The Design and Construction of a Potential Regulator of the Induction Type

A Thesis Submitted to

The Faculty of

MICHIGAN AGRICULTURAL COLLEGE

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Candidates for the Degree of

Bachelor of Science

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PREFACE

Due to the fact that the fire of March 5, 1916, destroyed the Engineering Hall and much of the Electrical apparatus in it, the need of new apparatus was keenly felt. Among the foremost needs was that of a potential regulator giving a large range and great flexibility for alternating current and voltage control. Since a regulator of the induction type would satisfy this need, and as a search among the ruins of the fire disclosed the stator of an induction motor and armature punchings of suitable size, it was decided that the design and construction of such a regulator could be made the subject of a thesis. The authors felt that the development of this subject would be an excellent opportunity to further their knowledge in design and construction as well as to provide the Department Engineering with a piece of much needed apparatus; we therefore asked to be assigned this subject.

The authors desire to acknowledge their appreciation for the suggestions and services of Professor J. A. Polson and Foremen of the various shops.

The descriptive matter is intended to give a discussion of the principles of potential regulators of the induction type, and, if studied in conjunction with the references given, should enable the reader to understand the operation of this particular machine.

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SECTION I.

GENERAL DISCUSSION OF THE THEORY
OF
INDUCTION REGULATORS

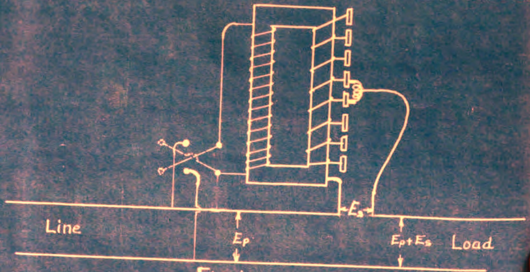


Fig. 1

Commercially the voltage regulator is used in connection with the most economical size of wire to compensate any excessive voltage drop in transmitting power. It has been found that by installing a wire large enough to keep the voltage regulation at the service point within the limits, without the use of a regulator as mentioned above, the cost of the line would be excessive and in some cases prohibitive. In the laboratory, however, conditions are much different, there the regulator will be used only in maintaining either a constant voltage or to obtain the variable voltages needed in performing experiments.

There are two types of regulators, the compensating and the induction type. The former is shown in fig.1, where a transformer is used with its primary "PP" connected across the feeder line thru the reversing switch "a", and taps brot out from various points along its low voltage secondary coil "SS" to contact blocks on a switch "b_1b_2", over which slides the contact arm "c". This arm is connected to the feeder in such a manner that the voltage E_s, induced in the secondary coil between the points "b_1" and "c", is either added to or subtracted from the primary voltage, depending upon the position of the reversing switch "a".

Thus, if E_s' be the maximum voltage that can be obtained from the secondary with "c" moved up to "b_2",

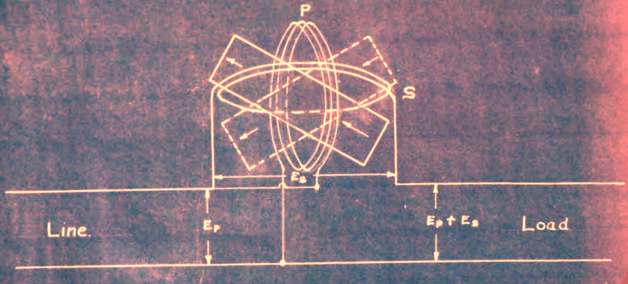
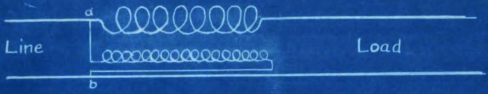


Fig 2.

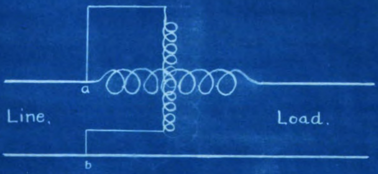
the limits of the voltage are, $E_p \pm E_s^1$, depending upon which way the switch "a" is thrown.

The induction type of regulator insures a smooth variation in the secondary voltage as no contacts or definite tapping points are used to obtain the required voltage control.

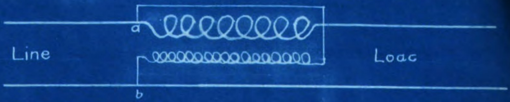
The operating principle is shown in Fig. 3. A primary coil "PP" is connected across the bus bars or the line as in the compensator type and produces alternating flux in the iron core "c". This flux induces an e.m.f. in a secondary coil "SS" (which is placed at an angle of 90 degrees with "PP") provided the core "CC" does not happen to lie in the same plane with this secondary coil. In the latter event, no e.m.f. is induced in "SS" because the flux is parallel to the turns of "SS" and does not link with them. The secondary coil is in series with the transmission line or feeder. If the core "cc" is turned in one direction thru the secondary coil "SS", the e.m.f. induced therein is in the same direction as the primary e.m.f. and the voltage on the load side of the regulator is greater than the voltage on the generator side by an amount equal to the voltage E_s, induced in the secondary coil. If the core "cc" be turned slightly so as to incline oppositely with respect to the plane "SS", while still approximately perpendicular to "PP" as before, the e.m.f. E_s induced in "SS" is in the opposite direction, and the feeder voltage becomes $(E_p - E_s)$. With E_p and primary



Primary and Secondary Connections
Single Phase
Fig 4



Primary and Secondary Connections
Single Phase
Fig 5



Primary and Secondary Connections
Single Phase
Fig 6

current growing in direction shown by the arrows, it is as if we thrust a north pole (shown by the arrows on "cc") upward thru "SS" in the first case, and downward in the second case. In either case E_s is in phase with E_p, or at 180 electrical degrees to it, and the load voltage ($E_p \pm E_s$) is the arithmetical sum or difference of E_p and E_s depending upon the angular position of "cc". The value of E_s will vary with this angle, as more or less of the primary flux is made to link with the secondary.

The following theory of the induction potential regulator is given in order that one not familiar with its operation, but having some knowledge of alternating current phenomena, may be able to follow our design of this machine.

The explanation of the regulator is that of a transformer having its secondary in series with some apparatus such as a motor (see fig. 4, 5, and 6), at which the voltage is to be held constant or is to be varied as desired. The primary is connected across the line and is so constructed that it can be rotated thru 180 electrical degrees with respect to the secondary. The magnetic circuits are so arranged that at an extreme position the voltage of the secondary is added to that of the line. At the other extreme, the secondary induced voltage is in the opposite direction thus reducing the service voltage (fig. 5). All possible values of voltage between these limits

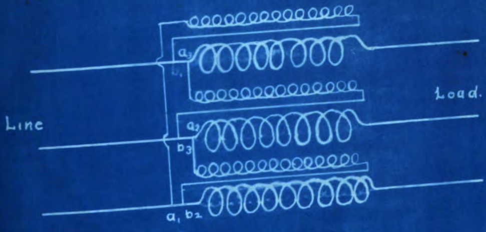


Fig. 6. (a)
Primary and Secondary Connections
3 Phase

Fig 6 (b)

are obtainable by different positions of the primary. It should be understood that in this type of single phase regulator the magnitude as well as the direction of the voltage is varied by the rotation of the primary. It will be noticed that at one position, the point of zero induced voltage, the secondary coil, being unaffected by the primary, would set up a field of its own, thus acting as a choke coil. This tendency is overcome by placing a short circuited coil on the primary core at right angles to the main winding. In the neutral position this short circuited winding serves the purpose of the short circuited secondary of a series transformer.

The polyphase regulator differs from the single phase in that the induced voltage in the secondary winding is constant and the regulation is affected by shifting the phase relation between the line voltage and the regulator voltage. The primary of the regulator is wound with as many circuits as there are phases and produces a rotating magnetic flux of practically constant value. The number of secondary circuits on the stationary core is the same as the primary and the voltage induced in them is of a constant value, as the magnetizing flux generated by the primary windings is constant. The regulation of the line voltage is obtained as follows: When the regulator is in the position of maximum boost, the line "AB" (fig. 6b represents the normal bus bar voltage, BC the regulator voltage and "AC" the resultant feeder voltage. When the

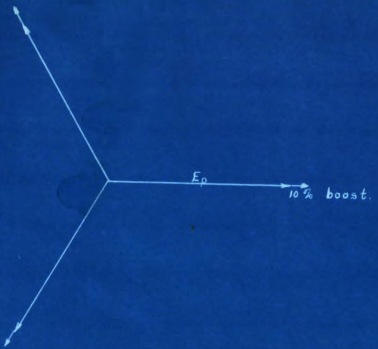


Fig. 7

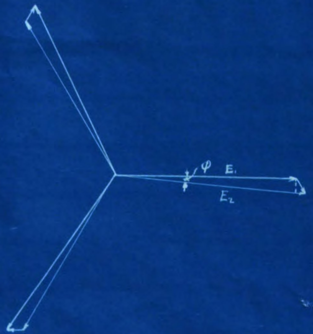


Fig. 8.

core is moved 180 degrees from this position we have the condition of maximum buck and a minimum voltage on the out going feeder, the regulator voltage is then represented by BD, and the resultant feeder voltage by AD. Intermediate compensating voltages may be obtained by rotating the moving element to any desired point. For example, by rotating the primary thru the angle "DBE", the resultant voltage may be made equal to "AE".

The three phase regulator is much the same as the single phase regulator except that the e.m.f. added has a constant value, but since it is added vectorially the vector sum may be anything from $E_p + E_s$, to $E_p - E_s$.

Where the induced e.m.f. is in phase with the original e.m.f. we have a 10% boost as in fig. 7. In the case where the rotor has moved thru 60 electrical degrees as in fig. 8, the resultant e.m.f. is thrown a little out of phase with the current. The exact angle is Θ.

$$\begin{aligned} \Theta &= \mathrm{Tan}^{-1}\ .0866\ E_1/E_1 \\ &= \mathrm{Tan}^{-1}\ .0866 \\ &= 4^\circ\ 57' \end{aligned}$$

In this case

$$\begin{aligned} E_2 &= E_1/\mathrm{Cos}\ 4^\circ\ 57' + .5 \times .1\ E_1 \\ &= E_1\ (.9962 + .05\ E_1) \\ &= 1.005\ E_1 + .05\ E_1 \\ &= 1.055\ E_1 \quad \text{or a } 5.5\% \text{ boost} \end{aligned}$$

When the primary has been rotated thru 120

Fig. 9

Fig. 10.

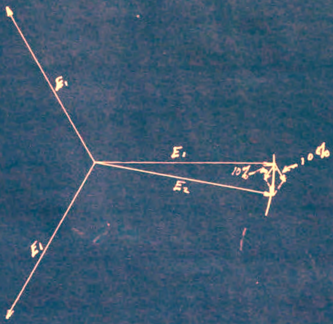


Fig. 11

electrical degrees from the neutral position making it add the e.m.f. to one which is 340 electrical degrees out of phase, it will buck or boost. In fig. 9,

$$E_2 = E_1 - .05\ E_1 / \text{Cos}\ \theta$$

$$\theta = \text{Tan}^{-1}\ .0866/.95$$

$$= \text{Tan}^{-1}\ .0912$$

$$= 5^{\circ}\ 10'$$

$$E_2 = .95/.995\ E_1$$

$$= .955\ E_1$$ then we have

$$1 - .955 = .045$$ or 4.5% buck

The e.m.f. has the greatest phase displacement when $E_2 = E_1$. Or when both cut the circle as in fig. 10. The third side of this triangle is then equal to .1 E_1. By the Cosine Law:

$$(.01\ E_1)^2 = E_1^2 + E_2^2 - 2 \times E_1 \times E_2 \times \text{Cos}\ \theta$$ but

$$E_1 = E_2$$ then

$$(.01\ E_1)^2 = 2 \times E_1^2 - 2 \times E_1^2 \times \text{Cos}\ \theta$$ and then

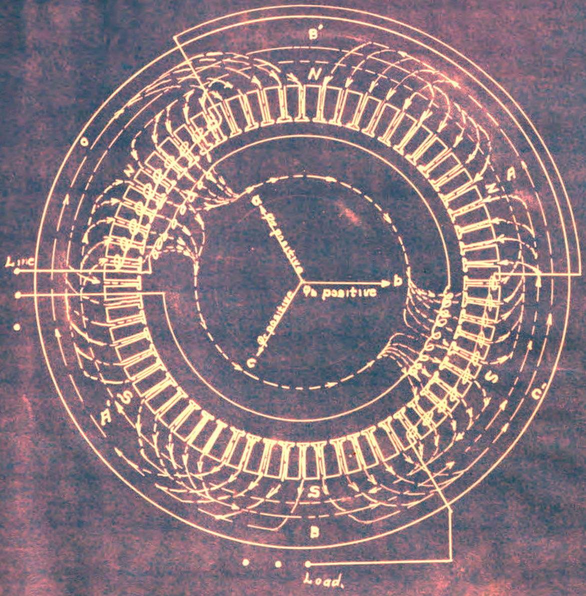
$$.01 = 2 - 2\ \text{Cos}\ \theta$$

$$2\ \text{Cos}\ \theta = 1.99$$

$$\text{Cos}\ \theta = .995$$

$$\theta = 5^{\circ}\ 45'$$ Which gives a power factor of .995 under the worst conditions, which is a very good performance.

The core positions are not arbitrarily chosen, but gradually swing the vectors thru the complete angle and may be stopped at any point. As in fig. 11 suppose



B'
N
A
N
Line
b
φ_b positive
φ_a positive
φ_c positive
c
S
C
A'
S
S
B
Load.

Fig. 12.

the primary is rotated thru 90 electrical degrees then two e.m.f.'s are added, one at 60 electrical degrees and one at 120 electrical degrees, and their resultant falls at 90 degrees to E_1 and is equal

$$E_1 = (E_1^2 + .01\ E_1^2)^{\frac{1}{2}} \quad \text{and}$$

$$= (1.01\ E_1^2)^{\frac{1}{2}} \quad \text{and}$$

$$= 1.004\ E_1$$

and has very little effect in buck or boost, while the phase angle is $5^\circ\ 45'$.

The stator of the induction regulator, which is the secondary in this case, is precisely like that of an induction motor and may have one or more pairs of poles per phase. In this case one pair is used making six poles in all. Instead of having alternately, north and south poles as in the generator or synchronous machine, we have (1) a maximum north, (2) a decreasing north, (3) an increasing south, (4) a maximum south, (5) a decreasing south, and (6) an increasing north. The pole which is a maximum north one instant, becomes a decreasing north the next, and the one which at the first instant was a decreasing north passes thru zero and becomes an increasing south,and so on, (each flux revolves around the stator) making a revolving field.

When the stator is wound for three phases the analysis of magnetic relations is shown in fig. 12, 13, and 14. When current flows in phase A only, in positive

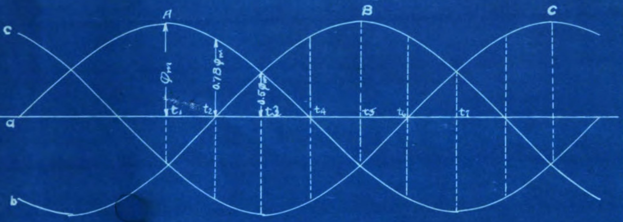


Fig. 13.

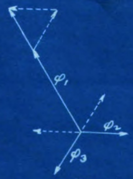


Fig. 14.

direction (A toward A'), the flux is in direction indicated by "Oa" in fig. 12; similarly, positive direction of current in phases B and C produce flux in the direction "Ob" and "Oc" respectively. At the instant t_1, we see from fig. 13 that phases A, B and C produce fluxes respectively as follows (the currents or component fluxes A, B, C of fig. 13 being 120° apart:

a = ϕ_m (in positive direction, as indicated by "Oa" in fig. 12)

b = ϕ_m sin 30° = .5 ϕ (in negative direction, or opposite to "Ob" in fig. 12)

c = ϕ_m sin 30° = .5 ϕ_m (in negative direction, or opposite to "Oc" in fig. 12)

In fig. 14 (t_1), these three component fluxes "a", "b", "c" are combined in proper relative values and directions, producing the resultant total flux R = 1.5ϕ_m, where ϕ is the flux that would be produced by the maximum instantaneous value of the current in any one phase alone. At the instant t_2, 1/12 period or 30 electrical degrees later, the "a" component has decreased to the value ϕ_m Cos 30° or .87ϕ_m, but is still in its positive direction (along "Oa" in fig. 12), the "b" component has reduced to zero; the "c" component has increased in value to ϕ_m sin 60° or .87 ϕ_m and still is negative, or in direction opposite to "Oc" in fig. 12. The resultant total flux at this instant is shown as "R" in fig. 14 t_2, and is seen to have moved 30° from its

previous position in fig. 14, t_1, 1/12 period earlier, altho it has exactly the same numerical strength, namely, 1.5 ϕ_m. Between the instants t_1 and t_4 the elapsed time is $\frac{1}{4}$ period, and we see from fig. 14 that meanwhile the position of the resultant flux "R" has progressed steadily at uniform angular velocity thru 90 mechanical degrees, maintaining meanwhile a constant strength represented by 1.5 ϕ_m.

SECTION II

DESIGN

DIVISIONS OF SECTION II

Part A --- General Conditions

Part B --- Calculations

Part C --- Construction

Part D --- Testing

Part E --- Conclusions

PART A

GENERAL CONDITIONS

This regulator is to be of a three phase induction type and will in all probability be used for laboratory experiments. The primary voltage is to be 220 volts alternating current of 60 cycles. The secondary voltage is taken as a plus or minus one-tenth of the primary voltage, or ± 22 volts.

The dimensions of the stator frame and rotor laminations reduced the possibilities of design by limiting the number of turns of wire that may be used.

The data concerning the given parts, that of the stator and of the rotor laminations, is given as follows:

STATOR

Number of slots 62

Minimum width of slots .... .3125 inches

Depth of slot .... 1.0 inches

Width of slot slit .... .094 inches

Length of slot ....6.312 inches

Minimum width of teeth .... .219 inches

Cross section area of one tooth ...... 1.38 sq. in.

Cross section area of frame ....13.4 sq. in.

(Magnetic conditions per pole)

Length of path ....23.60 inches

Cross-sectional area of path......... 13.40 sq. in.

Length of path in the stator teeth .... 3.00 inches

Cross-sectional area of teeth per pole 13.80 sq. in.

*Length of path in air gap (assumed).... .031 inches

Area of air gap per pole .... 30.00 sq. in.

Number of slots per pole 10.00

ROTOR

Number of slots 45.0

Width of the slots .... .406 inches

Depth of the slots .... .838 inches

Length of the slot .... 6.312 inches

Cross-sectional area of the frame .... 11.66 inches

Minimum width of the teeth .... .365 inches

Cross-sectional area per tooth .... 1.675 sq. in.

(Rotor Magnetic Conditions per pole)

Length of path in the rotor teeth .... 1.656 inches

Cross-sectional area of teeth per pole 13.56 sq. in.

Length of path in frame .... 13.55 inches

Cross-sectional area of path in frame 11.66 sq. in.

*I.C.S. Book 45B, Section 30, Page 40.

PART B

CALCULATIONS

Notation Used in the Calculations

ϕ_m = Maximum flux

E_p = Primary voltage

n_p = Number of Primary turns

w = 2 x 3.14 x f

f = Frequency, cycles per second

E_s = Secondary voltage

π = 3.14

n_s = Number of Secondary turns

A = Sectional area of the Rotor Frame

B = Magnetic Flux

u = Magnetic Permeability

NI = Ampere turns

l = Length of magnetic circuit with the proper subscript to the certain magnetic circuit.

I = Current in amperes

P_e = Eddy current loss

P_h = Hysteresis current loss

t = Thickness of one lamina in inches

r = Resistance in ohms

ML = Mean length of turn

AT = Ampere turns per inch of length

C = Coefficient for leakage

θ = Phase angle

CALCULATIONS

From the conditions given in Part A, the primary voltage is 220 volts.

The secondary voltage is assumed as 22 volts or E_s = 220 $\pm$ 22 volts.

The frequency is 60 cycles.

The cross-sectional area of the stator frame is given as 13.40 square inches, and let it be A_s.

The flux density in the stator frame was assumed as 30,000 lines per square inch.

Then in this case ϕ is equal to A_sB and is equal to 30,000 x 13.40 = 402,000 lines in the stator frame.

From Sheldon, Mason and Hausman

$$\phi_m = \frac{10^8 \sqrt{2} \times E_p}{n_p \times w}$$

When substituting n_s for n_p

$$n_s = \frac{10^8 \sqrt{3}\ E_s}{w \times \phi_m} = \frac{10^8 \sqrt{3}\ E_s}{3\pi f \times \phi_m} = \frac{10^8 \times E_s}{\sqrt{3}\pi f \quad \phi_m}$$

Therefore $n_s = \dfrac{10^8 \quad E_s}{\sqrt{3}\pi f \quad \phi_m}$

Substituting the above values $n_s = \dfrac{100{,}000{,}000 \times 32}{\sqrt{3} \times 3.14 \times 60 \times 402{,}000}$

$= 30.04$ turns

$\dfrac{n_p}{n_s} = \dfrac{330}{33}$, or $n_p = 300$ turns

From "Dynamo Electric Machines" by Weiner (page 339), also from I.C.S., Book 45B (page 40)

$AT_{air} = AT_{gap}$ per inch of length, and

$AT_{iron} = at_{rotor} + at_{stator} + at_{rotor}$ teeth $+ at_{stator}$ teeth

The flux density assumed for the stator frame is 30,000 lines per square inch, then

$at_{stator} = 5.5$ ampere turns per inch of length.

30,000 x 13.4 = 402,000 lines or total flux in the stator frame.

402,000 x .66 = 268,000 lines or total flux in the stator teeth.

In three phase work the flux (total) in the frame is 1.5 times that in single phase magnetic paths as discussed in Section I.
This condition is also discussed in Timbie and Higbie, Second Course, page 443.

$$\frac{268,000}{13.8} = 19,400 \text{ lines per square inch in stator teeth.}$$

$at_{stator\ teeth}$ = 3.5 ampere turns per inch of length.

From "Dynamo-Electric Machines" by S.P.Thompson, page 682.

C = Coefficient of leakage

= c x g/t where

c = A constant depending upon the ratio of pole pitch to core length.

g = Length of the air gap in inches.

t = Pole pitch in inches.

c = 17 (From tables page 682)

g = .031

t = 17.7

$$C = \frac{17 \times .031}{17.7} = 3\% \text{ of the flux is lost by leakage.}$$

100 - 3.5 = 97% of the rotor flux is used in the stator.

$$\frac{268,000 \times 100}{97.} = 276,000 \text{ lines or total flux in rotor teeth and the air gap.}$$

$$\frac{276,000}{20} = 13,800 \text{ lines per square inch in the air gap.}$$

$at_{air\ gap} = 13,800 \times .3133 = 4330$ ampere turns per inch of length.

$$\frac{276,000}{12.58} = 22,000 \text{ lines per square inch in the rotor teeth.}$$

$at_{rotor\ teeth} = 3.9$ ampere turns per inch of length.

$276,000 \times 1.5 = 414,000$ lines or total flux in rotor frame.

$$\frac{408,000}{11.66} = 35,500 \text{ lines per square inch in the rotor frame.}$$

$at_{rotor\ frame} = 6.6$ ampere turns per inch of length.

$$\text{Total AT} = at_{stator\ frame} \times l_1 + at_{stator\ teeth} \times l_2 + at_{rotor\ teeth} \times l_3 + at_{rotor\ frame} \times l_4 + at_{air} \times l_5.$$

Total ampere turns stator frame	5.5 x 23.6 =	129.8
Total ampere turns stator teeth	3.5 x 2.0 =	7.0
Total ampere turns air gap	4330.0 x .031 =	134.0
Total ampere turns rotor teeth	3.9 x 1.65 =	6.4
Total ampere turns rotor frame	6.6 x 12.5 =	82.5
Grand Total Ampere turns		359.7

$\frac{359.7}{300}$ = 1.8 amperes at full feeder load not including leakage and losses.

From "Dynamo Electric Machinery" by S. P. Thompson page 685, the Magnetizing Current is:

$$I_m = .23 \times B_{max} \times g\ (1 + i) \times \frac{P}{z}$$ where

B_{max} = Maximum lines of flux per square inch.

g = Width of the air gap.

i = Iron reluctance allowance

P = Number of pairs of poles per phase.

z = Turns per pole.

$$I_m = .23 \times 13,600 \times .031 \times 1.15 \times \frac{1}{100}$$

$$= 1.16 \text{ amperes}$$

From "Dynamo Electric Machinery" by S. P. Thompson (page 685), the Hysteresis Current is:

$$I_h = \frac{I_m}{3E_1}$$ where

E_1 = 220 volts

$$I_h = \frac{1.16}{3 \times 220} = .0017 \text{ amperes.}$$

The no load current from the above reference is:

$$I_o = \sqrt{I_m^2 + I_h^2} = 1.17 \text{ amperes.}$$

The total primary current equals 1.8 + 1.17 = 2.97 amps.

The size of wires selected are based upon a carrying capacity of 1000 amperes per square inch cross-sectional area.

From a B and S wire table a #14 wire was selected as the correct size to use for the primary circuit.

Assuming a maximum feeder load, as a 10 h.p. motor three phase, the current per phase thru the secondary is:

$$\frac{10 \times 746}{198 \times 3} = 21.5 \text{ amperes.}$$

From a B and S wire table a #6 wire was selected as the correct size to use for the secondary circuit.

The length of an average turn of the stator winding (around one tooth) is 15.5 inches, then

$$20 \times 15.5 = 310 \text{ inches}$$

$$\frac{310}{12} = 25.9 \text{ feet of wire used per phase and}$$

$$25.9 \times 3 = 78 \text{ feet of wire needed for the three phases.}$$

The length of an average turn of the rotor winding (around one tooth) is 15.0 inches, then

$$200 \times 15 = 3000 \text{ inches}$$

$$\frac{3000}{12} = 250 \text{ feet of wire used per phase and}$$

$$250 \times 3 = 750 \text{ feet of wire needed for the three phases.}$$

The following table is a list of the Specifications recommended by the authors:

	Size of Wire	Amperes Used	No. Lbs. Wire
Primary Circuit	14	2.97	10
Secondary Circuit	6	21.50	8

For the primary wiring use distributed windings. This will require 15 form wound coils of 26 wires each and 30 coils of 27 wires each.

In wiring a 7 slot pole, use 2 coils of 26 wires each and 5 coils of 27 wires each. Winding an 8 slot pole, use 3 coils of 26 wires each and 5 coils of 27 wires each.

For the secondary wiring use a distributed winding. This will require 60 coils of 1 wire each.

Wiring diagrams will be found in the pocket in the back cover of this book.

PART C

CONSTRUCTION

Drawings of the mechanical details may be found in the pocket on the back cover of this book.

PART D

TESTING

The authors had hoped to complete the construction of the regulator and run the following tests to ascertain the correctness of their design:

I. No load test to determine -

  a. Hysteresis current.

  b. Magnetizing current.

  c. Copper losses.

  d. Other losses.

II. Full load heat test.

III. Efficiency test.

PART E

CONCLUSIONS

Pocket has: 2 Suppls.