A paper presented at the 26th annual convention of the American Institute of Electrical Engineers, Frontenac, N. Y., June 28, 1909.

ALTERNATOR FOR ONE HUNDRED THOUSAND CYCLES

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Before entering into a description of the form of generator dealt with in this paper, it may be of interest to give a short review of the history of the high-frequency alternator. Heretofore the 10,000-cycle machine has represented the highest frequency in commercial use. Such a machine was designed by Steinmetz in 1900 and a number of them are now in service. A similar machine for 10,000 cycles was described by Lamme in a paper before the Institute in 1904.* Reference may be made particularly to a paper by Dudell read before the Physical Society of London, giving a synopsis of his work with this kind of apparatus and describing the experiments made by him.

In 1904 when the author began to develop for Professor Fessenden, an alternator which should have a frequency of about 100,000 cycles and an output sufficient for commercial work in wireless telegraphy, not much confidence was placed in the possibility of constructing such a machine. The doubts expressed in the discussion of Dudell's paper as to the practical application of such machines to wireless telegraph work seemed quite just, in view of the fact that the highest frequency that had been produced with any appreciable output was 10,000 to 15,000 cycles, while Dudell's machine, which had been worked up to 120,000 cycles, had an output of a fraction of a watt.

Since then three machines of the design described in the following pages, and referred to in several papers by Professor Fessenden, have been placed in service. In this paper there

* TRANSACTIONS A.I.E.E., 1904 Vol. XXIII. p. 417.

will be described a perfected form of the same general type, rated at 2 kw. and 100,000 cycles.

Early types. The stages of development which led to the present type of machine were substantially the following:

In view of the special precaution which had to be taken to reduce the core loss in the alternator built for 10,000 cycles, it was natural in the first attempts at building a machine for 100,000 cycles to try to eliminate the iron in the armature.

The first machine built was a model with a revolving armature of the Ferranti type, 3 in. in diameter. The experiment was encouraging, inasmuch as it demonstrated the possibilty of generating an appreciable amount of power at 100,000 cycles, but the machine could never be brought up to a corresponding speed on account of mechanical difficulties. The armature had 200 conductors consisting of 100 U-shaped phosphor-bronze wires anchored in insulated segments clamped in the rotating body. As long as the machine was run at no load, it acted comparatively well. The centrifugal force and air pressure on both sides of the wires seemed to keep them away from the stationary pole faces; but as soon as the field was applied the magnetic action on the current in the conductors was sufficient to distort the wires so that they would strike the poles and break.

From this experience it was apparent that a successful machine must have a stationary field winding as well as a stationary armature and that the armature should not contain any iron. The outcome of these conditions was a type of machine illustrated in Fig. 1. The armature is made of wood and the two rotating discs form a complete magnetic circuit which is energized by a stationary field coil suspended inside the armature between the discs. In connection with this machine a number of mechanical problems were to be solved, which will be referred to when describing the latest form of the alternator. The chief reason why this machine could not be considered as the final development was the fact that the rotating discs could not be made symmetrical. Owing to this fact the centrifugal force at high speed changed the shape of the discs in such a way that the air-gap between the field and the armature was increased; the result being that the voltage of the generator did not increase in proportion to the speed, but reached a maximum at about 60,000 cycles and decreased at higher speed.

Type of construction. Fig. 2 shows the construction arrived at in a machine recently completed. As there was a question whether it was practicable to use an iron armature at a frequency of 100,000 cycles, the machine was built with two kinds of armatures for trial, one of iron and one of the winding placed in wood. The iron proved to be preferable, giving a higher output and a better mechanical structure. The success of the iron

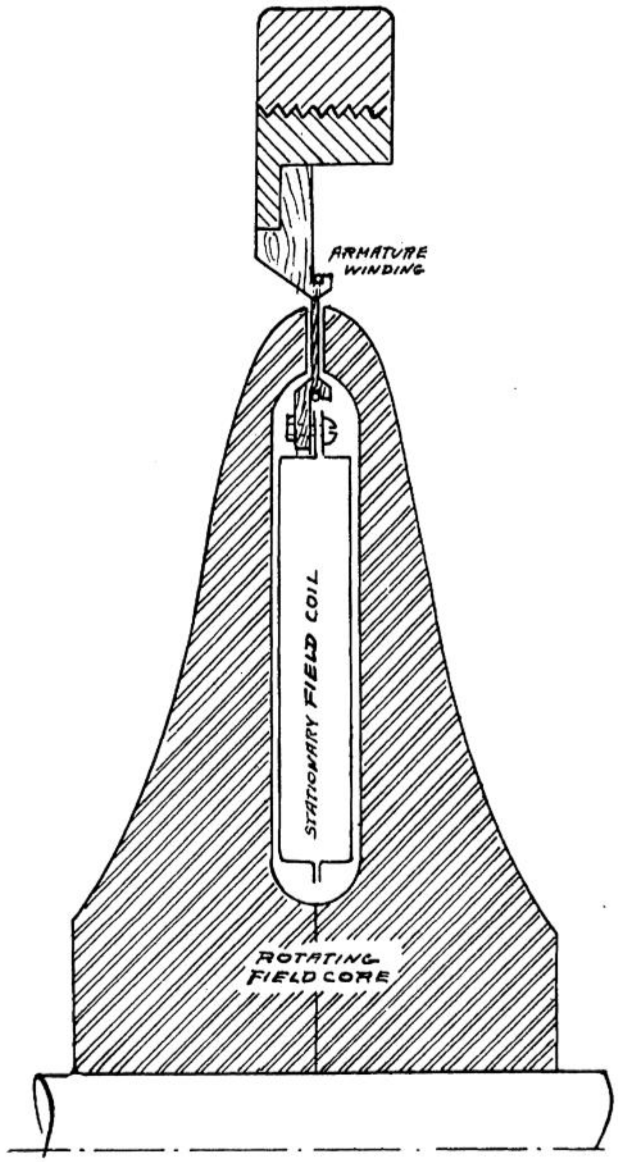

FIG. 1.

armature is largely due to the fact that the volume of iron subject to alternating flux is extremely small. The main part of the laminated armature carries a constant flux, while the pulsating flux occurs only in the teeth that separate the armature conductors.

The alternator shows in every way the same characteristics as a generator of moderate frequency. The following are the constructional data of the machine: the armature has 600 slots with one conductor per slot of 0.016 copper wire, triple-silk covered, and varnished. The wire is wound in a continuous wave up and down in the successive slots. The rotating field has 300 projections, which, as the machine is of the inductor type, correspond to 600 poles for a machine of the ordinary alternate-pole type.

It appears from the electrical characteristics that the output

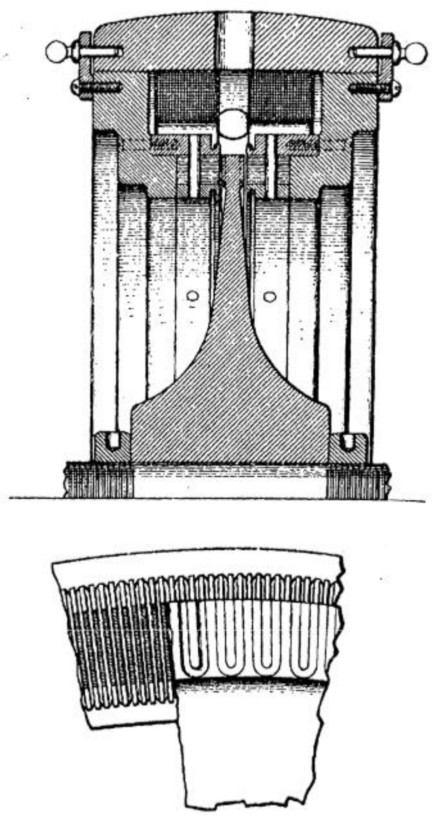

FIG. 2.

of the generator depends largely upon the air-gap clearance, because the voltage of the machine is nearly inversely proportional to the air-gap. The characteristic curves have been given at an air-gap of 0.015 in. but the output of the generator can be doubled if a smaller air-gap be used; in fact the machine has been operated with an air-gap as small as 0.004 in., though such a clearance would not be practicable for continuous operation. In view of this condition it is desirable to regulate the air-gap so as to offset any wear in the bearings, and to select the gap which is suitable for the work to be done. If the machine is to be operated continuously without attention, a comparatively large clearance is necessary, while for a special experiment in which higher power is required a small gap may be used.

The sensitiveness of the air-gap regulation is one of the reasons why, instead of using the usual drum winding construction of the armature, the winding was applied on a radial face, as shown in Fig. 2. The armature is mounted on a frame that is threaded into the stationary field frame, and the air-gap can be set exactly by screwing the armature tight against the disc and then moving it back a distance corresponding to the desired clearance. For this purpose the stationary frame is provided with a scale, so that rotating the armature on its thread one division corresponds to one thousandth of an inch change of the air-gap.

Flexible shaft. At a speed of 20,000 rev. per min., it would not be practical to use a rigid shaft as in ordinary machines. It was therefore necessary to adopt the principle employed in the deLaval steam turbine, that of a flexible shaft which allows the disc to revolve round its exact mass center, thus avoiding any strain on the bearings due to centrifugal force. In a turbine of this type designed for a speed of 20,000 rev. per min., the shaft is very thin, about the size of a lead pencil, but not very long. A shaft of such proportions would not be suitable for the alternator in which the exactness of the air-gap is essential and the disc is subject to the magnetic attraction between field and armature. The shaft of the alternator must have not only considerable stiffness, in order to keep the disc in an accurate position, but also sufficient flexibility to allow the rotating disc to adjust itself to its own mass center. To meet these requirements the shaft is designed like a stiff spring with uniform strength so as to obtain maximum work out of the material without exceeding the elastic limit in any part. It has a diameter of 1.25 in. in the middle and 0.625 in. at the ends, the length between the centers of bearings being 28 in.

When the machine is brought up to speed, severe vibration occurs at two distinct critical speeds, one at 1700 rev. per min. and the other at 9000 rev. per min. The vibration increases gradually when the machine approaches the critical speeds. When the vibration has reached its maximum, it ceases suddenly and the machine runs smoothly and with surprisingly little noise, indicating that the disc has fallen into step with itself, so to speak, and is rotating around its own mass-center. The critical speed, which can be predetermined approximately from the design of the shaft and the disc, occurs when the natural vibration of the shaft with the disc coincides with the revolutional speed.

The first point of resonance is the one at which the shaft vibrates like a string, as shown in Fig. 3. The spring force of

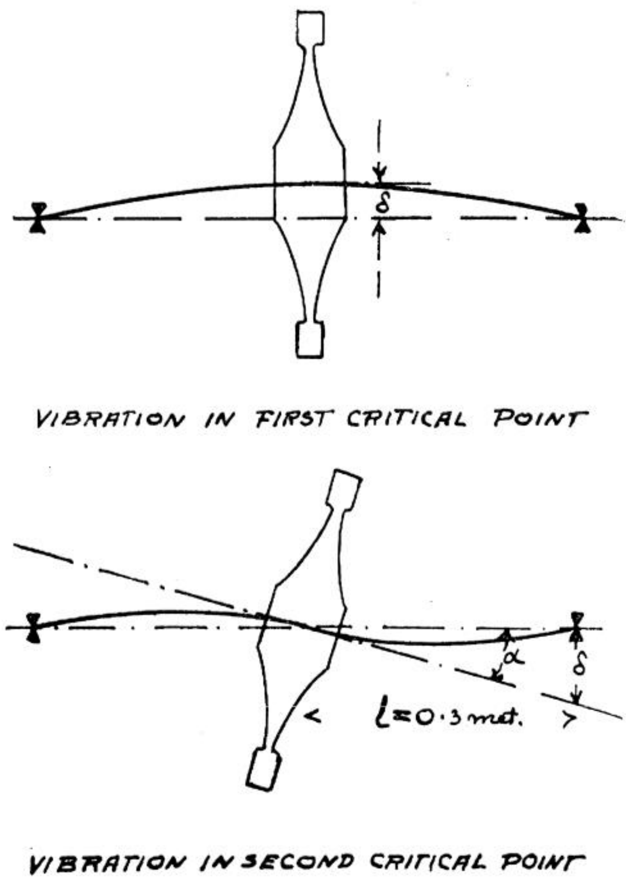

FIG. 3.

the sha t tending to hold the disc in its original position is proportional to the deflection from the same position.

Let the deflection $= \delta$
The spring force $= P$
Hence $P = k\,\delta$

in which k is a constant corresponding to the stiffness of the shaft. The constant k can be determined by calculating the deflection of the shaft from its dimensions. The result of such a calculation gives $\delta = 0.0024\ P$ cm. or 0.000024 meters, in which

P is expressed in kilograms. The weight of the disc is 13.6 kg. and the mass $= m = \frac{13.6}{9.8}$.

The equation for resonance in the first critical point is derived by assuming that the shaft swings as a string with a weight in the middle. In order to define the condition for resonance, it is assumed that the disc is brought out of center by an arbitrary amount δ. The condition for mechanical resonance occurs if the centrifugal force of the mass of the disc rotating at a radius δ is equal to the centripetal force created by the deflection of the shaft to the amount δ from its normal shape.

Centrifugal force $= m\,\delta\,\omega^2$

Where ω is the angular velocity.

The spring force of the shaft has been designated P

$$m\,\delta\,\omega^2 = P = \frac{\delta}{0.000024}$$

and introducing $m = \frac{13.6}{9.8}$

$$\frac{13.6}{9.8}\,\delta\,\omega^2 = \frac{\delta}{0.000024}$$

$$\omega^2 = \frac{9.8}{13.6 \times 0.000024}$$

$$\omega = 173$$

Rev. per sec. $\frac{\omega}{2\,\pi} = 27.5.$

Rev. per min. 1650.

The second harmonic is the one at which the disc vibrates around an axis vertical to the shaft and the shaft assumes an S shape. The momentum exerted by the spring force on the disc is proportional to the angular deviation of the disc.

The relation is $P\,l = k\,\alpha$.

The constant k can be derived from the dimensions of the shaft. In this case

$$k = \frac{l^2}{0.000024} = \frac{0.3^2}{0.000024} = 3750$$

The inertia of the disc for rotation around an axis vertical to the shaft may be designated I. In this case

$I = 0.0052$ expressed in meters and kilograms.

The equation for mechanical resonance is

$$I \, \alpha \, \omega^2 = P \, l$$

in which ω is the angular velocity.

Substitute $P \, l = k \, \alpha = 3750 \, \alpha$

$$I \, \alpha \, \omega^2 = 3750 \, \alpha$$

$$\omega^2 = \frac{3750}{0.0052}$$

$$\omega = 850$$

$$\text{Rev. per sec.} = \frac{850}{2 \pi} = 136$$

Rev. per min. = 8200.

A number of mechanical features which have been the principal problems in the development of this machine are described in the following.

Method of drive. The first machine built was belt-driven. After a good deal of experimenting with different kinds of belts and pulleys, it was found feasible to run the machine at 15,000 rev. per min., corresponding to 75,000 cycles. However, it also became apparent that this method of driving could not be accepted for practical use, so that the later machines have been equipped with gears. Although these gears are designed for reduction of speed, they appear to work satisfactorily when the action is reversed. The gear ratio is 10 to 1.

Revolving disc. The disc is designed so as to have uniform stresses in all parts and consequently the greatest possible margin of safety. The disc is made of chrome-nickel steel with an elastic limit of about 200,000 lb. per sq. in. At a frequency of 100,000 cycles the speed is 20,000 revs. per min. The diameter of the disc being one foot, the peripheral speed is 1,000 feet per second or 700 miles per hr.; in other words, the disc would roll over to Europe in 4 hr. The centrifugal force of the material in the edge of the disc is 68,000 times its own weight, but owing to the shape of the disc, which is designed for maximum strength, the stresses are only 30,000 lb. per sq. in., giving a factor of safety of 6.7 to 1.

Heating and air friction. If it be born in mind that the disc has 300 teeth on each side spaced at a distance of 0.125 in. and that these teeth pass the face of the stationary armature at a rate of 1000 ft. per sec. with a clearance of 0.015 in., it can be readily understood that the air friction in the gap must be considerable. It was found that the machine heated up excessively owing to air friction, but this has been overcome by filling the slots with non-magnetic metal so that the disc offers a perfectly smooth surface. Then another difficulty was encountered owing to centrifugal force acting on the fillers, each of which is subject to a centrifugal pull of 80 lb. During some of the first attempts, when the slots were simply filled with hard solder, it happened that some of the fillers broke loose. It was interesting to notice that an unbalancing centrifugal force of 80 lb., which would have been enough to bend the shaft at standstill, did not affect the machine, which, in every case, continued to run as if nothing had happened. In the final construction, in which the fillers are anchored so as to stand the strain, they consist of U-shaped phosphor-bronze

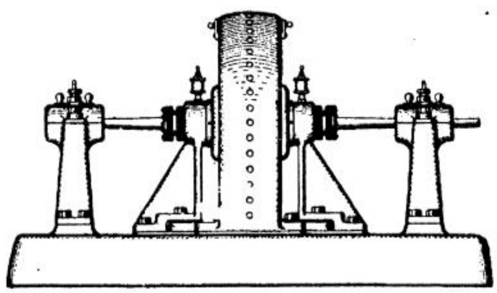

FIG. 4.

wires supported directly by the steel teeth so that the solder is needed only to fill the joints.

Bearings. The generator has two sets of bearings as shown in Fig. 4. The outside bearings support the weight of the revolving parts and are fed with a continuous stream of oil supplied by a pump. With this system of lubrication, the machine can run continuously at full speed with a temperature rise of the bearings of only 5 degrees above the temperature of the oil in the tanks. The necessity of the continuous oil feed is demonstrated by the fact that the temperature of the oil in the tank reaches 20 degrees above the surrounding air.

One of the functions of the middle bearings is to prevent excessive vibrations when the shaft passes the speeds of mechanical resonance. During normal operation, the shaft does not touch the middle bearings, which are bored out to give 1/64 in. clearance; at the critical speed, however, the shaft touches the bearings.

The end-thrust of the shaft is taken up partly on the middle bearings and partly on the end bearings. If the air gaps on both sides of the disc were not equal, the magnetic end thrust might be considerable, but with this arrangement of divided end thrust the adjustment seems to be to a certain extent

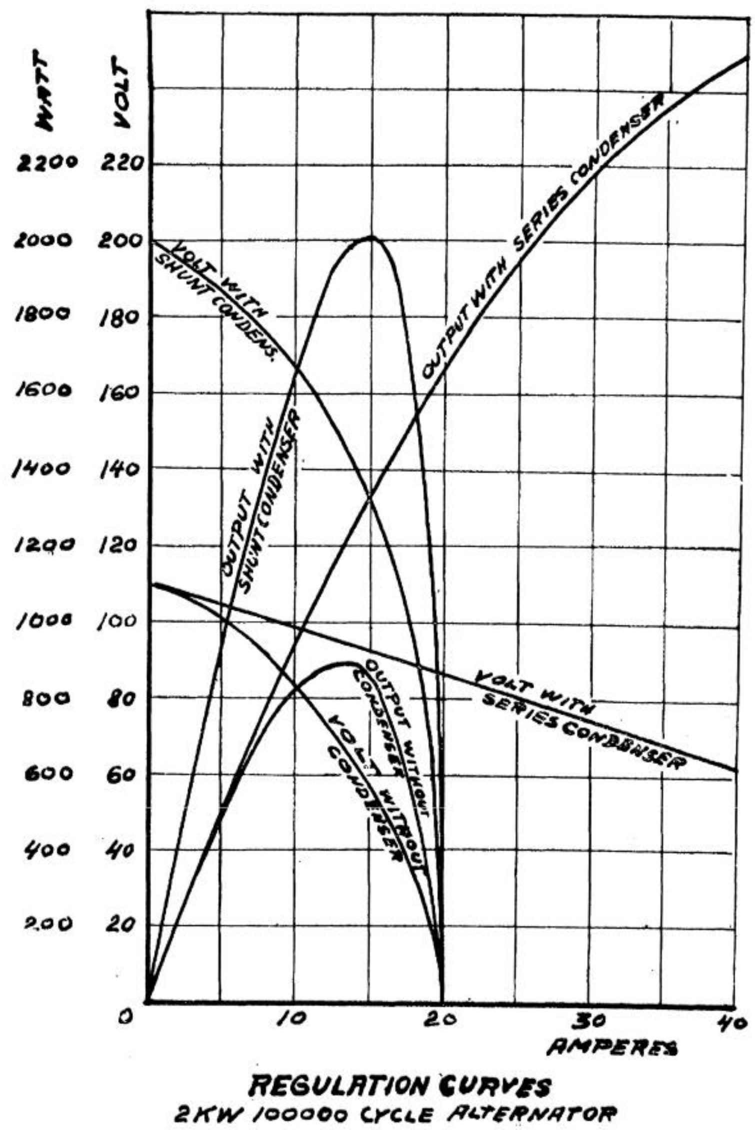

FIG. 5.

automatic. If the disc has a tendency to move over to one side due to a difference in size of the air-gaps, the corresponding middle bearing will heat up and the same side of the shaft will expand longitudinally, thereby relieving the middle bearing as well as correcting the air-gap.

Electrical characteristics. A generator of this kind is always used in connection with a capacity, which is located either in the aerial, as in the case of wireless telegraphy, or in a condenser of suitable capacity used in order to obtain the proper tuning. The best method of showing the characteristics of the generator, without reference to any certain application, is to assume the load to be non-inductive and use a condenser of a fixed capacity as an attribute to the generator. The most

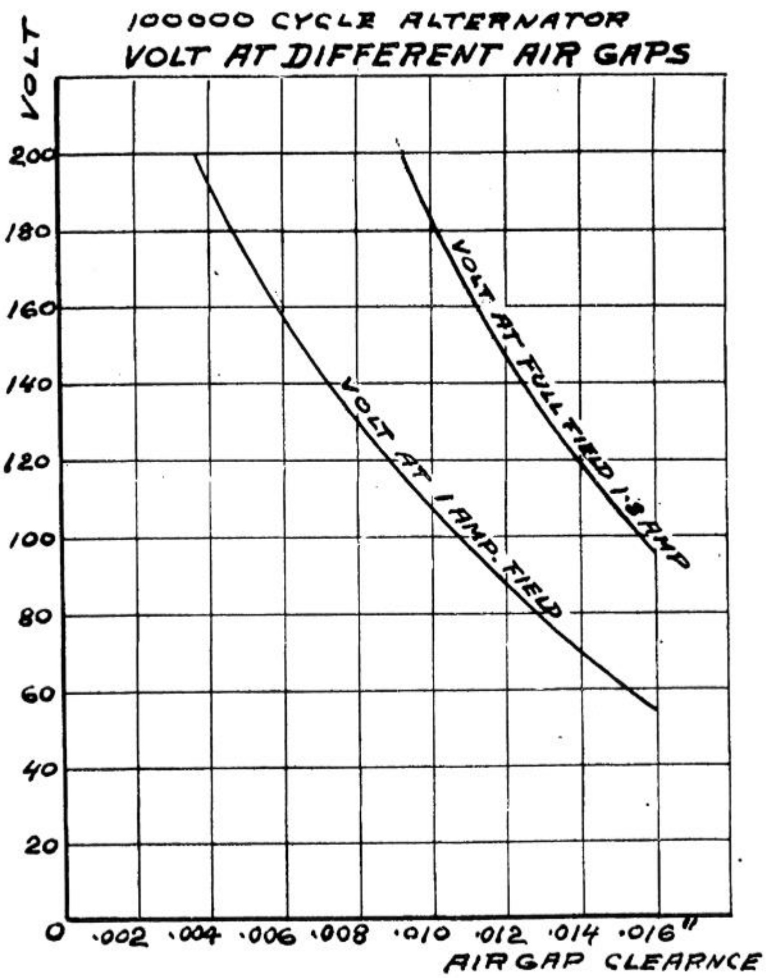

Fig. 6.

typical performance of the generator operating in conjunction with a condenser is the one in which the condenser has an impedance equal to the inductive impedance in the generator winding and is connected in series with the generator. This combination gives the generator a maximum output for any load. A condenser arranged in this way considerably increases the useful performance of the generator and should be regarded as a part of the generating outfit. The tests of the alternator described here show that the reactance of the armature winding is 5.4 ohms at 100,000 cycles. The condenser which ought to be used in connection with the machine at the same frequency should have the same impedance expressed in ohms. If the capacity is expressed as usual in microfarads, it should be

$$C = \frac{1}{5.4 \times 2\pi \times 100{,}000} \text{ farads}$$

$$= \frac{10}{5.4 \times 2\pi} = 0.3 \text{ microfarads}$$

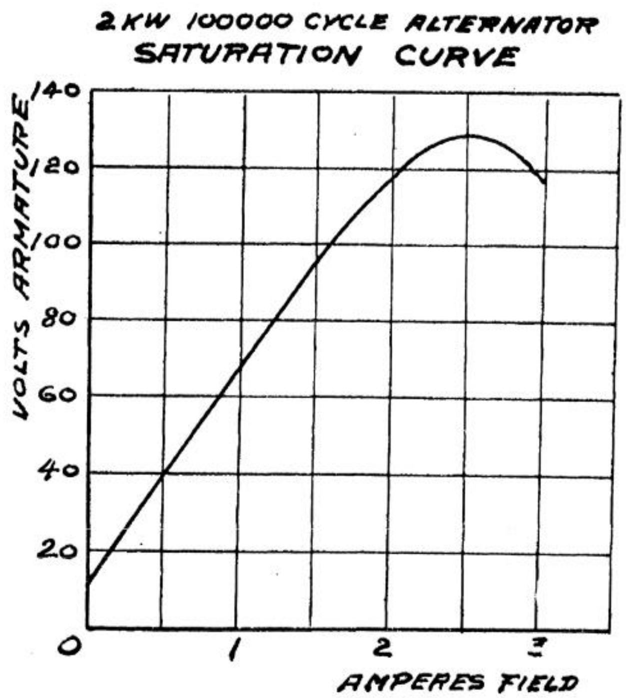

FIG. 7.

Regulation curves of the alternator are shown in Fig. 5. From this diagram it appears that the combination of alternator and series condenser gives the same terminal voltage at any load as would a generator which had the same electromotive force and the same ohmic resistance but no inductive drop. In other words, the condenser completely offsets the reactance of the winding, and the regulation is determined entirely by the ohmic resistance.

Tests, as well as practical use of these machines for wireless telegraph work, have shown that the commercial output of the alternator is limited by heating of the armature winding. In building these alternators for practical purposes, the need for a commercial rating of the machines has already been realized. The basis for rating which has been adopted for these machines

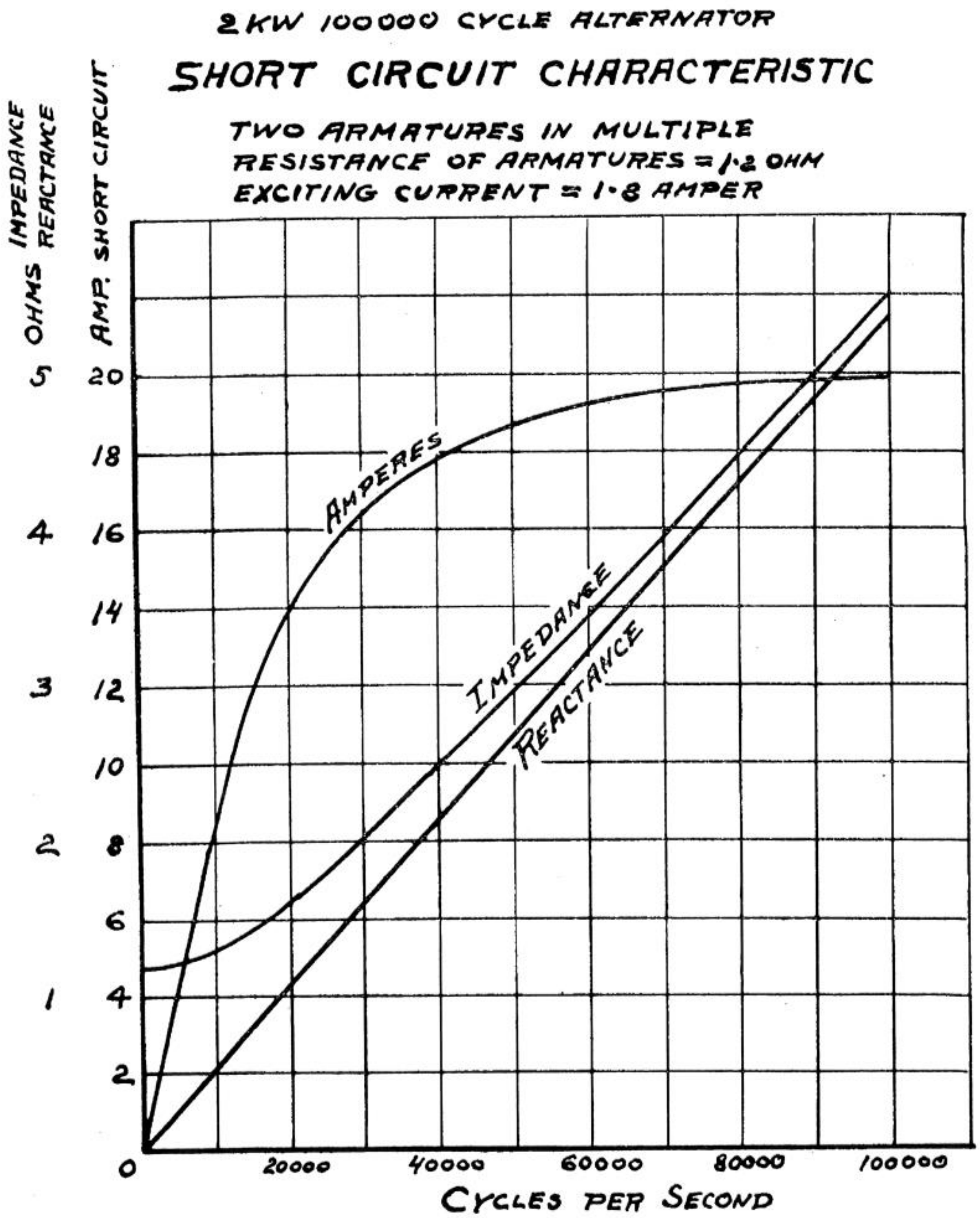

FIG. 8.

is illustrated by the rating of the 2-kw., 100,000-cycle alternator.

The characteristics of the machine as given by test are the following:

No load voltage, 110.

Ohmic resistance, 1.2,

Short-circuit current, 20 amperes.

Continuous capacity at 45 degrees rise, 30 amperes.

From the above data, it is apparent that the alternator cannot be operated up to its full thermal capacity without a condenser, and in selecting a condenser the capacity is regulated so as to compensate for the inductance of the winding as described. Under these conditions, the maximum continuous load of the alternator is 70 volts and 30 amperes or 2.1 kw. The commercial rating has therefore been made 2 kw.

It may be of interest to note that the product of the short-circuit current and the no-load voltage is 2.2 kilovolt-amperes, equal to the full load-capacity as determined by heating. However, the short-circuit current would not be a suitable basis for commercial rating; because the thermal rating depends entirely upon the ohmic resistance of the winding, while the short-circuit current is nearly independent of the resistance.

It would undoubtedly be of theoretical interest to be able to determine the properties of the iron core at the high frequencies dealt with in this generator. A test made at 60,000 cycles may be referred to for this purpose. The power required to run the whole set without excitation at the corresponding speed was 1340 watts and the additional power required to drive it at the same speed with full field was 330 watts. The only conclusion that can be drawn from this test is that the core loss is not higher than 330 watts. The main part of this loss is probably due to increased bearing friction by magnetic end thrust. By a more delicate laboratory test, it might be possible to separate the additional friction from the core loss, but the above is the only data that are available at present.

Regarding the possibilities of building high-frequency alternators of higher output, it may be mentioned that a machine for 50,000 cycles is being constructed of such dimensions that an output of 35 kw. can be expected. At the present state of the art, however, it is safer to build the machine first and determine its rating after it has been tested.

The question of whether machines can be designed for frequencies still higher than 100,000 cycles cannot be decided offhand. Considering, however, that the present generator has a large margin in the mechanical strength of the revolving disc as well as in the length of the air-gap, etc., it appears probable that still higher frequencies can be reached by direct generation with revolving machinery.