THESIS

A Cathode Ray Power Diagram Indicator.

by

Fred Lloyd Poole.

Department of Electrical Engineering.

THROOP COLLEGE OF TECHNOLOGY.

Pasadena, California.

1917

Sixteen years ago Professor Harris J. Ryan began to look for a feasable electrostatic power diagram indicator. This search resulted: first, in a cathode ray alternating current wave indicator; and second, in a power diagram indicator for high-tension circuits, also using the cathode ray tube. These were presented to the electrical fraternity in 1903 and 1911 respectively.

Its commercial value has since been recognized by the electrical industry; the most notable example of this is the active study and use of it in the General Electric Research Laboratories. It has become an essential instrument for any laboratory in which electrical research is conducted.

The cathode ray alternating current wave indicator represents the only available means for studying: first, transcient phenomena in transmission lines and electrical machinery due to switching or to short circuits; second, lightning disturbances involving frequencies of hundreds of thousands of cycles per second; and third, commutation problems in direct current machinery involving frequencies that vary between 800 and 8000 cycles per second.

The cathode ray power diagram indicator represents the best available means for studying the insulator problem, which is one of the most important problems confronting the Electrical Engineer today. It will measure losses in lines, cables, oils and other insulators with the exceptional accuracy of 0.03 watts at 10,000 volts and with an almost absolute sensitiveness to the wave forms involved.

The accompanying diagram shows the construction and dimensions of the cathode ray tube. A direct current potential of about 25000 volts applied between C and A, with C negative, causes a stream of negative electrical particles or electrons to travel at the rate of 50×10^8 cm. per sec. from the cathode C down the slender portion of the tube. Part of these electrons are intercepted by the disc, D, and part pass through the hole in this disc, continue in a straight line, strike the fluorescent screen, S, and cause a luminous spot to appear upon the screen. This stream of electrons is composed of negative electric charges and may therefore be deflected electrostatically. This stream of electric charges constitutes, in reality, an electric current and may therefore be deflected electromagnetically. These two facts form the fundamental facts upon which the practical application of the cathode ray tube is based. It is interesting to note that we have here a pointer without appreciable inertia.

The design of the power diagram indicator, in the form of problems, will be taken up first. A supplementary design for the oscillograph will be added thereto.

Problem one. Deflect the pencil of rays, which passes through the hole in D, proportional to the line voltage of 10000 volts or over.

The adopted solution for this problem is electrostatic deflection since it embodies three desirable qualities -- accuracy, facility in manipulation, and ease of construction -- only one of which can be obtained electromagnetically.

The accuracy of this method depends upon there being no lateral displacement of the pencil of rays, while under the influence of the electrostatic field. This is true because the presence of the glass tube practically eliminates the possibility of a uniform electrostatic field. If the ray occupies the same position in the field at all times the deflection will be accurately proportional to the voltage. Therefore electrostatic plates one centimeter long will be used to influence the rays precedent to any other influence.

Based upon Franklin and McNutt, Electricity and Magnetism, the following are calculations to determine the voltage necessary on the electrostatic deflecting plates.

The path of deflection is a parabola expressed by the equation

$$d = \frac{D^2 ge}{2mv^2}$$

d = distance deflected by the field.

D = distance along path under the electrical influence.

$\frac{g}{m}$ = ratio of charge to mass of the electron = 1800×10^4

e = volts per centimeter in the electrostatic field.

v = velocity of the electron = 50×10^8 maximum in cathode ray tubes.

Differentiating

$$\frac{dd}{dD} = \frac{2Dge}{2mv^2} = \frac{Dge}{mv^2} = \frac{1 \times 1800 \times 10^4 \times e}{50^2 \times 10^{16}}$$

From the dimensions of the tube it will be seen that when this differential reaches the value

$$\frac{4.75}{2 \times 15} = 0.158$$

the deflection will be sufficient to strike the edge of the screen. Hence

$$e = \frac{0.158 \times 2500 \times 10^{16}}{1 \times 1800 \times 10^4} = 2.32 \times 10^{11} \text{ abvolts per cm.}$$

$$= 2320 \text{ volts per cm.}$$

Distance between plates is 1.5 inches.

The voltage between plates will therefore be $1.5 \times 2.54 \times 2320 = 8850$ max or 6250 eff. sine wave volts.

This method of deflection is easiest to operate in this case because electrostatic voltage transformation is easier than any other transformation when the voltages are as high as these in question.

Its ease of construction over that of electromagnetic coils is evident.

Problem two. Deflect the pencil of rays at right angles to and subsequent to the above deflection and proportional to the current of .000005 effective-sine-wave amperes or more. This current is of the order encountered in insulator testing.

Electromagnetic deflection is the only solution for this problem, since the electrostatic deflection is eliminated for the reason previously given and the electromagnetic field is not distorted by the presence of glass.

Coils for this purpose may be 11 cm. outside diameter and six centimeters inside diameter without seriously affecting the accuracy of the electrostatic deflection.

Based upon Electricity and Magnetism by Franklin and McNutt, the following calculations determine the number of gauses needed for full deflection of the cathode ray pencil.

Diameter of the screen, 4.75 inches.

Distance from point of deflection to screen is 12 in.

The rays are deflected in a circular path expressed by the formula

$$d = \frac{gD^2h}{2mv}$$

In which h = gauses

and other notation is the same as in the electrostatic formula.

Differentiating with respect to D

$$\frac{dd}{dD} = \frac{Dgh}{mv} = \frac{6 \times 1800 \times 10^4 \times h}{50 \times 10^8}$$

since 6 cm. is assumed to be the effective diameter of the coil.

From the dimensions of the tube it is evident that when this reaches $\frac{4.75}{2 \times 12} = 0.198$ the ray pencil will strike the edge of the screen.

Hence the maximum flux will be

$$h = \frac{50 \times 10^8 \times 0.198}{6 \times 1800 \times 10^4} = 9.2 \text{ gauses.}$$

From Electricity and Magnetism by Franklin and McNutt the number of turns necessary may be calculated by the following formula

$$h = \frac{2\pi ZI}{r}$$

in which h = gauses.

Z = turns

I = abamperes

r = radius in centimeters.

$$9.2 = \frac{2\pi Z \times .000005 \times \sqrt{2} \times 10^{-1}}{3}$$

$$Z = \frac{9.2 \times 3 \times 10}{2\pi \times .00000707} = 62000 \text{ turns. Use } 60000 \text{ turns.}$$

Construct twelve coils each containing 5000 turns. This will give a large range of series, parallel, and series parallel combinations so that a good deflection may be obtained for a large range of currents.

Problem three. Eliminate the possibility of stray electrostatic or electromagnetic fields influencing the pencil or rays.

This may be easily solved by surrounding that portion of the tube with a ferrous metallic sheath.

Problem four. Arrange for the most satisfactory operation of the cathode ray tube.

First in inportance is to produce a unidirectional electromagnetic field whose intensity is variable at will and whose axis is coincident with that of the cathode ray tube. Its purpose is to focus the cathode rays upon the disc, D, with the result that the cathode ray pencil is the most intense possible and consequently the luminous spot is the brightest possible. The bright spot is especially desirable for photographic work.

The action of this field may be explained as follows: Due to mutual repulsion the electrons of the cathode discharge tend to diverge, but any motion of an electron radial to the axis of the tube is at right angles to the electromagnetic field. The result is a force which starts the electron in a spiral path. The circular component of this spiral path also cuts the electromagnetic field at right angles, which results in a force upon the electron forcing it towards the axis of the tube i.e., bringing it to a focus.

Both the strength of the field and the location of the coil to produce it have been determined experimentally. A coil having 2500 ampere turns and located in the plane of the cathode gives the best results. Its diameter should be about 7 inches.

Explore for the most satisfactory wire to use by trying several sizes.

#18 B.& S. wire requires 45 volts when carrying 5 amperes at 65° C. This voltage is too low for consideration.

#20 B.& S. wire requires 66 volts when carrying 3.15 amperes at 65° C. This voltage is within usable limits. Its weight should be 5.8 pounds.

#21 B.& S. wire requires 83 volts when carrying

2.5 amperes at 65° C. This voltage is usable. The weight of wire would be 5.9 pounds.

#22 B.& S. wire requires 104.5 volts when carrying 1.98 amperes at 65° C. This voltage is near the upper limit but is usable. The weight of wire would be 5.87 pounds.

Since #20 B.& S. wire gives the minimum weight and the voltage can easily be reduced to 66 volts by a series rheostat, this size wire was used.

The mounting of this coil requires special attention since the field it produces is combined with that of the earth to produce a resultant field. To secure easy adjustment to compensate for the earth's affect the coil should be pivoted upon two perpendicular axes.

Second in importance is to minimize the effect of the electrostatic field resulting from the high voltage direct current necessary to excite the cathode ray tube.

To do this the exciting voltage will be brought to the cathode ray tube by an armored cable, the center conductor being used for the negative and the grounded armor being used for the positive. The field is thus limited to the space between the center conductor and its armor.

Third in importance is to insure the cathode ray tube against damage from flash overs by interposing

100,000 ohms resistance between the cathode of the cathode ray tube and the negative conductor of the cable. The most satisfactory resistances for this purpose are lightning arrester resistance rods. Water in a tube may be used if proper precautions are taken to allow gasses to escape.

Fourth in importance is to prevent corona discharge between the two terminals of the cathode ray tube and thus eliminate the consequent intermittant action of the cathode rays.

Two methods are combined to accomplish this. The radius of curvature of the terminals is increased; and that end of the tube, including the terminals, is covered with a thick jacket of paraffin wax.

Problem five. Provision must be made for recording the indications on the screen, S. There should be two ways possible; photographic recording and recording by hand tracing. Visual observation should be possible at all times so that rapidly changing indications may be watched and photographed at the critical moment.

A lens placed coaxial with the cathode ray tube, as shown in the diagram, is used to throw an image of the figure on the screen, S, upon a photographic plate or film.

A concave mirror placed next to the lens, as shown in the diagram, is used to throw an image of the figure on the screen, upon a ground glass where the figure may be observed and tracings made.

A conversion of the power-diagram indicator to an oscillograph, for either voltage or current, presents just one problem. Some method must be employed to deflect the cathode-ray pencil according to some known law and at right angles to either the current or the voltage.

Investigation revealed a unique, flexible, dependable and direct method of solving this problem. The cathode-ray pencil is given a harmonic motion by a perfect sine wave curve passing through deflecting coils which may be revolved and set at any angle on the cathode-ray tube.

The unique part of the method lies in the combination of reactances and condensers to obtain the required sine wave. This combination is shown in the following circuit scheme.

The explanation of the circuit is as follows: In the first place the voltage across the inductance L' must be a large part of the voltage of the line between XY inorder to reduce the error of assuming the voltage wave form across L' similar to that across YX. It is a known fact that the third harmonic rarely exceeds 33 1/3% of the fundamental. Also it is a known fact that a reactance coil offers three times the resistance to the flow of the triple harmonic current that it does to the fundamental. This results in a reduction of the triple harmonic current thru L' to 11% of the fundamental; similarly the higher harmonics are reduced to a greater degree. This current, upon entering the resonant circuit, sets up an oscilating local current which is limited only by the power absorbed in the condenser and in the reactance L''. By proper design this oscillating current is limited to about 5 times the resultant current thru L'. The result of this current multiplying effect, which is merely the superimposition of a large pure harmonic current upon a small non-sinusoidal current, is to effect a reduction of the triple harmonic to 11/5 or 2.2% of the new fundamental. But the triple harmonic current passing through the inductance L'' passes the condenser with three times the facility of the fundamental and passes the reactance with three times the difficulty of the fundamental, thereby effecting a final further reduction of the triple harmonic current in L'' to 2.2/9% or .24% of the fundamental in that circuit.

The sine wave thus obtained is sufficiently accurate for all purposes.

A design of a satisfactory set of condensers and reactances will be considered next. Since the whole set depends upon an original assumption, four assumptions will be made and the four resulting designs carried in parallel.

The design will be used which proves to be the cheapest when the material is purchased.

The four designs will be designated as a, b, c, and d.

To begin the calculation of the sets of condensers and reactances assume

a - 10 m.f. condenser capacity.

b - 15 m.f. condenser capacity.

c - 5 m.f. condenser capacity.

d - 3 m.f. condenser capacity.

The condenser current at 50 cycles using telephone condensers at 280 effective volts is

a - $I_c = 280wC = 280 \times 314 \times .00001 =$ .88 amp.

b - $I_c = 280 \times 314 \times .000015 =$ 1.32 amp.

c.- $I_c = 280 \times 314 \times .000005 =$ .44 amp.

d - $I_c = 280 \times 314 \times .000003 =$ .264 amp.

Expressing this current by complex quantities, assuming a power factor of 0.02 for the condensers, we have

a - $I_c = 0.0176 + j0.88$

b - $I_c = 0.0264 + j1.32$

c - $I_c = 0.0088 + j0.44$

d - $I_c = 0.00528 + j0.264$

The current through the reactance L' must not be more than

a - $I_{L'} = 0.176$ amp

b - $I_{L'}$ = 0.224 amp.

c - $I_{L'}$ = 0.088 amp.

d - $I_{L'}$ = 0.0528 amp.

From bulletin #53, University of Illinois, the number of feet of the proper sized wire for L'' was found to be

a - 4800 ft. #20 B.& S. d.c.c.

b - 4000 ft. #18 B.& S. d.c.c.

c - 6300 ft. #22 B.& S. d.c.c.

d - 8600 ft. #23 B.& S. d.c.c.

This wire would weigh

a - 15.8 pounds.

b. - 21.0 pounds.

c - 13.3 pounds.

d - 14.5 pounds.

At some point account must be taken of the fact that this resonant circuit must be capable of being tuned for frequencies of 60 cycles and higher. This quality may be obtained most easily by the proper construction of the inductance coil, L''. Such construction will be considered here.

If the coils are wound according to the dimensions given in the bulletin $53, referred to above, but consist of two separate concentric parts, one of which may be revolved about an axis perpendicular to their common axis, the resultant inductance may be reduced and the curcuit tuned for higher frequencies.

The design of the inductance coil, L', remains to be considered. The voltage of 280 across the resonant circuit will be at practically right angles to that across the inductance L'. In order to have the voltage across L' a large part of the total voltage, which is a necessity, and also use a standard voltage for convenience, a voltage of 340 is used across L' which gives a total voltage of 440.

From the bulletin #53 referred to it is found that the wire needed for this coil will be:

a - 10000 ft. or 5.62 lbs. #28 B.& S. d.c.c.

b - 1900 ft. or 1.66 lbs. #26 B.& S. d.c.c.

c - 14000 ft. or 6.4 lbs. #29 B.& S. d.c.c.

d - 20000 ft. or 7.44 lbs. #30 B.& S. d.c.c.

To summarize, the bills of material are, for the sets

a - 10 m.f.

15.8 lbs. #20 B.& S. d.c.c.

5.62 lbs. #28 B.& S. d.c.c.

b - 15 m.f.

21 lbs. #18 B.& S. d.c.c.

1.66 lbs #26 B.& S. d.c.c.

c - 5 m.f.

13.3 lbs. #22 B.& S. d.c.c.

6.4 lbs. #29 B.& S. d.c.c.

d - 3 m.f.

14.5 lbs. #23 B.& S. d.c.c.

7.44 lbs. #30 B.& S. d.c.c.

CONSTRUCTION DETAILS.

A frame of oak was constructed according to the diagram with such modifications as were advisable during the work. A broad stable base of box construction provides room for the auxilliary resonant circuit and serves also as a photographic box. Two uprights serve to support the cathode-ray tube and its supplementary apparatus in their correct relative positions.

A piece of 6 inch o. d. well casing was bored out and used; primarily, for the ferrous metallic sheath, and secondarily, to carry the weight of the cathode-ray tube.

Preparatory to constructing the current-deflecting coils the probable voltages to be dealt with were investigated.

From bulletin #53 of the University of Illinois the inductance of one unit of six coils in series is approximately 1.5 henries. At 50 cycles this gives a reactance of 470 ohms. The resistance at 65° C. is 17000 ohms. The impedance is approximately 17000 ohms also. The voltage will be 17000 x .000005 or .085 which is negligible.

The following are some important facts regarding the construction of the current-deflecting coils. If affords great convenience in actual testing to have several current ranges; therefore it was deemed advisable to construct the coils in sections. In order to get a maximum number of ranges for a minimum number of coils, 12 sections were decided upon. The sections should have approximately equal effect upon the cathode rays and in addition should draw equal currents when operated in parallel, which demands that they be constructed in the form of "pies". If the sections most remote from the tube were to have their due influence the space factor had to be a minimum. These requirements were hard to meet.

Bakelite impregnation of these coils was decided upon for two reasons: first, because it assisted materially in reducing the space factor and, second, because it afforded an opportunity to become familiar with a recent development in electrical insulation.

A very small wire, #37 B.& S. enamel, was used in order to get the required number of turns in a minimum space.

The coil form developed and used for these coils consisted of machined discs of hard (half and half) solder which were covered on their flat surfaces with paper and stacked and bolted on a mandrel. The reasons for selecting metal for the material are: first, the delicate nature of the wire required a smooth true-running form, and second, the Bakelite required a non-impregnable material in order that the form should not become part of the coil. The reason for selecting solder, in particular, is that it can be melted from the coils after the baking process is completed without reaching a temperature harmful to the coils, for the forms can be removed in no other way.

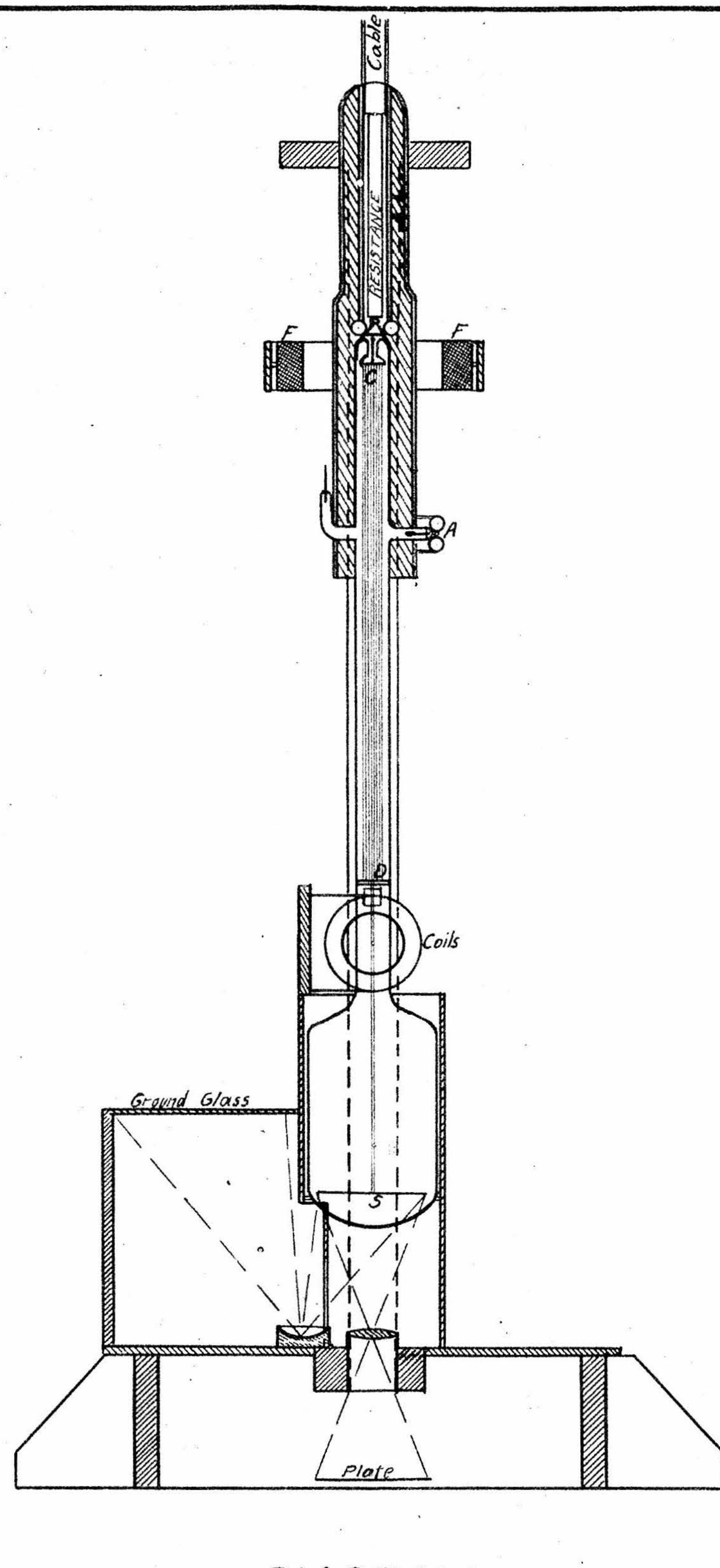
A machine to properly guide the wire on to the coil-form was devised instead of guiding the wire by hand. There were two reasons for this: first, theoretically correct mechanical feed gives a more compact coil than haphazard hand feed; and second, the collection of superfluous Bakelite in the coil form, incident to passing the wire through the Bakelite as it left the spool, made hand feeding a matter of guesswork and the result dependant upon luck.

A motion-reducing mechanism of levers was constructed to receive motion from the lathe carriage and deliver it, properly reduced, to the grooved wire-feeding pulley. The operation of mechanically feeding the wire was thus reduced to the act of reversing the lathe carriage at each end of an indicated travel.

Very satisfactory coils were produced in the above manner. They were then bound together in units of six coils each. The two units were mounted upon a terminal board in such a manner that they were on opposite sides of the cathode-ray tube at the position indicated in the diagram.

The focussing coil was wound, impregnated with Bakelite layer by layer, and baked; resulting in an excellent coil. It was mounted according to the requirements previously stated. In order to increase the machine's usefulness in experimental work, the coil was mounted with a vertical adjustment also.

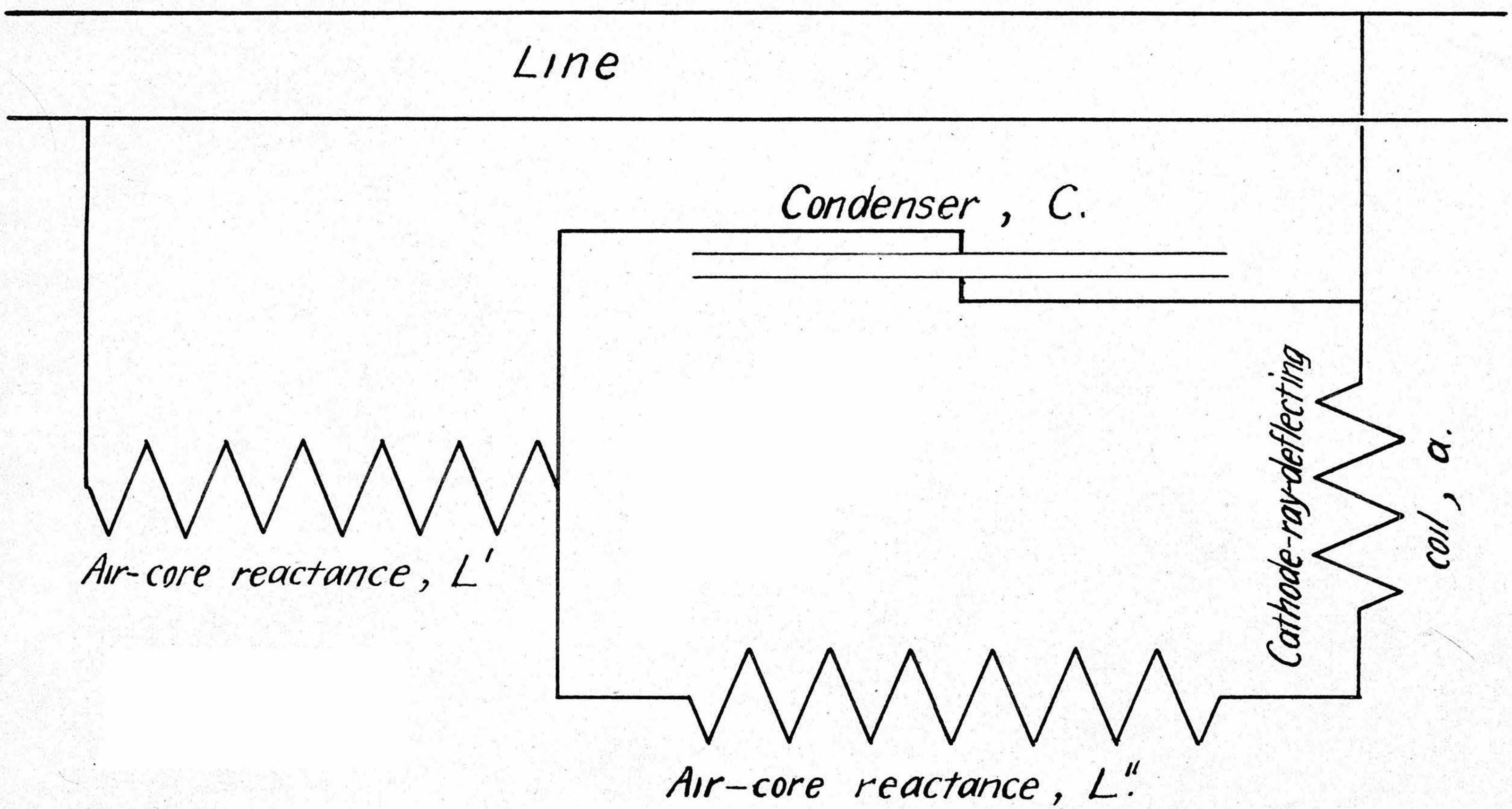
All other construction was either a matter of development of methods or finishing up the machine, and is unworthy of any special comment.



DIAGRAM

Scale 1" = 8"

CIRCUIT SCHEME
FOR SINE-WAVE CURRENT



Circuit, C, L'', a, is resonant. Sine wave current occurs in L'', a.

BIBLIOGRAPHY.

Some Characteristics of Cathode-ray Tubes

By J. P. Minton. G.E. Review July 1915.

The Cathode-Ray Tube and its Application.

By M.E. Tressler. G.E. Review Aug. 1915.

Cathode-Ray Alternating Current Wave Indicator.

By H. J. Ryan. A.I.E.E. Vol. 22 pp. 539

A Power Diagram Indicator.

By H. J. Ryan. A.I.E.E. Vol. 30 pp. 1089

Dielectric Losses With the Cathode-Ray Tube.

By J. P. Minton. A.I.E.E. July 1915, pp. 1627.

Cathode Rays and their Properties.

By J. P. Minton. G. E. Review. Feb. 1915, pp. 118.