts from slip-ring to neutral equals:

\[
\frac{125}{(3)^{\frac{1}{2}}} = 72.
\]

Since the cutting of \( 10^8 \) lines of force per second induces an average and not an effective volt, we find the average voltage corresponding to the required effective voltage per phase, and then proceed as in the direct current design.
Thus:-

Average volts per phase = $\frac{72}{1.11} = 65$.

Let $N_c$ = the number of inductors per phase.

Then :-

$$(6 \times 409,000 \times 20 \times N_c) \times 10^8 = 65.00,$$

since each inductor swings past all of the 6 poles carrying 409,000 maxwells, twenty times per second.

Solving for $N_c$:-

$N_c = 132.5$

Since for a concentrated winding, there is one slot per phase per pole, we have:-

No. of Ind./slot = $\frac{132.5}{6} = 22\frac{1}{2}$.

This is changed to 21 to give a wider and shallower slot. This in turn changes $N_c$ which now equals 126.

(4) Size of Armature Conductor.

The armature conductor must be selected with a view to the heating effect of the current. Otherwise, the temperature will rise to a dangerous degree and it will be impossible to run the machine at rated load for any length of time.

Assuming for calculation that the radial depth of armature core is 3", and allowing for $\frac{3}{4}$" ventilating duct in the middle, we have the sum of all the end radiating surfaces is equal to:-

$$3 \times 4 \times 19 \times 3.1416 = 238 \text{ sq. in.}$$

Cylindrical radiating surface is equal to:-

$$16 \times 3.1416 \times 4 = 200 \text{ sq. in.}$$
Hence the total radiating surface available for dissipating energy:= 200 + 238 = 438 sq. in.

Current per phase is equal to:

\[ \frac{4,000}{72} = 55.5 \text{ ampere.} \]

To find the approximate value of the specific temperature increase, we may consider the armature to be revolving at an internal peripheral velocity of 5,000 ft./min. From Wiener (p.127), we find 40°C as specific temperature increase for this velocity. Assume a temperature rise in armature of 35°C.

Then the total allowable energy loss in armature is equal to:

\[ \frac{(448 \times 35)}{40} = 390 \text{ watts or 130 per phase.} \]

Consider all of this loss as ohmic.

Then the resistance of one phase is equal to:

\[ \frac{130}{55^2} = 0.042 \text{ ohms.} \]

Approximate length of one coil is equal to:

\[ \frac{16 \times \sqrt{3}}{2} + \frac{1416}{\sqrt{3}} \approx 1.8 \text{ ft.} \]

Approximate length of wire per phase is equal to:

\[ \frac{(126/2)1.8}{113} = 113 \text{ ft.} \]

Specific resistance (ohms/ft.) required is equal to:

\[ \frac{0.042}{113} = 0.000372 \text{ ohms per foot.} \]

Since all of the allowances for safety have been liberal, we may take #6 B.& S. wire having a specific resistance of 0.000393 for the armature conductor.
Arrangement of Coils in Slots.
(5) Size of slots.

Lay the wires in the slot three wide and seven deep as shown in the figure.

Diameter of #6 wire D.C.C. equals 0.18\".

Allow 15 mils for side and bottom insulation and 30 mils for taping.

Then the width of slot is equal to:

\[ 3 \times 0.18 + 2 \times 0.015 + 2 \times 0.030 = 0.63". \]

For convenience, take the width of slot as 5/8\".

In figuring the depths, we proceed in like manner, but add an additional 3/16\" for a cover piece.

Then the depth is equal to:

\[ 7 \times 0.18 + 2 \times 0.015 + 2 \times 0.030 + 0.2 = 1.55". \]

(6) Dimensioning of Armature.

The flux from each pole divides upon entering the armature. Hence, the flux through the armature core is equal to:

\[ \frac{409,000}{2} = 204,000 \text{ maxwells.} \]

Length of laminated iron = 4\".

Equivalent length of solid iron = 0.9 \times 4 = 3.6\".
Assume an armature density of 40,000 lines per square inch. Then the net area of section of the magnetic circuit in the armature is equal to:

\[
\frac{204,000}{40,000} = 5.11 \text{ sq.in.}
\]

and the radial depth is equal to:

\[
\frac{5.11}{3.6} = 1.42'' .
\]

This is the radial depth exclusive of the teeth.

(7) Calculation of probable leakage factor.

Since only a portion of the flux generated by the field coil passes through the armature, it is necessary to determine upon a leakage factor before proceeding with the magnet coil calculations. The leakage factor, however, varies with the size and type of machine. The most accurate method of procedure is to assume a leakage factor, calculate the total flux through the magnetic circuit, and then find the sizes of the various parts of the field. Once the dimensions are obtained, the probable leakage factor may be calculated as follows.

The leakage factor may be defined as the ratio of useful flux to total flux. But since any flux is equal to the M.M.F. producing it times the permeance of its path, and knowing that the M.M.F. which generates the useful flux is identical with that which produces all stray fluxes, we may cancel this factor in both numerator and denominator and take simply the ratio of total to useful permeance.
The reluctances of the useful flux path are in series, so the useful permeance is equal to the reciprocal of the sum of its various reluctances, i.e., the reciprocal of the sum of the air-gap reluctance, reluctance of the circuit through the teeth, and the reluctance of the solid armature core.

The principle of magnetic potential as defined by Wiener is used; namely, any two points in a magnetic circuit which are separated by two magnet cores in series are considered as having unit difference of potential, and when only one core intervenes the potential is one-half. These potentials, when multiplied by their respective permeances, give a quantity which, though not equal to the flux, is a true measure of the flux between any two surfaces.

Take 1.3 as trial leakage factor. Then flux through field is equal to:-

\[ 1.3 \times 409,000 = 532,000 \text{ maxwells}. \]

The following dimensions are now assumed.

- Length of pole piece \( \ldots \ldots \ldots \frac{1}{2}'' \)
- Length of pole core \( \ldots \ldots \ldots 3\frac{1}{4}'' \)
- Length of field hub parallel to shaft 5''

Assume a density of 70,000 lines per sq.in. in the field core. Then area of core section is equal to:

\[ \frac{532,000}{70,000} = 7.6 \text{ Sq.in.} \]
For convenience, take the core section as 3 by 2½ inches. This gives an area of 7¾ sq.in. and a corresponding density of 71,000 lines per sq.in..

Radial depth of hub is equal to:

\[ 8 - \frac{1}{2} - 3\frac{1}{4} = 4\frac{1}{4}'' \]

From Wiener, p.186, the diameters of the shaft are taken as follows: 3" for the bearing portion and 2½" for the part carrying the field. This gives 4½ - 1\frac{1}{8} or 3\frac{1}{8}" as the radial depth of hub to the outside of the shaft, and the cross-sectional area is equal to:

\[ 3\frac{1}{4} \times 5 = 15(5/8) \text{ sq.in.} \]

Since the magnetic circuit bifurcates at the bottom of each core, we have only one-half the flux per pole passing through the hub circuit. Hence the density in the hub is equal to:

\[ \frac{532,000}{(3 \times 15.625)} = 17,000 \text{ lines per sq.in.} \]

Pre-calculation of magnetic leakage.

(a) Permeance of armature magnetic circuit.

Density in tooth is equal to:

\[ \frac{50.3}{39} \times 20,200 = 26,000 \text{ lines per sq.in.} \]

Permeability at 26,000 for wrought iron = \( \frac{2,920}{1000} \)

Density in armature body = 40,000.

Permeability at 40,000 for wrought iron = 2,900.

Width one-half pole face = 2½".

Width of one slot = 0.625".

Circumferential width of magnetic circuit in the teeth is equal to:-
The net length of laminated iron parallel to the shaft is 3.6". Then the area of the path in the teeth is equal to:

\[ 1.62 \times 3.6 = 5.84 \text{ sq.in.} \]

Length of two teeth = 3.1".

Therefore, the reluctance of the path in the teeth is equal to:

\[ \frac{3.1}{(5.84 \times 2,920)} = 0.000182. \]

In the armature core body, the length = 8", and the area = 5.11 sq. in. Hence, the reluctance of the path in the solid core is equal to:

\[ \frac{8}{(5.11 \times 2,900)} = 0.00054. \]

The area of one-half of the pole shoe is equal to:

\[ 4 \times 2 \frac{1}{4} = 10.13 \text{ sq.in.} \]

The length of two air gaps is \( \frac{1}{4} \)". Hence, the reluctance of the path through the gap is equal to:

\[ \frac{0.25}{(10.13 \times 1)} = 0.0247. \]

Then the total reluctance is equal to:

\[ 0.0247 + 0.00054 + 0.000182 = 0.0254. \]

The total useful permeance is equal to:

\[ \frac{1}{0.0254} = 39.4. \]

**Stray Permeances.**

1. a to a.

Length = \( 5\frac{1}{4} + \frac{1}{2}(3.1416) = 6.83". \)
Diagram for Calculating Permeances.
\[
\text{Area}_a = \frac{1}{2} \left\{ \frac{2 \tan \left( \frac{21/2}{71/2} \right)}{360} \right\} (3.1416) 8^2 - \frac{1}{2} (2.35) 7^{1/2} = 0.76 \text{ sq.in.}
\]

Permeance = \(0.76 / (6.82)^2\) = 0.223.

2. \text{b to b.}

Permeance = \((0.125 \times 4.5) / 3.625 = 0.155\).

3. \text{b to c'.}

\[
\text{Permeance} = \frac{1}{2} \left\{ \frac{2}{3.4} \right\} = 0.45.
\]

4. \text{a to d'.}

Permeance = \(\frac{1}{2} (0.76/3.5)^4 = 0.435\).

5. \text{c to c.}

\[
\text{Permeance} = (\frac{3}{4} \times 4^{1/2}) / 4^{1/2} = 0.794.
\]

6. \text{c to c'.}

\[
\text{Permeance} = \frac{1}{2} \left\{ \frac{2}{3^{1/2}} \right\} = 0.9.
\]

7. \text{d to d.}

\[
\text{Permeance} = (1.5/6^{1/2})^2 = 0.48.
\]

8. \text{d to d'.}

\[
\text{Permeance} = \frac{1}{2} ((1 \times 1^{1/2}) / 3^{1/2}) = 1.16.
\]

9. \text{e to e.}

\[
\text{Permeance} = \frac{1}{2} \left\{ \frac{3^{1/2} \times 2^{1/2}}{3^{1/2}} \right\} = 1.16.
\]
10. e to c'.

\[ \text{Permeance} = \frac{\left(\frac{3}{2} \times \frac{3}{4} + 2\frac{1}{2}\right)}{2} \times 2 = 1.33. \]

11. f to f.

\[ \text{Permeance} = \frac{\left(\frac{1}{2} \times \frac{3}{4}\right)}{5.35} \times 2 = 0.91. \]

12. f to d'.

\[ \text{Permeance} = \frac{\left(\frac{1}{2} \times 3\frac{1}{2} + 2\right)}{2} \times 4 = 1.375. \]

Total permeance = 39.4 + 0.223 + 0.435 + 0.155 + 0.45 + 0.794 + 0.9 + 0.48 + 0.96 + 1.16 + 1.33 + 0.91 + 1.375 = 8.12.

Leakage factor = 39.4 / (39.4 + 8.12) = 1.2+.

The assumed leakage factor, 1.3, is enough larger to allow for any uncalculated leakage so it is used in the remainder of the field computations.

The specific magnetizing forces (ampere turns per inch of length) for the various parts and for their corresponding densities are taken from Wiener (p. 336). These values multiplied by their respective length give the ampere turns for the different portions of the field circuit, and their sum is the total field excitation needed to give the specified voltage at no load.
To tabulate;

<table>
<thead>
<tr>
<th>Part.</th>
<th>Density</th>
<th>Substance</th>
<th>Length</th>
<th>AT/in.</th>
<th>Total AT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arm. core.</td>
<td>40,000</td>
<td>W.I.</td>
<td>11.</td>
<td>7</td>
<td>77</td>
</tr>
<tr>
<td>Teeth.</td>
<td>27,000</td>
<td>W.I.</td>
<td>3.1</td>
<td>4.9</td>
<td>15</td>
</tr>
<tr>
<td>Air gaps.</td>
<td>20,200</td>
<td>Air.</td>
<td>.25</td>
<td>6256.</td>
<td>1566</td>
</tr>
<tr>
<td>Pole shoes.</td>
<td>26,000</td>
<td>C.S.</td>
<td>1.</td>
<td>6.</td>
<td>6</td>
</tr>
<tr>
<td>Pole cores.</td>
<td>71,000</td>
<td>C.S.</td>
<td>6.5</td>
<td>23.5</td>
<td>153</td>
</tr>
<tr>
<td>Hub circuit.</td>
<td>16,900</td>
<td>C.S.</td>
<td>4.3</td>
<td>4.5</td>
<td>19</td>
</tr>
</tbody>
</table>

No load excitation for two cores ............... 1836.

Total for machine = 3 X 1836 = 5508.

To this must be added the back ampere turns which are found as follows. Two slots at the most will be between adjacent pole shoe corners at any time. Hence, the back ampere turns are equal to:--

\[ 2 \times 21 \times 55 = 23,000 \] per pole.

The total back ampere turns for the machine are equal to:--

\[ 2300 \times 6 = 13,800. \]

The total full load excitation, neglecting I.R. drop, is equal to:--

\[ 13,800 + 5,500 = 19,300. \]

Let 75% of 110 = 80 be the terminal field voltage. Then, \[ 80 = 19,300 \times 1.17 \times x \] where 1.17 is the approximate length in feet of one turn of wire on the armature, and \( x \) is the specific resistance (ohms/ft.) required. Solving, \( x = 0.0035 \).
#16 B. & S. wire is selected for the field winding. It has a specific resistance of 0.004 ohms/ft. and gives 90 volts across field terminals.

To find the Number of Turns per Core.

From Wiener, one watt per sq.in. in a magnet coil traveling at 75 ft. pr. sec., gives an approximate temperature rise of 30° C. The total core radiating surface is equal to:

\[ 6 \times 2 \times 3 \frac{1}{4} (3 + 2\frac{1}{2}) = 214 \text{ sq.in.} \]

Hence, 214 watts loss may be allowed in the field winding. Then,

\[ 214 = \frac{R^2}{R} = 8,100/R, \text{ whence } R = 38 \text{ ohms.} \]

Let \( T \) = the number of turns on the field. Then,

\[ T \times 1.17 \times 0.004 = 38 \text{ whence } T = 8,130. \]

The number of turns per pole = 8,130/6 = 1,355.

#16 B. & S. winds 268 turns per sq.in. and so the square inches of winding space required is equal to:

\[ 1355/268 = 5 \text{ sq.in.} \]

By carefully utilizing all the winding space around each core 5 sq.in. of cross-section of winding space may be obtained without much difficulty, and the design in this respect is satisfactory.

Pre-calculation of Losses.

Calculation of Hysteresis.

The volume of iron in the armature = 0.345 cu.ft.
The density raised to the 1.6 power is equal to:

\[ 40,000^{1.6} = 25,150,000 \text{ maxwells}. \]

From Wiener (p.111),

\[ P_h = 5 \times 25,150,000 \times 60 \times 0.345 \times 10^{-7} = 260 \text{ watts}. \]

**Calculation of Eddy Current Loss.**

From Wiener, p.120,

\[ P_e = e \times f^2 \times M. \]

Where \( M \) is the mass in cubic feet, \( f \) is the frequency, and \( e \) is the hysteretic constant. \( e = 0.046 \) for a density of 40,000 and for laminations 20 mils thick. Then,

\[ P_e = 0.046 \times 3600 \times 0.345 = 57 \text{ watts}. \]

**Calculation of efficiency.**

Allowing 4\% for friction and windage we have,

Friction loss = 0.04 \times 12,000 = 480 watts.

\( I^2R \) in the armature = 420 watts.

\( I^2R \) in the field = 214 watts.

Iron losses = 317 watts.

Total losses = 1430 watts.

The commercial efficiency is then equal to:

\[ 12,000/(12,000 + 1,430) = 89\frac{1}{2}\%. \]

The electrical efficiency is equal to:

\[ 12,000/(12,000 + 634) = 95\%. \]

The efficiency of conversion is equal to:

\[ 89\frac{1}{2}/95 = 94.3\%. \]
Rotating Field with Spools

Field Shaft
~ End Elevation of Frame and Bed Plate ~