The Design and Construction of a Constant Current Transformer.

A Thesis Submitted to

The Faculty of

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THESIS

PREFACE.

The object of designing and building a constant current transformer of the floating coil type was not only to further the designer's knowledge of transformer construction, but to leave a piece of apparatus to be used in experimental work in the Department of Electrical Engineering at the Michigan Agricultural College.

The calculations found herein were worked out from standard formulae. The design being the ideas and knowledge of the writer on capability of working, strength of apparatus, economical construction, and appearance. Any of the points are susceptible of demonstration, thus doing away with all methods leading to complexity.

While the working qualities of any apparatus approaches a standard that is desirable only after much experimenting and designing, and this being only the second one of its kind ever built, probably could be made more efficient after the final test has been performed. The idea in mind of designing and constructing of such apparatus, however, was to form a starting point whereby others may profit by that which has been done and, thus assisted, be able to construct one more efficient in its performances.

H.J.H.

This thesis, a design of an experimental constant current transformer of the floating coil type, was selected with an object in view to construct and test the transformer and note how the test results agreed with the theoretical results. The latter being derived from the theoretical formulae on transformers.

A constant current transformer is in some respects like an ordinary constant potential transformer of the shell type. The latter having a constant voltage impressed on the primary and a constant voltage taken from the secondary. This is not so with the former, while it is like the latter in regard to the primary, it differs in the secondary having a varying voltage and constant current. This result may be obtained in various ways, but in this design it is accomplished by varying the distance between the primary and secondary coils as the load changes. This element of design makes it impossible to have the coils interleaved, as it is in many of the constant potential transformers, but that they must be separate and distinct. Another difference is that there must be a low magnetical reluctance or more leakage in the core and that it must be of greater length to allow for the separation of the coils.

In general, there are two types of constant current transformers, first with floating coils, which has both coils movable, second with semi-floating coils, which has but one coil movable (usually the secondary). The latter type is the one selected for designed due to its simpler mechanical construction, and also because smaller sizes of this transformer are more often of this type. The movable secondary coil is suspended from an arm which is pivoted near its middle point. From the outer end of the other arm is suspended a weight which counterbalances the secondary coil.

The theory of the operation of this transformer is as follows. First considering the primary coil, with a constant E. M. F. impressed upon this coil the total magnetism within the coil will be practically constant at all times. The strength of the field surrounding the secondary coil will govern the E. M. F. generated by that coil. In all types of stationary transformers the secondary current is nearly opposite in time-phase relation to the primary current, so that there is not only a repulsive thrust between the two coils but there exists a tendency for the magnetic lines from the primary coil to be forced out into space without penetrating the secondary coil. In the ordinary potential transformer this repelling action is prevented from producing motion between the two coils by the rigid mechanical construction, while the proximity of the two coils limits the magnetic leakage. In the constant current transformer, however, the repelling action is utilized to adjust the secondary coil into a position relative to the amount of electrical pressure used; when the secondary coil is at a great distance from the primary the paths for the leakage lines are increased and the lines which interlink the secondary are less than when the coils are nearly together. The counter weight mechanically attached to the movable coil is so adjusted that, when the desired current exists in the secondary coil (independent in its position along the core), the weight is just balanced. An increase in current increases the repulsion and causes the coils to move further apart. With any current less than normal, the repelling force diminishes and the secondary coil falls nearer to the primary, thereby restoring the current to normal.

This type of transformer is used to produce constant current for series nitrogen filled lamp circuits which are being used very extensively in street illumination.

This transformer, when completed, most likely will be used for laboratory experiments and as the one which was in the laboratory was destroyed in the recent burning of the Engineering Building, it was necessary to use the frequency and voltage that would be supplied to the laboratory. Therefore some of the specifications were fixed. First, the available primary voltage was 220. The frequency was 60 cycles. The secondary load was to be a number of four amps series mazda lamps giving a secondary output of about 600 watts, when all the lamps were burning.

Knowing this, the most logical order of procedure was as follows:

1. Calculations and design.
2. Construction of mechanical, electrical and magnetic parts.
3. Assembly.
4. Testing.
5. Reports.

ELECTRICAL AND MAGNETIC DESIGN.

The design involved an investigation of what had previously been done along this line. It was found that there were no books which treated of constant current transformer design. However, with some information of the theoretical results by a General Electric designer and the results of the former thesis by Messrs. Lester and Fox, it was decided to use some of their ideas. Their finished piece of apparatus showed that the leakage was far too small as was the limits of motion between coils. This was overcome by decreasing the size of core and increasing the number of turns in the coils. It was also decided to design the transformer as a constant potential transformer of lengthened magnetic circuit, which it would be if the two coils were in contact at all times. As it was impossible to get the required constants for the transformer iron it was necessary to use those and the method outlined in Sheldon, Mason, & Hausmann's, "Alternating Current Machinery," (page 155 to 160).

Notation Used in the Design.

ϕ_m = Maximum flux.

E_p = Primary Voltage.

n_p = Number of primary turns.

w = $2 \pi f$

f = Frequency, cycles per second.

E_s = Secondary voltage.

π = 3.1416

n_s = Number of sedondary turns.

A = Sectional area of core.

B = Magnetic flux density.

u = Magnetic permeability.

NI = Ampere turns.

l = Length of magnetic circuit.

R = $\frac{l}{uA}$ = Magnetic reluctance.

I = Current in amperes.

P_e = Eddy current power.

K = A constant depending upon the resistivity of the iron.

V = Volume of core in cm^3.

P_h = Hysteresis power.

η = The hysteresis constant of the iron.

t = Thickness of one lamina in cm.

r = Resistance in ohms.

ML = Mean length of turn.

Caloulations.

The size of core decided upon was as shown in the blue print No. 1.

The delivered secondary voltage at full load $= \frac{600}{4}$ $= 150$.

5 volts were approximated as the secondary voltage drop.

Therefore $E_s = 150 + 5 = 155$ volts induced in the secondary.

B was taken as 80,000 lines per square inch.

$f = 60$ cycles.

$A = 1.75 \times 1.75 = 3.06$ sq. in.

$\phi = A \times B = 3.06 \times 80,000 = 245,000$.

$l = 31$ inches.

From Sheldon, Mason & Hausman

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

from which $n_p = \dfrac{10^8 \sqrt{2}\, E_p}{w \times \phi_m} = \dfrac{10^8 \sqrt{2}\, E_p}{2\pi f \times \phi_m} = \dfrac{10^8\, E_p}{\sqrt{2}\, \pi f \phi_m}$

Therefore $n_s = \dfrac{10^8\, E_s}{\sqrt{2}\, \pi f \phi_m}$

Substituting above values $n_s = \dfrac{100,000,000 \times 155}{2 \times 3.1416 \times 60 \times 245,000} = 237$

$$\frac{n_p}{n_s} = \frac{320}{155} \quad \text{or } n_p = 348$$

From "Dynamo Electric Machines," by Wiener, (page 336) u for annealed wrought iron (B= 80,000).

$NI_{air} = 0.3133 \times 80,000 = 25,064$.

$NI_{iron} = 31.2$

$$u = \frac{NI_{air}}{NI_{iron}} = \frac{25,064}{31.2} = 803.3$$

$$R = \frac{l}{uA} = \frac{31}{803.3 \times 3.06 \times (2.54)^2} = 0.00196$$

$$I_{magnetizing} = \frac{10\ R\phi_m}{4\sqrt{2}\,\pi\, n_p} = \frac{10 \times 0.00196 \times 245,000}{4 \times \sqrt{2} \times 3.1416 \times 348}$$

$$= 0.775 \text{ amperes.}$$

$$P_e = Kvf^2t^2B_m^2$$

$$K = \frac{1.6}{(10)^{11}}$$

$$V = 1.75 \times 54.25 \times (2.54)^3 = 1555$$

$$f^2 = 3600$$

$$t^2 = (0.015 \times 2.54)^2 = 0.00145$$

$$B_m^2 = \left(\frac{80,000}{2.54}\right)^2 = 154,000,000$$

$$P_e = \frac{1.6 \times 1555 \times 3600 \times 0.00145 \times 154,000,000}{100,000,000}$$

$$= 20.00 \text{ watts.}$$

$$P_h = \frac{V \times f \times \eta \times B^{1.6}}{(10)^7}$$

$$= \frac{1555 \times 60 \times 0.0021 \times (12,400)^{1.6}}{10,000,000} = 69.5 \text{ watts.}$$

$20 + 69.5 = 89.5$ watts, iron loss.

Primary current required to supply iron loss $= \frac{89.50}{220}$

$= 0.4068$ amperes.

$$I_{exciting} = \sqrt{(0.775)^2 + (0.4068)^2} = 0.875 \text{ amperes.}$$

Exciting $NI_p = 0.875 \times 348 = 304$ turns.

From the blue print No. 1, ML of coil = 15 inches.

Length of wire in Primary Coil $= \frac{348 \times 15}{12} = 435$ feet.

Length of wire in Secondary Coil $= \frac{237 \times 15}{12} = 297$ feet.

A current density of approximately 1000 amperes per sq. in. was chosen as being allowable.

Area of secondary wire = $\frac{4}{1000}$ = 0.004 sq. in.

No. 13 wire, D.C.C., B and S gauge, has an area of 0.0041 sq. in. so this size was used.

4 ÷ 0.0041 = 983 amperes per sq. in. density in secondary.

N_s = 237.

Resistance of No. 13 wire per foot at 60°C. = 0.002277 ohms.

Secondary resistance = 297 x 0.002277 = 0.675 ohms.

I_sR_s = 4 x 0.675 = 2.70 secondary voltage drop.

$I_s^2R_s$ = $(4)^2$ x 0.675 = 10.8 watts, secondary copper loss.

600.00	watts delivered power.
89.50	watts iron loss.
10.80	watts secondary copper loss.
14.70	watts assumed as primary copper loss.
715.00	watts primary supplied power.

Assuming a power factor of 85% we have $\frac{715}{220 \times 0.85}$ = 3.82 primary amperes.

Assuming a current density of 1000 amperes per sq. in. as before.

Area of primary wire $\frac{3.82}{1000}$ = 0.00382 sq. in.

Using a No. 13 wire (area 0.0041) the current density is $\frac{3.82}{0.0041}$ = 932 amperes per sq. in. density in primary.

N_p = 438.

Primary resistance = 438 x 0.002277 = 0.9905 ohms.

$I_pR_p = 3.82 \times 0.9905 = 3.79$ primary voltage drop.

$I_p^2R_p = (3.82)^2 \times 0.9905 = 14.75$ watts, primary copper loss.

This value is nearly what was assumed.

Adding again

$$\begin{array}{r} 600.00 \\ 89.50 \\ 10.8 \\ \underline{14.75} \\ 715.05 \text{ watts.} \end{array}$$

$$\frac{600}{715.05} = 0.840 = 84\% \text{ Efficiency.}$$

Diameter of No. 13 double cotton covered wire = 0.084 inches.

Using a coil 15 wires wide and 23 wires high gives a coil for the primary of 345 turns.

Using a coil 15 wires wide and 16 wires high gives a coil for the secondary of 240 turns.

Size of primary coil in cross section:

$23 \times 0.084 = 1.932$ inches high.

$15 \times 0.084 = 1.260$ inches wide.

Size of secondary coil in cross section:

$16 \times 0.084 = 1.344$ inches high.

$15 \times 0.084 = 1.260$ inches wide.

This gives 12 - (1.932 1.344) = 8.724 inches of motion for secondary coil to travel in.

Results of Calculations.

Delivered secondary voltage at full load = 150.

Number of turns in the primary = 348.

Number of turns in the secondary = 237.

$u = 803.3$

$R = 0.00196$.

$I_{magnetizing} = 0.775$ amperes.

$P_e = 20.00$ watts.

$P_h = 69.50$ watts.

Total iron loss = 89.5 watts.

Exciting current = 0.875 amperes.

Exciting ampere turns = 304

Primary current density = 932 amperes per sq. in.

Secondary current density = 983 amperes per sq. in.

Size of wire No. 13, D.C.C., B and S gauge (both coils).

Primary Resistance = 0.9905 ohms.

Secondary Resistance = 0.675 ohms.

Secondary IR drop = 2.70 volts.

Sedondary copper loss = 10.8 watts.

Length of wire in primary coil = 435 feet.

Length of wire in secondary coil = 297 feet.

Power supplied to primary at full load = 715.05 watts.

Primary current at full load = 3.82 amperes.

Primary IR drop = 3.79 volts.

Efficiency of transformer at full load = 84%.

Power factor at full load assumed at 85%.

Primary coil:

23 layers, 15 turns per layer.

1.932 inches high, 1.26 inches wide.

Secondary coil:

16 layers, 15 turns per layer.

1.344 inches high, 1.26 inches wide.

Mechanical Design.

The mechanical requirements were as follows.

A suitable base including an arrangement for clamping lower ends of laminations.

A cap or top containing a like clamping arrangement for the upper ends of the laminations and also furnishing a bearing for the weight and coil arms.

A suitable means of mechanically connecting base and cap in a rigid and substantial manner.

Suitable weight and coil arms providing sufficient lift and means for adjusting the weight effect.

A means of clamping or holding the primary coil in a stationary position and clamps for the movable or secondary coil to which supporting cords could be attached.

Provision for a dash pot.

Binding posts.

In the mechanical design the writer first considered the most natural material for base and cap, that of cast iron. On a more thorough investigation of strength, adaptability, economical construction, and appearance the frame was built up out of angle-iron, channel iron, and mild steel bars. The dimensions of the frame being determined by the core, appearance, and strength necessary. This design clamps the core in correct position as well as sustaining the arms and bearing.

It was decided to make the weight and coil arms of wrought iron, rather than of cast iron, because of their peculiar shape, and also because of greater strength of the former material and the fact that the arcs had to have a groove turned in them. The bearing for these arms had necessarily to be of a kind that would not have much friction, for it was not expected that the repulsive action between coils would be very great and it was desirable to have the transformer as sensitive to changes in load as possible. There were two types of bearings which would fulfill the requirements. First, ball bearings; second, knife edges. The ball bearings were chosen because with this type a greater swing of arc was allowable, which made it possible to make the coil and weight arms shorter than would have been the case had knife adges been used, and still maintain the same lift. Another reason for this selection was that the adjustment of the bearings would not be easily disturbed as would knife edges. The weight arm was designed to be pivoted as shown to allow for increasing, decreasing or keeping the weight effect constant as the coils separated.

It was decided to wedge the primary coil in position

as the only tendency to move would be downward.

Little can be said of the secondary coil supports, dash pot and binding posts as their size and shape were largely a matter of decision of the writer.

In all of the construction the ordinary shop methods were used. It might be mentioned that the laminations were cut with tinner's snips, and the coils had to be wound in the lathe.

Pocket has: 3 Blueprints

111
893
THS
Blueprint 1