

THE ALEXANDERSON SYSTEM FOR ELECTRO-MECHANICAL PRODUCTION OF RADIO-FREQUENCY ENERGY

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The development of the Alexanderson alternator represents the apotheosis of mechanical generation of continuous wave radio-frequency energy. From its inception to the completion of the twenty huge 200-kW units that General Electric produced, the history flirts with the interaction between three distinct schools of engineering. One thought in terms of power factor, kilowatts, and phase angle; the second in terms of wave length, decrement and tuning; and the third in terms of angular velocity, critical speed and proper bearing design.

The Alexander system of RF generation is a tangible artifact that welds together the interaction between scientific thought and the practicality of three separate engineering disciplines.

A consulting engineering department, staffed by a select group of engineers, was established at General Electric in Schenectady. It was conceived and headed by Charles Steinmetz, who had postulated the theories of eddy currents and hysteresis loss in iron, developed a symbolic algebra to solve complex equations, and had written a text on alternating current phenomena.¹

As early as 1900, Steinmetz was interested as a result of a letter sent to him by Reginald Fessenden describing the general specifications for a high-frequency alternator to be used for wireless transmission. Fessenden expressed the hope that Steinmetz would design such a machine and have the General Electric shops in Schenectady build it. The request was not an easy one to fulfill, but Steinmetz accepted orders for the design and manufacture of a test alternator in the early part of 1901. By spring the alternator was ready, but the results were disappointing. The Steinmetz alternator reached a maximum frequency of only 10 kHz at 4000 rpm before the rotary armature started to fly apart.²

Fessenden was not able to use this machine as he originally planned, that is, as a direct radiator of RF. However, he made the best of what he had and connected the output of the alternator to a spark gap and used the spark to excite the antenna. This combination of high-speed alternator and quenched spark obtained a frequency of 20 kHz, but the signal was noisy and the emission was still a damped wave.

On the 8th of December, 1904, Fessenden submitted a second alternator order to General Electric. The request this time was for an alternator that would distinctly function as a transmitter by itself, involving a frequency

specification of 150 kHz and a power output of 25 kW. For some reason, Steinmetz did not care to pursue the project any longer and assigned the project to Ernst Alexanderson.

Alexanderson's educational foundation paved an easy pathway for him to enter the G.E. consulting department. He was born in Sweden in 1878 and was granted an electrical engineering degree from the Royal Technical University in Stockholm in 1900. While in Germany the following year, he studied the book *Alternating Current Phenomena* written by Steinmetz. Alexanderson became so interested in the subject that he came to America with the hope of working under Steinmetz.

Following a job interview and subsequent job offer by Steinmetz, Alexanderson started to work in the testing department in General Electric in 1902. While there, he invented a power-circuit switching system and was then given a desk in the engineering department where he continued to invent under the watchful eye of Steinmetz. Alexanderson was given a free hand in the design of the new alternator. He realized the weakness of the Steinmetz design due to the limit placed on the rotational speed of the armature. Alexanderson chose to develop an inductive type of alternator using a stationary armature and a stationary field with a toothed disc rotating between them. The decision to use the inductive type of alternator was pivotal in the subsequent development of the entire Alexanderson system, for it provided the key to high rotational speeds without fear of destruction.³

On February 6th, 1905, Patent No. 905,621 was filed. Alexanderson states in the patent that "My invention relates to dynamo-electric machines for producing alternating current of high frequency and its object is to produce a commercially operative machine capable of generating currents of extremely high frequency, such as 50,000 to 100,000 cps. In order to obtain such enormous frequency by magnetic induction, two things are obviously necessary; the distance between the poles must be extremely small and the relative movement of the poles and armature conductors must be extremely high." To attain the high rotational speed of the mechanical members, Alexanderson chose a "novel arrangement" of two discs tapered toward the periphery, and connecting the disc to a common shaft. Machining problems gave an indication that warping would occur, so a single tapered disc was developed.⁴

The magnetic circuit of the inductor alternator (Fig. 1) is made up of the field yoke, the air gap, the pole face of the rotor and the field coil.

The rotor is slotted to vary the intensity of magnetic saturation as it revolves past the stationary armature. The armature coils are wound in equidistant slots on the pole face of the field yoke. The variation between the iron and phosphor bronze of the rotor creates a maximum and minima of flux density such that an alternating electromotive force is created. The emf is substantially related to the revolutions of the rotor and the number of teeth cut in the disc. The field yoke is excited by a constant D.C. source. The rotational speed of the rotor is crucial in maintaining a constant radio frequency.

Fessenden was steadfast in his theory that the eddy currents and hysteresis losses would become enormous at high speeds.⁵ So, when the test machines

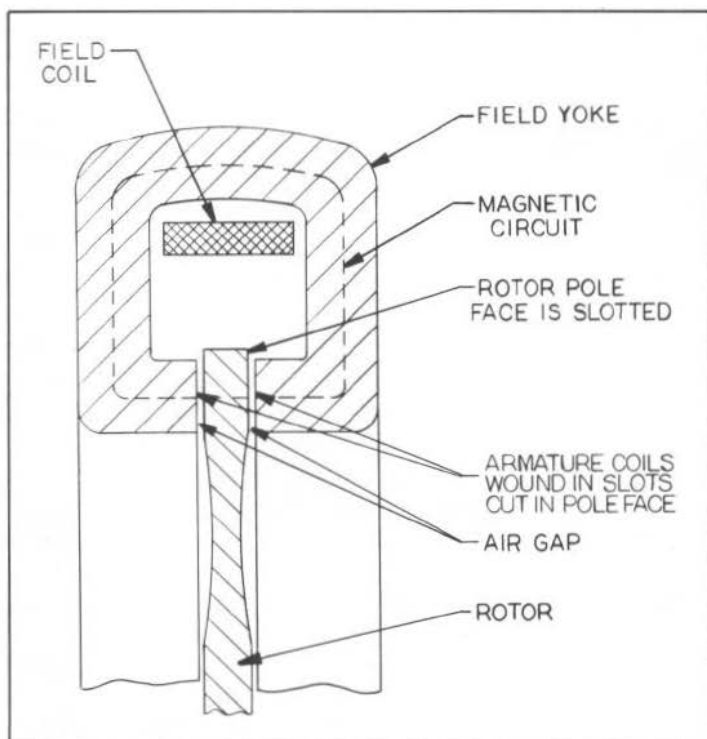


Fig. 1. Cross section of a 200-kW Alexanderson inductor alternator.

were made, two of them were built, with one having a stationary armature made of wood and the second one having an armature made of iron. The test results were surprising.

The iron armature proved to be preferable. It gave a higher output and most certainly a better mechanical structure. The key to the success of the iron was largely due to the fact that the volume of iron that was subject to the alternating flux was quite small. The voltage of the alternator was found to be inversely proportional to the air gap. The design mean air gap was around 0.015", but in the test the gap was reduced to 0.004" (about the thickness of a sheet of paper) causing an appreciable rise in voltage.⁶

The design speed of the 100,000-Hz alternator was 20,000 rpm., and difficult mechanical problems arise in machinery of any size running this fast. It is not practical to use a rigid shaft at these speeds, so Alexanderson chose to adapt the DeLaval steam turbine principle that uses a very light, almost pencil-thin shaft to allow the disc to revolve around its own mass center. In the 100,000 Hz machine, the shaft was 1 1/4" in the center, 5/8" at the ends, and the distance between the bearings was 28 inches.

Whenever a piece of machinery is brought up to rotational speed, points of natural resonance occur. These points of resonance are called the critical speeds. Vibration at the first critical point occurs in the form of up and down motion, as if a rubber band were stretched between two points and plucked in

the center. Vibration at the second critical point acts in a violent sinusoidal twisting motion. In the 100,000-Hz machine these points occur at 1700 rpm and 9000 rpm respectively. After these two points are passed, the shaft assumes its mass center and very little vibration occurs.

It is interesting to note that Alexanderson must have been a remarkable designer, or at the very least have had the skills to go to the right mechanical people for quick solutions, and then integrate interdepartmental disciplines. General Electric was one of the foremost manufacturers of steam turbines at the time and was right on the leading edge of that technology.

In the early tests, notches were cut in the disc to serve as the flux inductor, but it was discovered quickly that windage played a big part at those speeds. Originally the slots were filled with hard solder to try to solve the problem, but under test they failed. Each filler was subject to a centrifugal force of 80 pounds. Imagine yourself lifting an 80 pound bag of cement. Then visualize 300 of those bags equally spaced and whirling on the outside edge of a disc running at 20,000 rpm. The centrifugal force of the material at the edge is 68,000 times its own weight. The solution to the problem was found to be an angular shape of phosphor bronze that was swedged into the disc and machined off to the final contour when the disc itself was machined.

At such high rotational speed it was thought that molecular air friction or mechanical abrasion by dust particles accounted for the extremely high polish on the disc after some time of operation. At a speed of 20,000 rpm, the peripheral speed of the disc is 1,000 feet per second or 700 miles per hour. Running at such high speeds presents bearing problems also, and the 100,000-Hz alternator was provided with two sets of bearings. The outside bearings supported the weight of the revolving parts and were pressure fed. The inside bearings, that is, those closest to the disc, were actually bored $1/64''$ over the shaft size and only functioned as the shaft touched them coming up through the critical speed. The inner bearings were also provided with a radial-thrust face to ensure correct air-gap centrality between the disc and the stationary field armature. The need for continuous oil feed was shown to be necessary because the oil-tank temperature rose 20 degrees above the ambient air temperature, and the bearing temperature itself was another 5 degrees above that of the oil.⁷

When it was discovered that Stenmetz's law of hysteresis, eddy currents, and skin effect were as true at 100,000 Hz as they were at 25 Hz, it was also found that the conceptions of power factor, phase displacement, and leading and lagging currents were just as applicable and useful in the radio-frequency range. That discovery gave the go-ahead to commercial development.⁸ With the development of a working 100,000-Hz, 2-kW unit, Alexanderson realized that an entire system must be developed to fulfill Fessenden's dream of mechanically produced RF. This development needed to include: 1. the design of an alternator to directly generate RF; 2. the design of a regulator that was sensitive enough to hold the speed of an induction motor constant to within a few hundredths of 1%; 3. the improvement of existing antenna systems to efficiently use the alternator's output. That is what Alexanderson did. Not only did he develop a high-frequency alternator capable of up to 200 kW at a variety of

frequencies, but he integrated the system requirements together to form, as he put it, "a complete radio power plant."⁹

Let's take a look at one of the 200-kW giants. The most singular mechanical observation that is evident is that now the shaft is massive. No longer does the alternator have to be driven through the two critical periods. As a matter of fact, the shaft operates well below its own fundamental frequency of resonance. With the absence of the center bearing, it was necessary to produce a means of axial control to centralize the rotor between the two fields. In order to minimize large losses due to magnetic leakage, the air gap was maintained at 0.015" (each side). It was important to keep the gap equal because if not equal, the coils on one side could become overloaded and abnormal heating would occur.

The axial adjustment was obtained by using a labyrinth thrust bearing interconnected by a set of equalizing levers. Any tendency towards an air-gap change was automatically taken up by the equalizers. The alternator was driven by a 600-hp, wound-rotor induction motor that was operated from a 2,300-volt, 2-phase power supply. The motor was connected to the gearbox through a coupling of the Franke (some used Bartlett-Hayward) flexible type, which was delivered rough bored and finished in the G.E. Schenectady shops.

The gearbox was a double-helical step-up box with a ratio determined by the operating frequency, with its own internal oil supply, and connected to the alternator through a Franke lubricated coupling. By means of a suitable combination of motor speed, gear ratio, and alternator poles, the frequency generated by the Alexanderson alternator covered a range of 10,325 to 29,200 Hz, corresponding to a wavelength range of 29,038 to 10,268 meters.

The following tables show the wavelength and frequency of the combinations of alternator poles and standard gear ratios, using the standard motors.

A special combination of a 10-pole, 60-Hz motor with a 3.324 gear ratio was used to obtain a frequency range of 19470 to 23460 Hz, corresponding to a wavelength range of 15400 to 12780 meters, at Bolinas, California.¹⁰

Proper bearing design allowed Alexanderson to achieve critical axial

TABLE 1. 8-Pole 60-Hz Motors

Alternator Poles	Gear Ratio	Frequency Range in Hz 4% Slip
1220	3.324	29198
1220	2.973	26115
1220	2.675	23497
976	3.324	23360
976	2.973	20892
976	2.675	18798
772	3.324	18476
772	2.973	16525
772	2.675	14869

TABLE 2. 8-Pole 50-Hz Motors

Alternator Poles	Gear Ratio	Frequency Range in Hz 4% Slip
1220	3.324	24331
1220	2.973	21762
1220	2.675	19581
976	3.324	19465
976	2.973	17410
976	2.675	15665
772	3.324	15396
772	2.973	13771
772	2.675	12390

location, yet have a very large bearing surface to support the main shaft and keep the alternator in line. He achieved this by the use of an inner and outer sleeve. The outer sleeve was shaped like a knuckle and would pivot, within given limits, similar to a ball and socket. (See Fig. 2.)

The main bearing and labyrinth were then placed in their own carrier and allowed to be displaced axially, within given limits, in the knuckle. (See Fig. 3.)

The complete package and shaft then would resemble the sketch shown in Fig. 4.

These bearings were pressure lubricated, at pressures ranging from 5 to 15 pounds per square inch, depending on the demand of the bearing. The oil was pumped from an oil supply tank located in the base casting of the alternator. On startup, a separate 15-hp motor drove a pump until the alternator came up to speed. The separate motor pump was then cut off and the main pump, geared to the main drive shaft, supplied the oil flow. The main bearings were also water cooled by a series of copper pipes which ran through the bearing shell. The same flow of cooling water passed through a series of parallel copper tubes which were cemented in the frame alongside the laminations of the armature, thus cooling it.

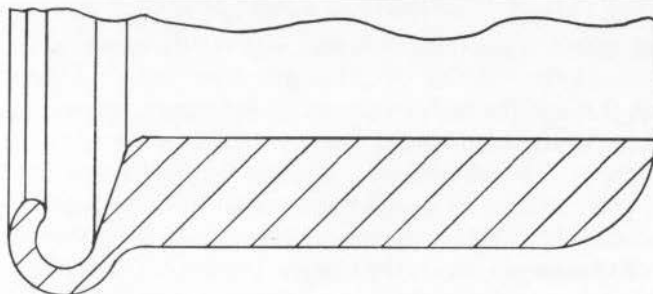


Fig. 2. Cross Section of bearing knuckle. The outside diameter rests in the bearing-support casting, while the inside diameter carries the labyrinth and main bearing.

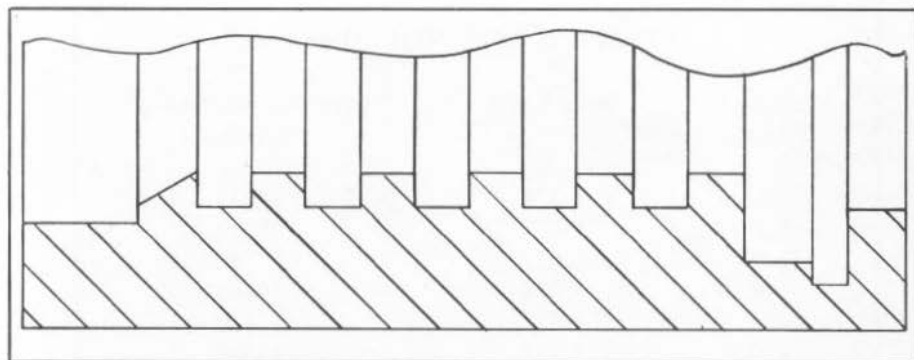


Fig. 3. Cross section of the main bearing and labyrinth.

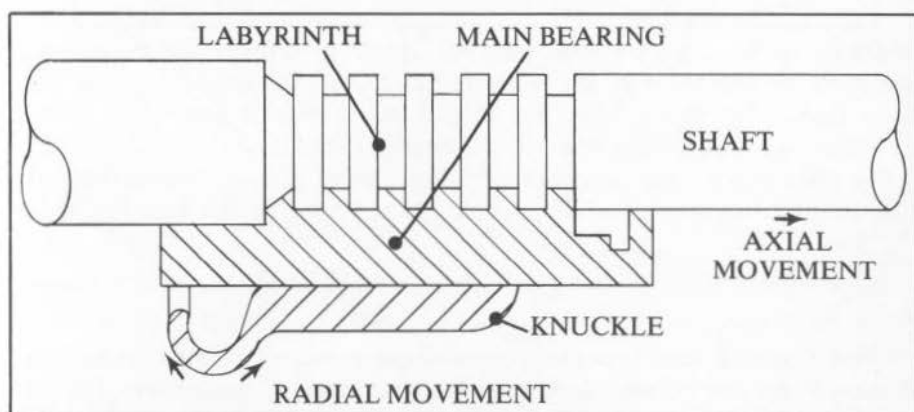
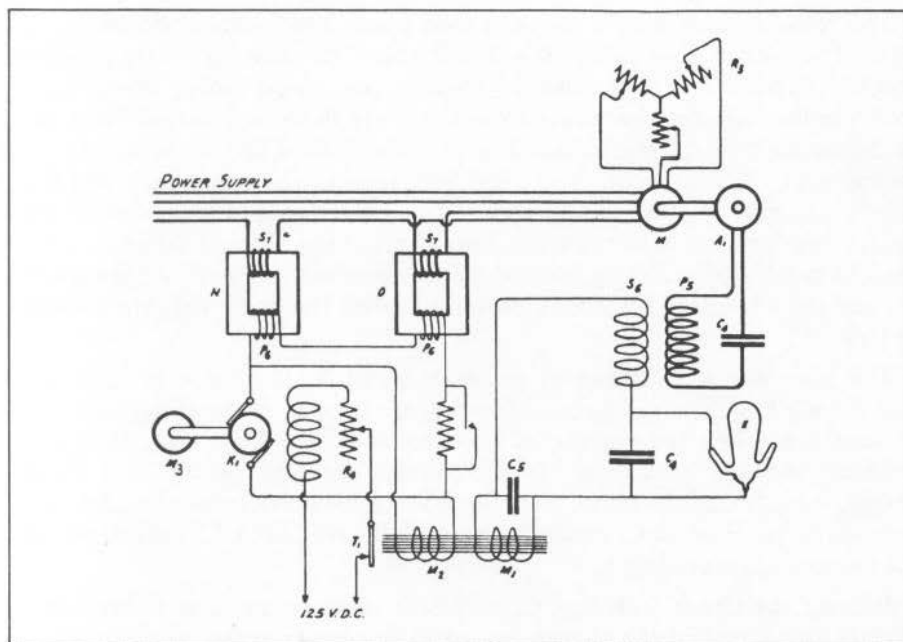


Fig. 4. Cross section of the bearing assembly and shaft.

It is interesting to observe that the labyrinth technology was already well developed in the steam-turbine discipline. The decision to use that type of bearing was an excellent choice, because it allowed Alexanderson to provide axial adjustment in both directions from a mean location.¹¹

The second system requirement was met with the development of the speed regulator. Because the antenna circuit is directly coupled to the alternator-output circuit through the high-frequency transformers, any change in rotational speed of the alternator will throw the alternator out of resonance with the antenna circuit. The variable load imposed by the key-up and key-down condition of radio telegraphy causes the speed of the alternator to vary, and Alexanderson calculated that a change in speed of 1% from that necessary to maintain resonance would reduce the antenna current to one-half its full value. He realized that the speed must be held much closer than that, and did obtain, with the use of his regulator, a regulation of speed within one-tenth of one per cent. With a design motor speed of 900 rpm, that control is regulating a total variation of 0.9 rpm.



The solution to the problem was found by Alexanderson in the use of a series-resonant circuit, tuned slightly above the frequency to be maintained by the alternator. One of the armature coils was tapped to supply the regulator circuit with current, and because it was a series-resonant circuit, the current in the circuit rose with alternator speed as resonance was approached. The voltage was rectified and superimposed on a voltage-regulator circuit, powered by a separate motor-generator set which supplied saturation current for a set of variable impedances in the two phases of the motor-supply circuit. Additional compensation for the load imposed when signaling was provided by a relay, operating through the D.C. control circuit to vary the line impedance.

Figure 5 is a diagram of the speed-regulator circuit. A coil in the alternator supplies a constant voltage at the frequency of the alternator. C_4 and P_5 are a capacitor and an inductor, tuned to a slightly higher frequency than the alternator was to produce. The coil S_6 is closely coupled to P_5 , but not so close as to affect the tuning of the resonant circuit. E is a rectifier of the G.E. Tungar or mercury-arc type. M_1 is an auxiliary control coil of the voltage regulator. By opening and closing contact T_1 , the voltage of the generator K_1 is controlled.

The resistors consist of a series of iron plates which extend down into a tank. The tank is then pumped with electrolyte (usually carbonate of soda (Na_2CO_3) and water) to the desired level. A centrifugal pump, driven by a small motor, lifts the electrolyte from the lower to the upper tank. A valve in the upper tank can be adjusted to give the desired level. The continued pumping of the electrolyte from the lower tank to the upper tank and the subsequent gravity flow back causes a rapid circulation and dissipates the heat energy with a minimum amount of steaming. Liquid controls were used in motors over 200 hp because of the simplicity, large thermal capacity, and the advantage for Alexanderson of being free from definite notches or steps.¹²

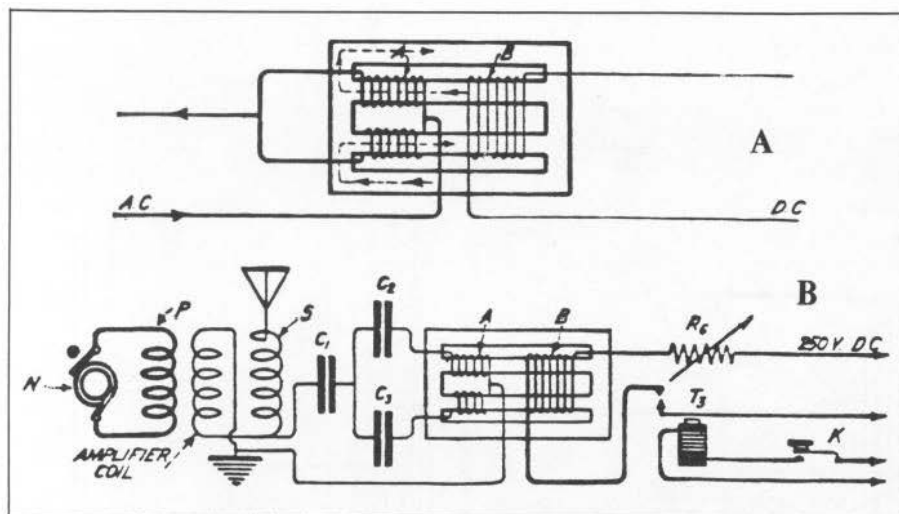
The generator K_1 is driven by motor M_3 , and is provided with field current from a D.C. source of constant voltage, varied by rheostat R_4 . Generally speaking, when the current in impedances N and O is zero, their impedance becomes maximum. If the current through central coil P_6 is enough to saturate the cores, their impedance becomes minimum. Any intermediate value of D.C. control current will vary the A.C. impedance of the two coils S_7 accordingly.

Because the circuit including C_4 and P_5 is series resonant to a frequency slightly above that of the alternator, it will develop increased current as the motor M speeds up. This sends a D.C. component through coil M_1 , aiding the D.C. already flowing in M_2 . By holding control T_1 open for a longer period of time, the voltage of generator K_1 decreases. This in turn decreases the current through central coils P_6 , and thereby increases the impedance in the power-supply circuit, decreasing the speed of the motor. When the motor speed falls, the rectified voltage through M_1 decreases, causing the voltage regulator to maintain a higher voltage on the generator (K_1) and increase the current through control windings P_6 , and again decrease the impedance in the power supply. In operation, a mean current is maintained through the central coils P_6 , holding the speed of the driving motor constant.

X The magnetic amplifier, an iron core surrounded by two sets of windings (Figs. 6A and 6B), was Alexanderson's solution for keying the alternator. High-speed keying without destructive arcing while handling the large antenna currents was the requirement. The magnetic amplifier was a variable impedance which was connected in parallel with the output of the alternator. Its function was to reduce the voltage of the alternator and detune the antenna system when the key was open, and to allow full voltage and antenna resonance when the key was down.

Winding A is connected in parallel with the alternator (N). Coil B is an excitation winding which includes both the positive-going and the negative-going flux produced by the A winding. Because these fluxes "buck" each other, no RF voltage is produced in winding B. Looking at Figure 6A, it is clear that any tendency to introduce a voltage on one side of the coil is counteracted by an opposing voltage on the other branch.

If the flux in the control winding B reaches saturation, the effect is that the impedance of coil A becomes that of a coil without an iron core; that is to say, reaches minimum impedance. If the opposite condition is present, that is,



Figs. 6A and 6B. Fig. 6A is a simplified drawing of the magnetic amplifier, and 6B is the magnetic-amplifier circuit.

when no control current is present in coil B, the impedance becomes maximum. With the addition of condenser C_1 , an increase in control sensitivity is achieved, and with the selection of proper capacity an almost-linear control curve can be achieved. In actual operation, the reduction in output was from 100% to 9% of the total current in the antenna circuit with telegraphic speeds reaching 500 words per minute. Condensers C_2 and C_3 served as decouplers, presenting a low resistance to RF currents. These condensers had no appreciable effect on amplifier-circuit tuning.

Relay T_3 , along with compensating relay T_2 (Figure 7), form the telegraphic signal-input circuit. The compensating relay shorts the resistance R_2 when the telegraphic-input circuit is closed, decreasing the impedance of N and O and increasing the power-supply input to the motor by an amount equal to that imposed by the load, without changing speed. This lightens the load on the speed regulator, and makes it responsible only for power-supply variation.¹³

The magnetic amplifier was also applied as a radio-frequency modulator for telephony. The control current was modulated by a bank of pliotron amplifiers, which in turn were driven by a carbon-button microphone. Using a 50-kW alternator and a modulated magnetic amplifier, telephony tests were performed between Schenectady and New York City. A variation in control current of 0.2 amperes changed the power of the antenna from 5.8 to 42.7 kilowatts—a change of nearly 37 kW. At the time it was believed that this was the greatest amount of radio energy ever controlled by telephony.¹⁴

The third requirement for an efficient antenna system resulted in Alexander's development of the multiple-tuned antenna, a radical departure from the types of antennas used at that time for high-power radio transmission. The

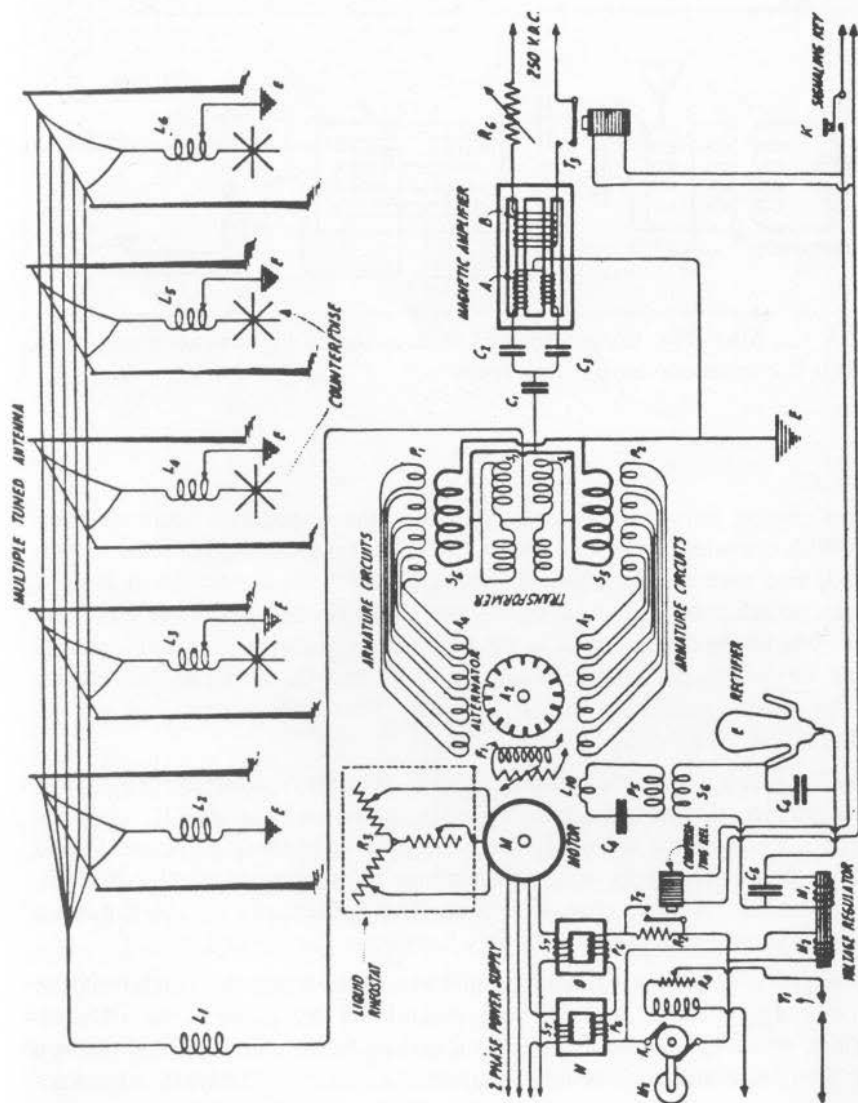


Fig. 7. A simplified circuit of a typical 200-kW station.

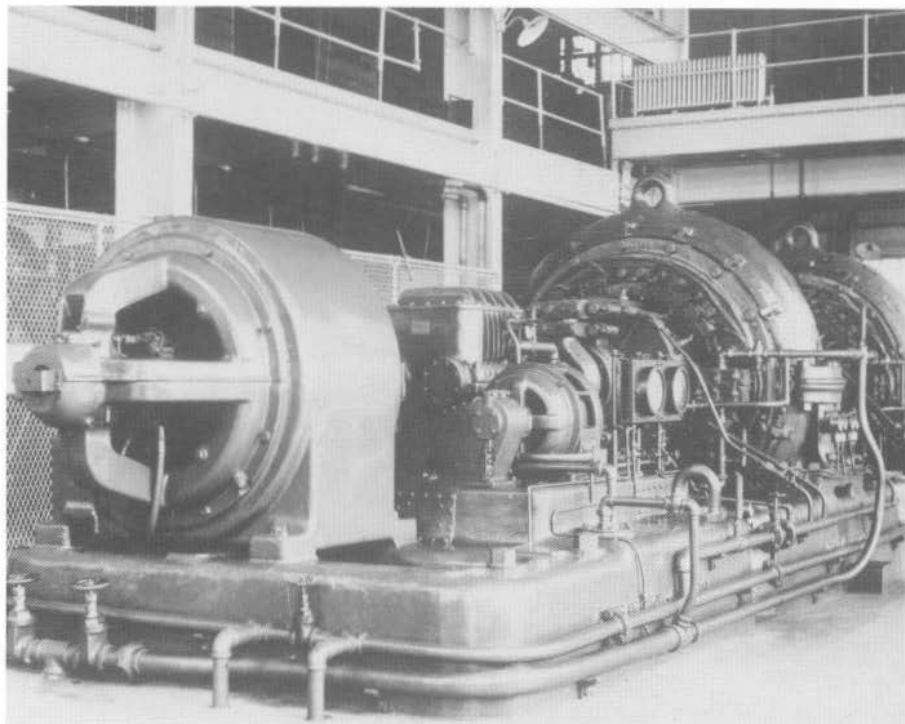


Fig. 8. The Alexanderson alternator at station WII, New Brunswick, N.J., showing the drive-motor end of the unit.

object of the multiple antenna was to reduce the wasteful resistance of the flat-top aerial. It has, instead of a single ground connection, six equally-spaced leads routed through tuning inductors to the earth. The capacitive reactance of the flat top is neutralized by the inductors, making the multiple antenna the equivalent of six independent radiators—all in parallel and resonant at the same wave length. The effective wasteful resistance is much less than that of an antenna with a single ground. To maintain 600 amperes in the multiple tuned antenna at New Brunswick at a resistance of $1/2$ ohm, the power required was $600^2 \times 0.5$, or 180 kW. To maintain the same antenna current with a resistance of 3.7 ohms exhibited in the flattop, 1330 kW were required. The same audibility at the receiving station, combined with less wasted power, was an important consideration from the standpoint of daily operation.¹⁴

With the fulfillment of the basic criteria for a "central power station for radio communication", the alternators were built at the rate of two per month. Their useful life, however, was short. The demise of the great units was foretold by the development of the high-power vacuum tube. The tube was cheap to make and could be operated at higher frequencies. However, the vision of mechanical radio-frequency generation had been fulfilled, and this passage from an address given by Alexanderson in 1920 gives insight into the

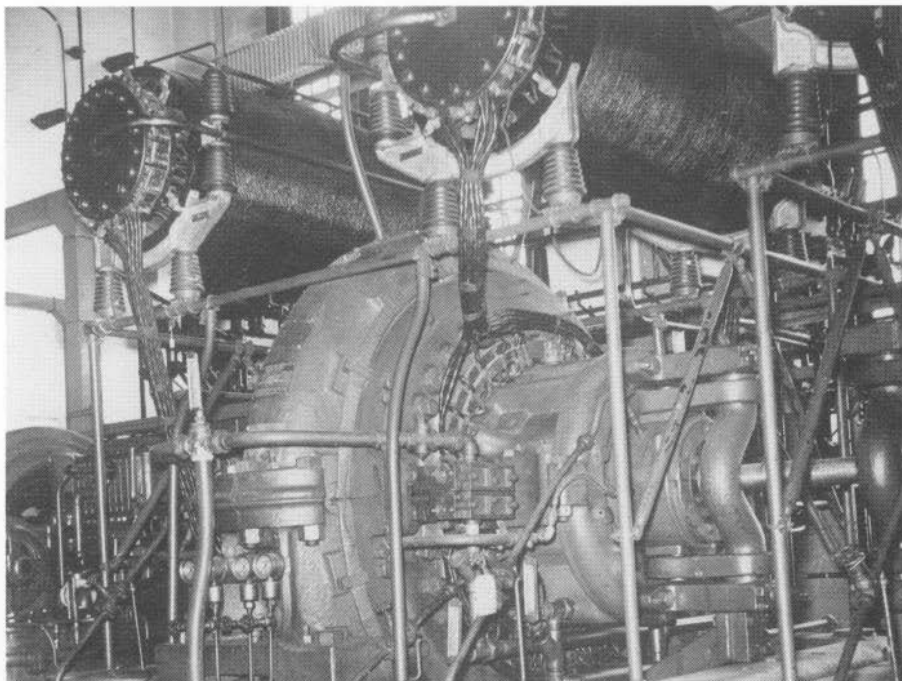


Fig. 9. The alternator at station WCI-WGG, Tuckerton, N.J. Shown are the main bearing, the equalizer lever, and the RF transformers on the pipe-frame supporting structure.

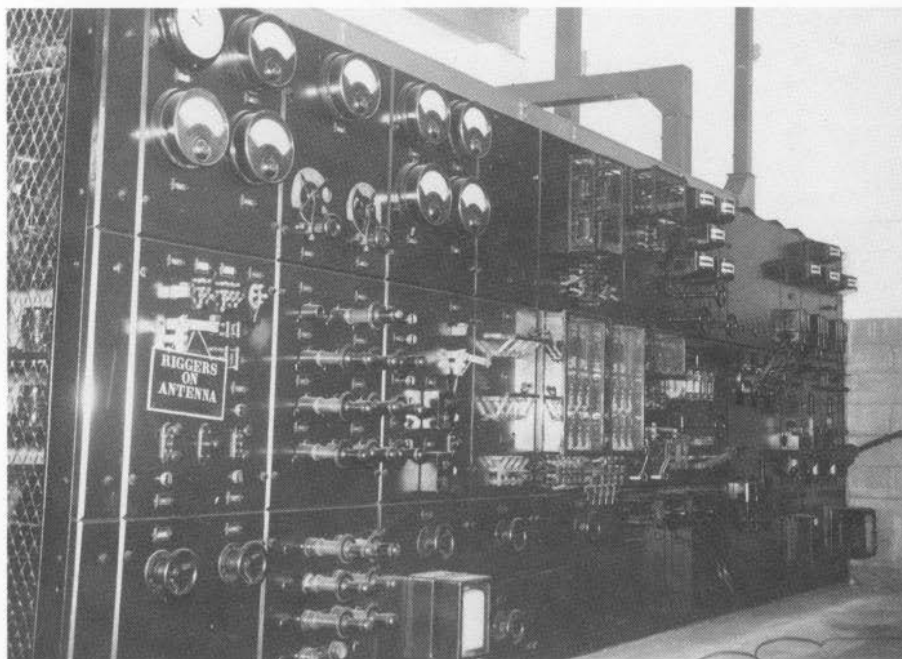


Fig. 10. The control panel at station WCI-WGG, Tuckerton, N.J. The speed-regulator board is the second panel from the left.

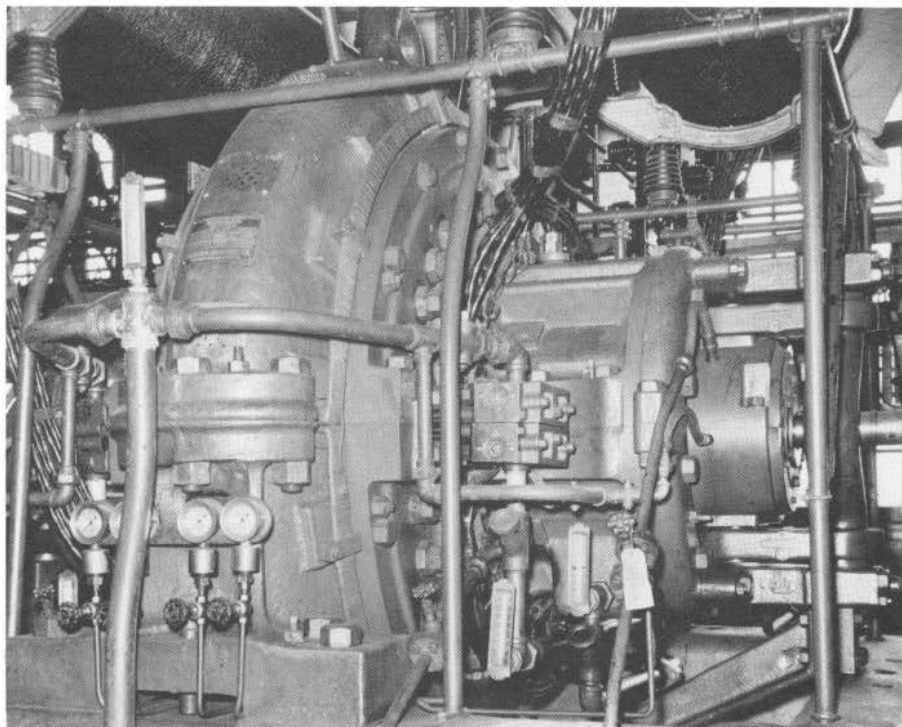


Fig. 11. A view of the water and oil-feed lines to the armature and bearings of the alternator at station WCI-WGG, Tuckerton, N.J. The oil-pressure gauges were not as important as the sight glass in the oil-return line on the other side, as a clogged line would continue to show pressure.

nature of the man who made it possible.

“Radio achievements are often referred to as belonging in the realm of mystery, and it is indeed wonderful that we are now able to speak with a voice that carries through empty space across the oceans. Whenever knowledge conquers a new force of nature for the use of humanity, it ceases to be a mystery, but the pursuit of the knowledge makes an even greater appeal to the imagination.”¹⁶

NOTES AND REFERENCES

1. See C.P. Steinmetz, *Theory and Calculation of Alternating Current Phenomena*, McGraw Hill, 1908, 4th Edition.
2. Hugh Aitken, *The Continuous Wave*, Chapter 2, p. 65, Princeton University Press 1985.
3. Alexanderson was not the first to use the inductor alternator at high frequency. See B.G. Lamme, "Data and Tests on a 10,000 Cycle-Per-Second Alternator", *AIEE Transactions*, Vol. 23, May, 1904, pp. 417-428.
4. U.S. Patent No. 905,621. *Specifications of Patents*, December 1, 1908, pp. 1020-1023.
5. R.A. Fessenden, "Electromagnetic Mechanism With Special Reference To Telegraphic Work", *Journal of the Franklin Institute*, July, 1900, pp. 62-80.
6. Rupert Staley, *Textbook on Wireless Telegraphy*, Vol. 11, Chapter XV, pp. 284-285. Longmans, Green & Co., 1919.
7. E.F.W. Alexanderson, "Alternator For One Hundred Thousand Cycles", *AIEE Transactions*, Vol. 28, June, 1909, pp. 399-412.
8. E.F.W. Alexanderson, "Magnetic Properties Of Iron At Frequencies Up To 200,000 Cycles", *AIEE Transactions*, Vol. 30, November, 1911, pp. 2433-2448. Especially permeability with respect to skin effect.

$$l_p = \frac{3570}{\sqrt{\lambda \mu f}}$$

Also see James E. Brittain, "The Alexanderson Alternator and the Distinction Between Engineering and Science," *Radio Club of America* (adapted from a paper published by Davidson College), 1984.

9. E.F.W. Alexanderson, "Central Stations For Radio Communication", *Proceedings of the IRE*, Vol. 9, 1921, p. 84.
10. William Graham "Description of the 200-kW Alexanderson Alternator", Engineering Dept. Circular No. 405, RCA Corporation, Nov. 1924.
11. Terrell Croft, *Steam Turbine Principles & Practice*, Division 5, Section 99, pp. 96-100. McGraw Hill, 1923.
12. James and Markle, *Controllers For Electric Motors*, Chapter 19, pp. 300-305. McGraw Hill, 1952.
13. See Elmer Bucher, "Technical Description of the Alexanderson System For Radio Telephone Transmission", *Radio Corporation of America*, 1920.
14. Alfred Goldsmith, *Radio Telephony*, Chapter V, pp. 116-126, Wireless Press, 1918.
15. E.F.W. Alexanderson, "How Some Problems In Radio Have Been Solved", *G.E. Review*, Issue 27, 1924, pp. 373-379.
16. E.F.W. Alexanderson, "Central Stations For Radio Communication", *Proceedings of the IRE*, Vol. 9, 1921, p. 83.

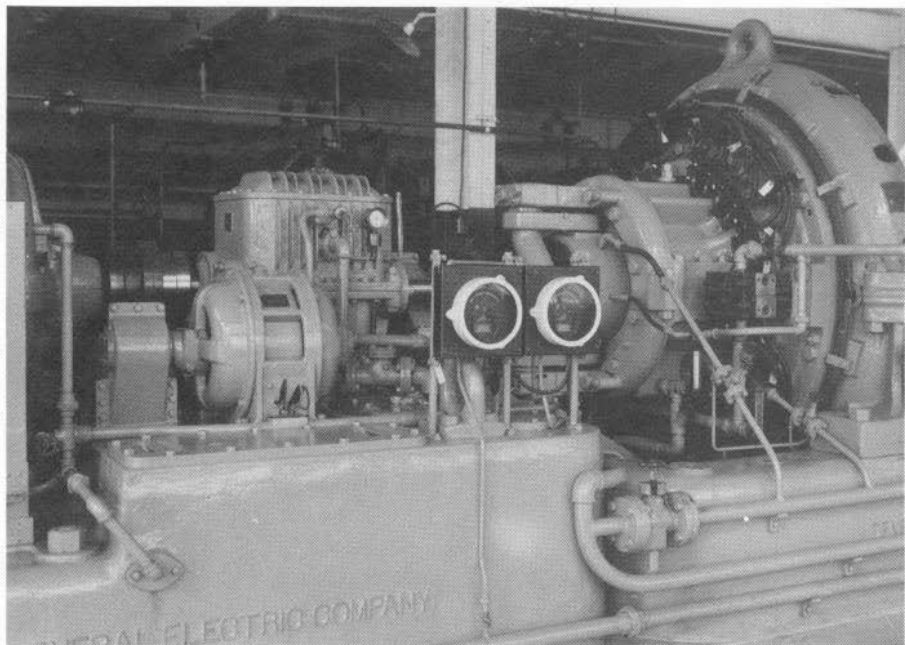


Fig. 12. The gearbox and separate oil-pump motor of the alternator at station WQR-WSO, Marion, Mass. Note the flexible coupling between the main driving motor and the gear box.

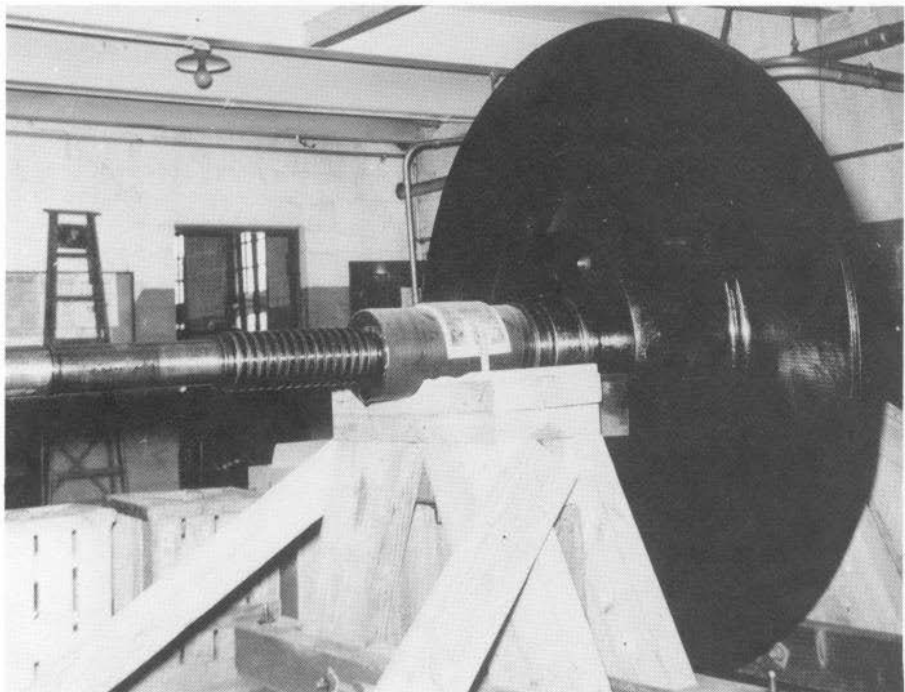


Fig. 13. A spare rotor covered with cosmoline. Note the main journal, protected in paper, and the labyrinth on the left.



Glen C. Fuller

Glen, an active A.W.A. member since 1980 and a second-term member of the Board of Directors, also served as an assistant curator of the A.W.A. museum. After becoming a licensed amateur in 1964, Glen developed an interest in early wireless and telegraphy, including researching the mechanical methods of radio-frequency generation and the life and works of Steinmetz. His strong background in historical wireless, coupled with his vocation as a tool and die maker, are currently being melded together in his construction of a working replica of Branly's Tripod Detector Receiver of 1908.

Photos: A.W.A. Museum