AN OSCILLATING ELECTRIC GENERATOR

By

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PREFACE

Technological developments of the last few years have brought forth a need for electrical power sources that heretofore have not been seriously considered. In connection with this problem, the Oklahoma A & M College was awarded a contract by the United States Air Force for the purpose of studying unconventional electrical power sources.

This thesis is a treatise on the oscillating electromagnetic generator which is considered an unconventional source of electrical power. It is hoped that the information presented in this thesis will stimulate further interest in this power source.

I wish to thank Professor Paul A. McCollum for his interest and valuable criticism in the preparation of this thesis. I also wish to extend thanks to Mr. Warren D. Stone for his help in gathering the experimental data contained in this thesis. I wish to thank Dr. H. L. Jones for making it possible for me to write this thesis and for his many helpful suggestions during the preparation stages. Thanks are also in order for the Thomas A. Skinner engineering staff for suggestions on the design of the permanent magnet generator.

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CHAPTER I

INTRODUCTION

The fundamental principle of operation for the generation of power by an oscillating electric generator is that of varying the flux linking a coil. Although this principle is well known, there seems to be no well formulated plan for using this principle as a power source. The question that naturally arises then is: "Does this method of generation of electrical energy have the qualifications that are desired for a practical power source?" This question is the foundation for this thesis.

The method of generation of electrical energy under discussion can be classified as an unconventional method.[1] "A conventional power source is a type, the use of which is common practice, and consists of primary or secondary batteries or of rotating machinery."[2] For classification purposes, all other sources of power generation are considered unconventional.

Three variations of electrical power generation by the oscillating electric principle were explored in the development of this thesis. The first system employs a coil moving in a magnetic field which is produced by a direct-current electromagnet. The coil mechanism can be operated with and without mechanical resonance. The second method makes use of a moving coil in a magnetic field which is produced by a strong concentric

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[1] Attie L. Betts and Paul A. McCollum, Unconventional Power Supply Sources, WADC Technical Report 54-509, September, 1954, p. 7.

[2] *Ibid.*

permanent magnet. The third method, known as the variable reluctance type, utilizes the variation of the air gap as a means of changing the strength of a magnetic field. Due to time limitations, the latter two methods are treated more lightly and only in a theoretical manner. They are discussed mainly for the purpose of showing the possible variations that can be applied to the oscillating type of generator.

It is believed that the unconventional power supply source described herein may have many applications when the efficiency, weight, reliability, and life expectancy are established. The procedures outlined in this thesis are those directed toward the successful oscillating electromagnetic generator. Much of the work contained in this thesis may be considered original in nature stemming from a background in electrical engineering. It must be pointed out, however, that the author has used many sources in search of a suitable approach to the solution of the problem and has given due credit to those concerned in each case.

When the overall scope of this work is considered, it is hoped that the compilation of these facts and experimental data will be helpful to those who will do further research on this subject.

CHAPTER II

BACKGROUND THEORY

The Action of a Conductor in a Magnetic Field

A very important discovery that helped bring about the development of present day electrical machinery was made by the English experimental physicist, Michael Faraday.[1] The experiment which led to Faraday's discovery may be performed by anyone who has a coil of wire, a bar magnet, and a sensitive current indicator such as a galvanometer. Assuming that one has the above equipment and wishes to learn of the action of a conductor when placed in a magnetic field, such as the one illustrated in Figure 1, he may carry out the following procedure.

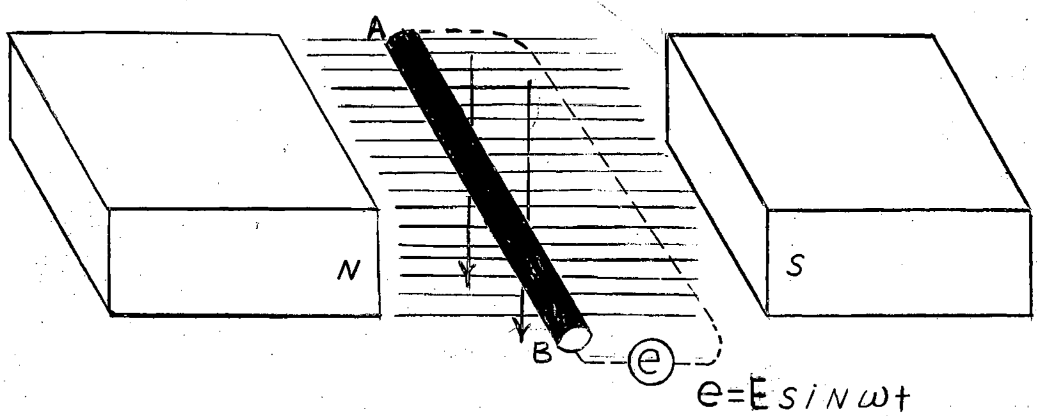

Figure 1. Conductor in a Magnetic Field.

In Figure 1, if the conductor A-B is allowed to move in the direction of the lines of flux, there will be no voltage generated by this

[1]Keith Henney and Glen A. Richardson, Principles of Radio (New York, 1948), p. 82.

action and no current flow will be registered by the galvanometer. If the conductor is moved perpendicular to the lines of flux it will cut these lines of flux and a voltage will be induced and a current flow will be indicated by the galvanometer. The magnitude of the induced voltage is dependent upon the strength of the magnetic field and the speed with which the conductor cuts the lines of force. Faraday's discovery was that of electromagnetic induction, which is outlined in the preceeding discussion and explains briefly the action of a conductor in a magnetic field.

The Elementary Electric Generator

An electric generator utilizing the fundamental principles set forth by Faraday, is a device for converting mechanical energy to electrical energy.[2] The principle of operation of such a generator is that an electromotive force is generated in a conductor which is subjected to the action of a varying magnetic field in such a manner that the conductor cuts the lines of magnetic flux. This principle is further illustrated in Figure 2.

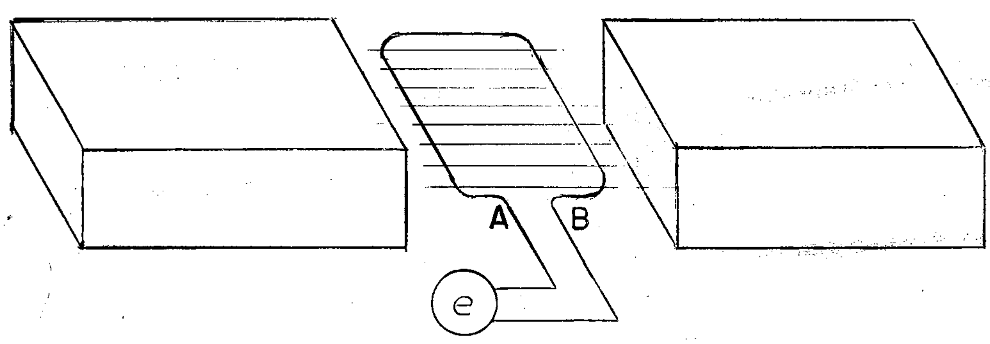

Figure 2. Elementary One-Turn Electric Generator.

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[2]Earl M. Morecock, Alternating Current Circuits (New York, 1954), p. 2.

In Figure 2, if the coil is rotated in such a manner that the conductor A-B is moved in the direction of the lines of flux there will be no voltage generated in the conductor. If, however, the conductor is moved so that it cuts the lines of flux, then a voltage will be induced in the coil that can be determined by the equation,

$$E = B\ell V \tag{1}$$

where $E =$ voltage in absolute volts,

$B =$ flux density of the air gap,

$\ell =$ length of the one-turn coil in centimeters,

$V =$ speed at which the coil cuts the lines of flux in cm. per sec.

If the single-turn coil is connected to a resistive load there will be a flow of current of I amperes, the exact value of which will depend upon the load resistance of the circuit in accordance with Ohm's law. The conductor will be acted upon by a force,

$$F = BI\ell \tag{2}$$

where $F =$ force in dynes,

$\ell =$ length of coil in centimeters,

$I =$ current in amperes.

The force, F, will be in a direction opposite to the motion, hence, to maintain the action, a driving force must be applied to the conductor and work must be done at the rate

$$FV = BI\ell V = E \cdot I \text{ ergs per second.} \tag{3}$$

In this discussion of the elementary electric generator only one conductor was assumed for the purpose of simplicity. Also, it was assumed that all of the energy supplied reappears as useful energy after the conversion process has been completed. Neither of these conditions are realized in practice since single-turn coil cannot generate sufficient useful energy for most applications and the energy supplied by the prime mover must be greater than the amount converted by an amount equal to the loss of energy due to friction, windage, and heating.

If the elementary electric generator described in the foregoing paragraph is expanded to include an armature with many turns, as illustrated in Figure 3, a more complete concept of the action of the generator is realized.

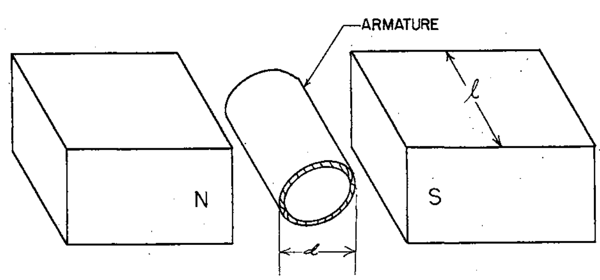

Figure 3. Elementary Electric Generator.

If the air gap between the poles faces N and S and the armature core is uniform, as is the case in machines of this type,[3] the magnetic lines of force will tend to cross the air gap on radial lines, and the field strength will be practically uniform everywhere under the poles. If it is assumed that a single turn of the generator in Figure 3 is passing parallel to the lines of flux, this will represent point zero on Figure 4.

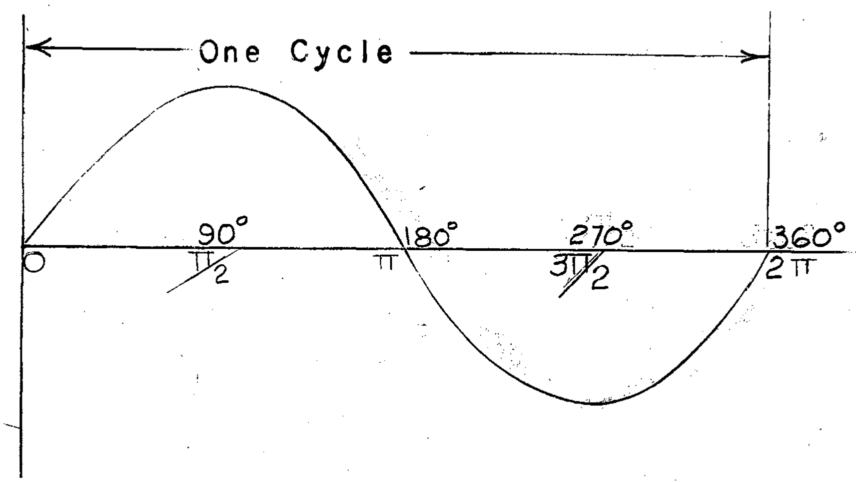

Figure 4. Sine-Wave Voltage Produced by an Electric Generator.

Assuming a machine has only two poles then one complete revolution will complete 360 electrical degrees. The position of the rotating member of a generator may be described in terms of the angle through which it moves. As the armature turns through the magnetic field, the voltage will increase until the maximum point is reached at $\pi/2$ radians, or 90 degrees. The voltage will decrease to zero again at π radians or 180 degrees, then the cycle is repeated in the opposite direction so that after two alternations, or one revolution, the complete cycle is traced

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[3]Alexander S. Langsdorf, Principles of Direct Current Machines (New York, 1937), p. 86.

out as indicated in Figure 4. One complete revolution is known as a cycle. The number of cycles per second is known as the frequency. The time required for one complete cycle is called the period and is the reciprocal of the frequency.

If the diameter of the armature is d centimeters, the active length of the armature ℓ centimeters, and if the driving speed is N revolutions per minute, the tangential velocity of a conductor on the armature is expressed as,

$$V = \pi D \frac{N}{60} \text{ centimeters per second} \tag{4}$$

When the conductor is cutting the magnetic field and the flux density has a radial component of B gausses, the generated voltage per conductor is

$$E = B \ell V \cdot 10^{-8} = \pi D \ell \frac{N}{60} \cdot 10^{-8} \text{ Volts} \tag{5}$$

Equation (5) may be generalized by assuming that there are Z conductors on the armature, and may be written as

$$E = \pi D \ell \frac{N}{60} ZB \cdot 10^{-8} \text{ Volts} \tag{6}$$

The basic principle of operation of all types of electric generators utilizing Faraday's Law is the same. Any differences in the analytic analysis of various machines is due to the mechanical configuration of the machines.

Oscillating Electromagnetic Induction

An electric generator incorporating the principle of oscillating electromagnetic induction also utilizes a means of varying the magnetic flux lines linking a coil.[4] Two electrical devices that use this principle are the variable reluctance phonograph pickup and the sound powered telephone. A discussion of these devices is not included in this thesis since they operate with a mechanical excitation of varying frequency, and aside from the fact that they make use of the Faraday's Law, these types have little relation to the power type of generator under study.

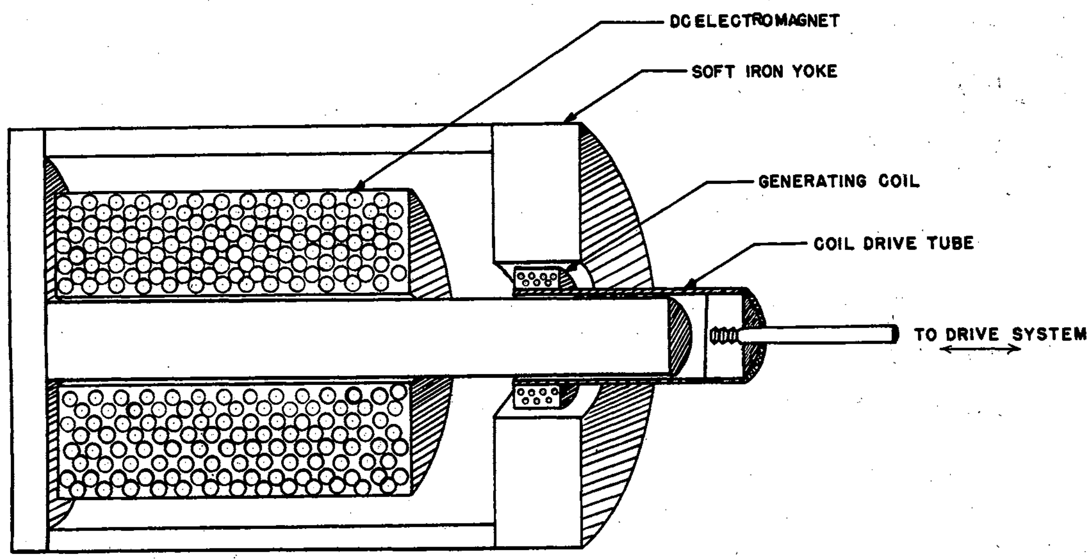

Figure 5. Cutaway View of Oscillating Electromagnetic Generator.

A cutaway view of an oscillating electric generator is shown in Figure 5. The direct-current electromagnet provides sufficient field strength to produce a large flux across the air gap. The coil is vibrated in this air gap at a frequency determined by the prime mover which produces the driving force. The voltage generated in this manner may be calculated as

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[4]Betts and McCollum, p. 3.

$$E = N\frac{di}{dt} = \frac{N}{10^8}\frac{di}{dt} = \frac{N\omega B\pi D s}{10^8}\cos\omega t \qquad (7)$$

where $s =$ total lateral displacement of coil in inches,

$\phi_t =$ total flux lines cut,

$\phi_i = BA(t) =$ instantaneous total lines cut,

$S = s \sin\omega t,$

$A(t) = \pi D S(t) = \pi D s \sin\omega t,$

$$\frac{d\phi_i}{dt} = -\omega B\pi D s \cos\omega t.$$

A more complete description of an experimental oscillating electric generator is included in Chapter V.

CHAPTER III

THE VARIABLE RELUCTANCE OSCILLATING GENERATOR

The purpose of this chapter is to acquaint the reader with the principle of the variable reluctance method of voltage generation. Time did not permit an investigation into this principle to the extent necessary for the design of an experimental model. The design problem is quite difficult due to the difficulties involved in the application of the variable reluctance principle. It is the opinion of the author that considerable time should be spent in the gathering of experimental data from a laboratory model in order to establish definite boundary conditions for a practical design of a device employing this principle. The principle of operation and problems of design are discussed in the following paragraphs.

Principle of Operation

A drawing of a typical variable reluctance type of generator is shown in Figure 6. The device consists of a strong permanent magnet, a generating coil, an oscillating element composed of soft iron, and a set of springs.

The oscillating element is allowed to move back and forth in the field produced by the permanent magnet at a frequency determined by the prime mover. The variation of the flux density due to the change in the air gap will produce an alternating voltage in the output coil. The springs are attached to the oscillating element in order to bring it into mechanical resonance and thus reduce the mechanical losses.

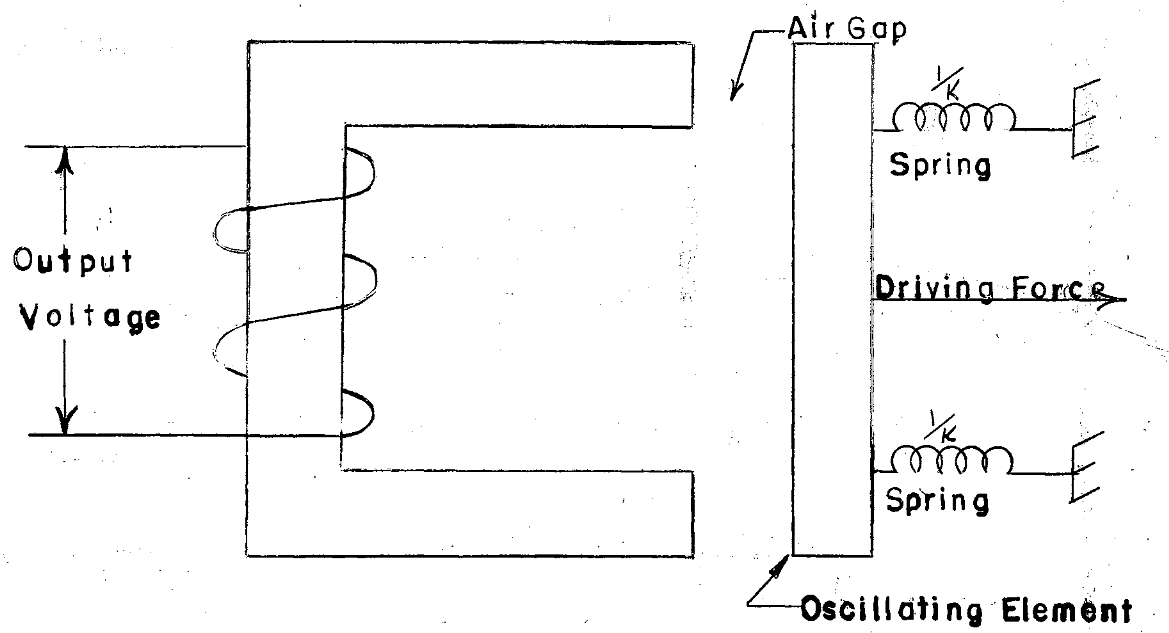

Figure 6. Variable Reluctance Generator.

A further discussion of mechanical resonance is included in Chapter V and is verified by experimental results.

This type of generator has two distinct advantages over the oscillating coil type of generator. The first advantage is that a greater number of turns may be used without adding mass to the moving element. The second advantage is that the loss due to friction is less due to lighter loading on the bearing surfaces. The disadvantages of this device results from the nature of the varying flux density. This introduces magnetic losses and produces a greater harmonic content in the output voltage because the flux variation across a variable air gap is seldom linear to a magnetic circuit. Also, the force delivered by the prime mover is not uniform throughout a cycle of operation.

Design Problems

In the design of the variable reluctance type of generator, two problems are immediately encountered. The first problem deals with the spacing of the air gap, the flux density, and optimum size for desired voltage output. The second problem is that of leakage flux and fringing effects.

In examining the first problem, it is not easy to determine the minimum spacing of the air gap because the maximum pull is imparted to the oscillating element at the point where the field strength is greatest. It is also difficult to determine maximum spacing of the weaker field strength for this condition. Due to the fact that the flux density in the air gap does change during a cycle of operation, and since this change cannot be expressed analytically, any design procedure becomes one of an empirical process.

The experimental approach would appear to offer a more direct solution to the problem. However, it is believed that a considerable amount of data would have to be obtained in order to establish the optimum spacing requirements. The problem of flux fringing and leakage would require refinement of the configuration of the magnet and oscillating member once the length of the air gap was established. The best solution here would also appear to hinge on experimental results.

CHAPTER IV

THE PERMANENT MAGNET GENERATOR

The purpose of this chapter is to explain how the permanent magnet type of oscillating generator may be designed. No experimental data is included, but since a small size generator would probably incorporate a permanent magnet, it is considered important that this type of design be discussed in some detail. The general theory is presented first, followed by the design of a permanent magnet generator of the oscillating type.

Permanent Magnet Characteristics

Permanent magnets are shaped pieces of ferromagnetic material, usually alloys of iron, which once having been magnetized, show definite resistance to external demagnetizing forces. The basic function of a permanent magnet is to supply, usually in an air gap external to the magnet, a permanent magnetic field without the application of external energy.

Hard magnetic materials differ from soft magnetic materials in that a larger applied field or magnetizing force is needed to induce the same amount of resultant magnetism in the material.[1] Permanent magnets require a high coersive force to remove the resultant magnetism. The permeability, μ, or the ratio between the resultant magnetism, B, expressed in gausses, and the applied field, H, expressed in oersteds, is low for hard permanent magnets and high for soft magnets.

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[1]Mueller, George V. Introduction to Electrical Engineering (New York, 1940), p. 168.

<u>The Hysteresis Loop</u>

In order to be able to make the proper choice of a permanent magnet for a given application, it is necessary to understand the magnetization curve, and the hysteresis loop.[2] The magnetization curve, shown in Figure 7 by the line from 0 to X, is obtained by subjecting a magnetic material, which has not been magnetized before or which has been carefully demagnetized, to a gradually increasing magnetizing force, H. This may be accomplished by gradually increasing the electric current in a coil of wire wound around a material.

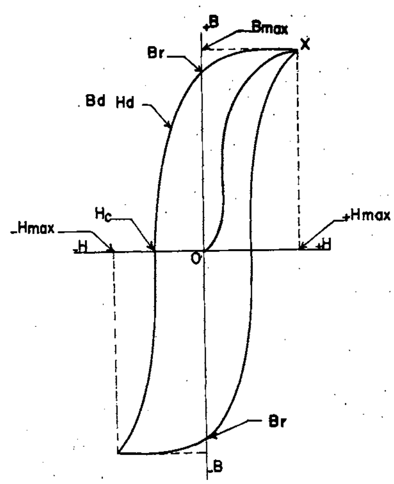


Figure 7. Hysteresis Curve.

As shown, point X represents the peak saturation of magnetic flux density, B_{max}, in the material when subjected to the peak magnetizing force $+H_{max}$.

[2]Mueller, p. 147.

If the magnetizing force, H, is gradually reduced from the highest applied value, $+H_{max}$, to zero, the resultant magnetization in the material decreases to the value B_r which is known as the residual magnetism. If the magnetizing force is then reversed and increased in the negative direction, the resultant magnetization in the material is eventually reduced to zero. At this point, the value of the demagnetizing force is $-H_c$, which is known as the coersive force. Increasing the demagnetizing force to $-H_{max}$ results in changing the value of B from positive to negative or changing the magnetic polarity of the material. The negative B_{max} corresponds in value to the positive B_{max}. The right-hand side of the curve is obtained by a repetition of the same procedure but starting with negative H_{max}. In this manner a complete hysteresis loop for a permanent magnet material is obtained.

Demagnetization and External Energy Curves

The demagnetization curve used for magnet design is the portion of the hysteresis loop in the second quadrant. The curve, from B_r to $-H_c$ is shown on the left in Figure 8 and on the right in the product or external energy curve.

If the product of corresponding values of Bd and Hd at any point on the magnetizing curve are plotted, the external energy curve is obtained as shown in Figure 8.

The residual magnetism, B_r, is the point where the demagnetization curve intersects the B axis and is a measure of the ability of a magnet to retain its magnetism when it is not subject to adverse treatment. It is the magnetic flux density corresponding to zero magnetizing force.

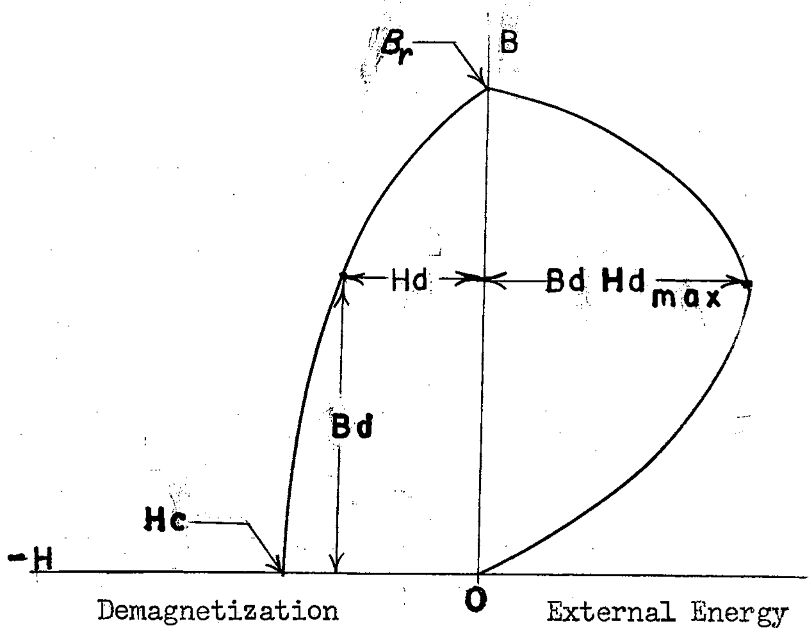


Figure 8. Demagnetization and External Energy Curve.

This value of magnetic flux, B, indicates the manner of flux lines per square centimeter that the magnet can maintain in a closed magnetic circuit. The higher the value of residual magnetism, the smaller the cross section of the magnet required to maintain a given total flux.

The coersive force, H_c, is the point where the demagnetizing curve intersects the H axis. This value of H_c is the demagnetizing force required to reduce the residual magnetism to zero. In general, the higher the coersive force, the shorter the magnet required to maintain a given air gap density.

The external energy curve, which indicates the product of the values of Bd and Hd for any given point on the demagnetization curve, is a graphical representation of the variation of available potential energy which the magnet can furnish for external use at the various operating flux densities. The product, Bd x Hd, is therefore, proportional to the magnetic external energy.

The external energy curve signifies the optimum magnetic flux density, B, at which a permanent magnet will give the maximum energy output. Therefore, if a permanent magnet is to have a minimum volume, the design factors must be so controlled that the magnet will operate at this optimum flux density for the maximum available energy.

Fundamental Magnet Terms

Some basic magnet terms have already been discussed. However a tabulation and explanation of the more important terms are in order before the actual design problem is considered. The following terms are employed:

Bd = Flux density in the magnet

Bg = Flux density in the air gap

Hd = The H coordinate on the demagnetizing curve corresponding to BD

Am = Cross sectional area of the magnet measured at right angles to the flux

Ag = Cross sectional area of air gap measured at right angles to the flux direction

Lm = Length of the magnet measured parallel to the flux direction

L = Lg Length of the air gap measured parallel to the flux density

f = Reluctance factor which varies from 1.1 to 1.4 normally; 1.3 is generally used, in design

F = Leakage factor which varies from 1.5 to very large values depending upon the circuit.

The Design of an Oscillating Permanent Magnet type of Generator

The design of a generator of the permanent magnet type may be broken down into two main parts, the magnet with yoke, and the oscillating coil. In the design outlined an Alnico II[3] magnet was chosen because it has high flux density and is not as brittle as other high flux producing magnets. Also, hysteresis, demagnetization, and external energy curves are readily available for this particular magnet.

Design of the Magnet

A concentric configuration was chosen since this type of magnet has less flux leakage and also produces a radial magnetic field. A drawing of the magnet is shown in Figure 9. It is desired that this magnet produce maximum flux in the air gap with the dimensions of K, J, and M that are given on the drawing in Figure 9.

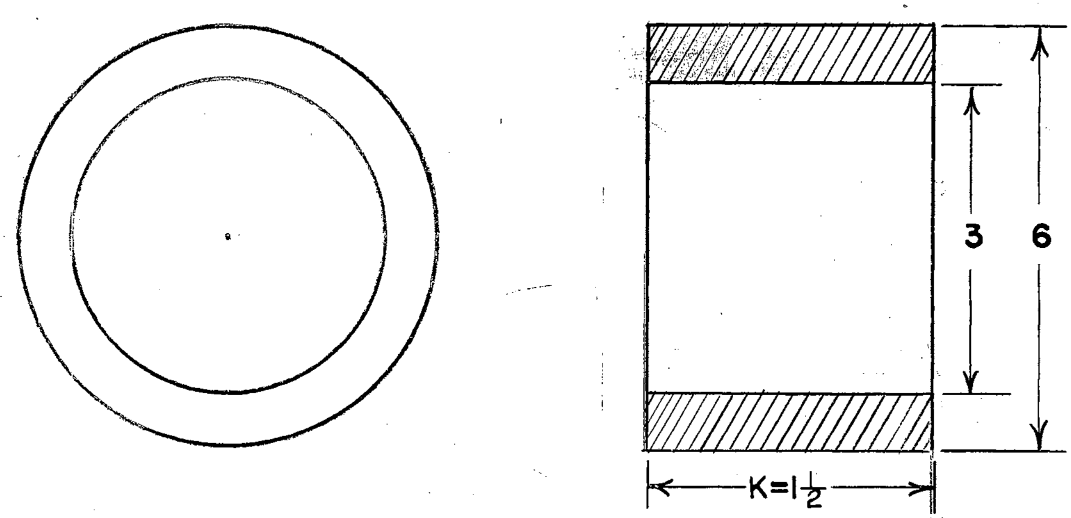


Figure 9. Concentric Permanent Magnet.

[3]Alnico II, an alloy magnet with a nominal composition of 10% aluminum, 17% nickel, 12% cobalt, 6% copper, and 55% iron.

It follows then that,

Area of the magnet (Am) = K(J-M) = 1 1/2 (6-3) = 4.5 in^2,

Length of the magnet (Lm) = $\pi/4$ (J + M) = .785 (6 + 3) = 7.07 inches,

F = 2.5 (estimated),

f = 1.5 (estimated),

Area of air gap (Ag) = (1 1/2) (2π) = 9.42 in^2,

Length of air gap (Lg) = 1",

$$Bd/Hd = \frac{(F)(Ag)(Lm)}{(f)(Am)(Lg)} = \frac{(2.5)(9.42)(7.07)}{(1.5)(4.5)(1)} = 23.4.$$

From the curve in Figure 10, Bd vs Hd, Bd = 4800, gauss, Hd = 220 oersteds,

$$Bg = \frac{(Bd)(Am)}{(F)(Ag)} = \frac{(4800)(4.5)}{(2.5)(1)} = 8{,}650 \text{ gauss.}$$

The Yoke

The magnetic yoke that is to hold the magnet should be of soft iron of high permeability. A cutaway view of the yoke is shown in Figure 11.

The pole piece should have a cross-section area as large as the rest of the frame in order to prevent saturation. Also, the pole piece should extend beyond the edge of the magnet in order to reduce the fringing effects. The dimensions shown on Figure 11 were chosen after the magnet was designed. It should be pointed out that the dimensions are not overly critical as long as a good flux path is assured. It is desirable for the frame work to be cast in one piece and then machined to the proper dimensions.

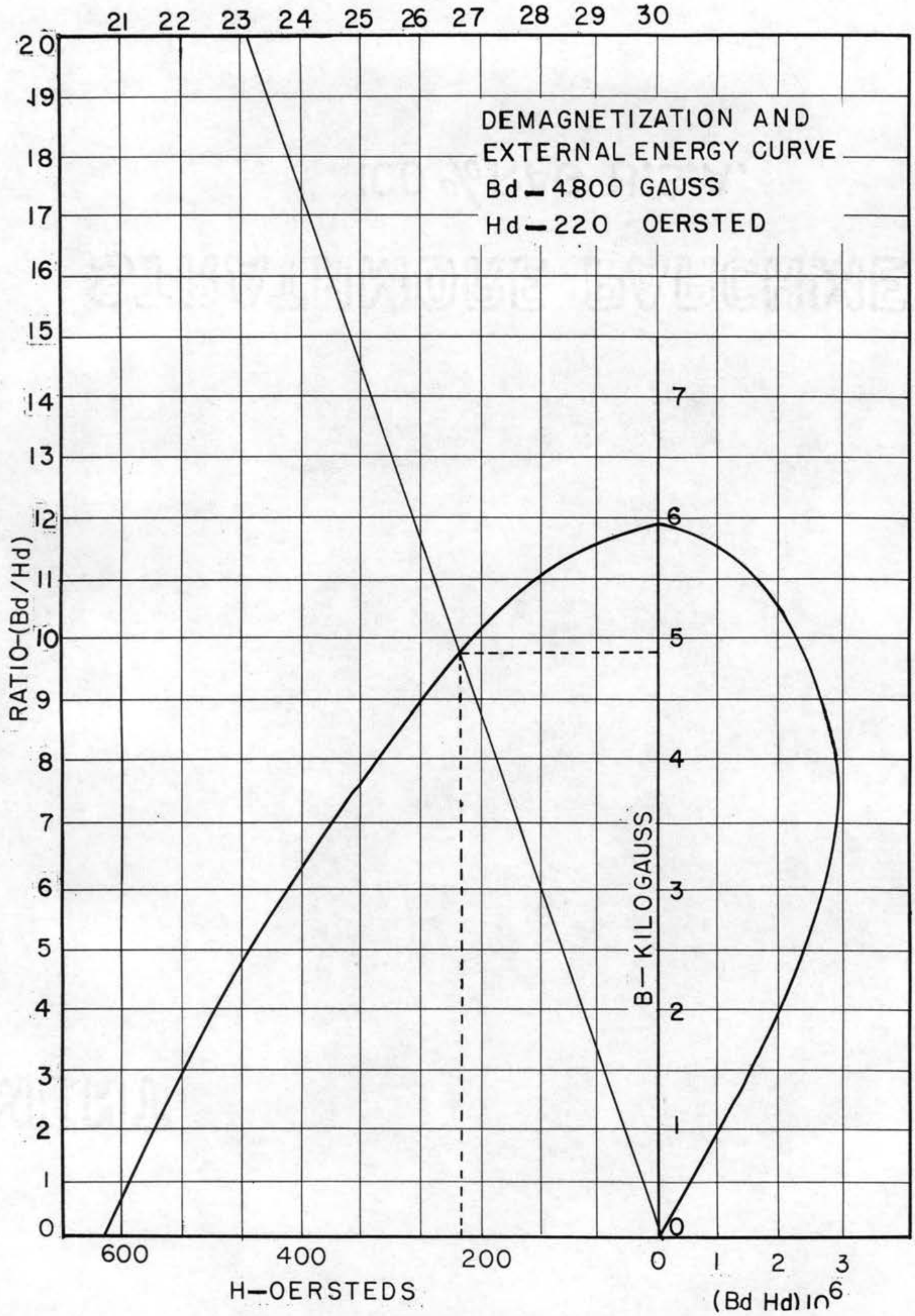


Figure 10. Demagnetization and External Energy Curve for Alnico II Permanent Magnet.

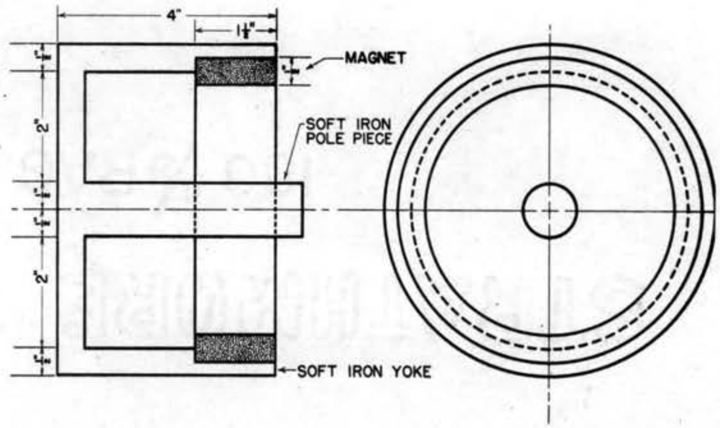


Figure 11. Cutaway View of Magnetic Yoke.

Design of the Generating Coil

The size of the generating coil is determined after the magnet has been designed, as the coil has to oscillate freely in the air gap of the magnet. The coil should be slightly smaller than the air gap in the center of the magnet in order to move freely on the pole piece. Once the flux density in the air gap is determined and the material for the coil has been chosen, a coil of suitable dimensions may be designed to produce a desired voltage output. In this case, it is assumed that size 24 copper wire is to be used and an Alnico magnet that produces 12600 lines per square centimeter across the air gap. A drawing of the proposed coil is shown in Figure 12.

The area of the coil, Ac, will be

$$Ac = L(M-N) = \frac{1}{2}\left(2\tfrac{7}{8} - 1\right) = 0.875 \text{ square inches.}$$

If size 24 AWG enameled copper wire with a circular mil area of 404 circular mils per wire is used, the total number of turns will be

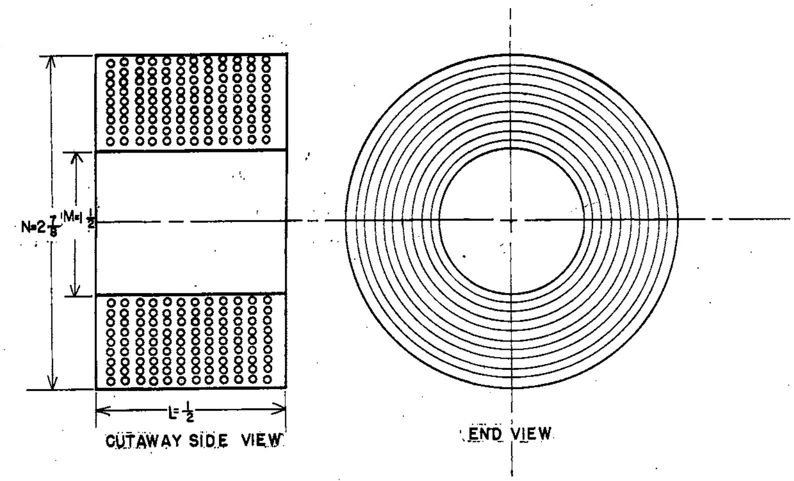


Figure 12. The Oscillating Coil.

equal to, $\frac{\text{total area (circular mils)}}{\text{Area of \# 24 wire (circular mils)}}$ = 1000 turns.

If the magnet produces a flux of 12,600 gauss (line per square centimeter) in the air gap there would be approximately 5000 lines of flux across the particular air gap of Figure 11. If the total lateral displacement of the coil is 1/2 inch, the the voltage produced may be calculated as

$$e = -N\frac{di}{dt} = -\frac{N\omega B\pi Ds}{10^8}\cos\omega t \qquad (7)$$

A peak voltage of approximately 50 volts may be obtained from this generator if the oscillating frequency is 20 cycles per second.

If the value of the resultant voltage output does not meet the requirements at hand, changes in the flux density, the number of coil turns or the length of coil travel can be made. The available rated current output of the generator is limited by the size of the wire on the coil. In general, an allowable current of one ampere per 500 to 1000 circular mils is accepted as a maximum limit for the coil current.

The use of permanent magnets on large generators is not considered economically feasible at the present time. However, for small generators, the use of a permanent magnet as a source of field flux would allow simplification of the generator as well as a reduction in weight and volume. Furthermore, it should be pointed out that many variations in output voltage waveform could be attained simply by controlling the motion of the generating coil with various shaped cams.

CHAPTER V

THE CONCENTRIC OSCILLATING ELECTROMAGNETIC GENERATOR INCORPORATING MECHANICAL RESONANCE

The Experimental Generator

An experimental model of the oscillating electromagnetic generator of concentric design was constructed and tested to verify the theoretical concepts that were advanced in Chapter II. An exploded view of the generator is shown in Figure 13.

The component parts of this generator consists of a housing, assembly, a d-c electromagnet, pole piece, a concentric iron yoke,

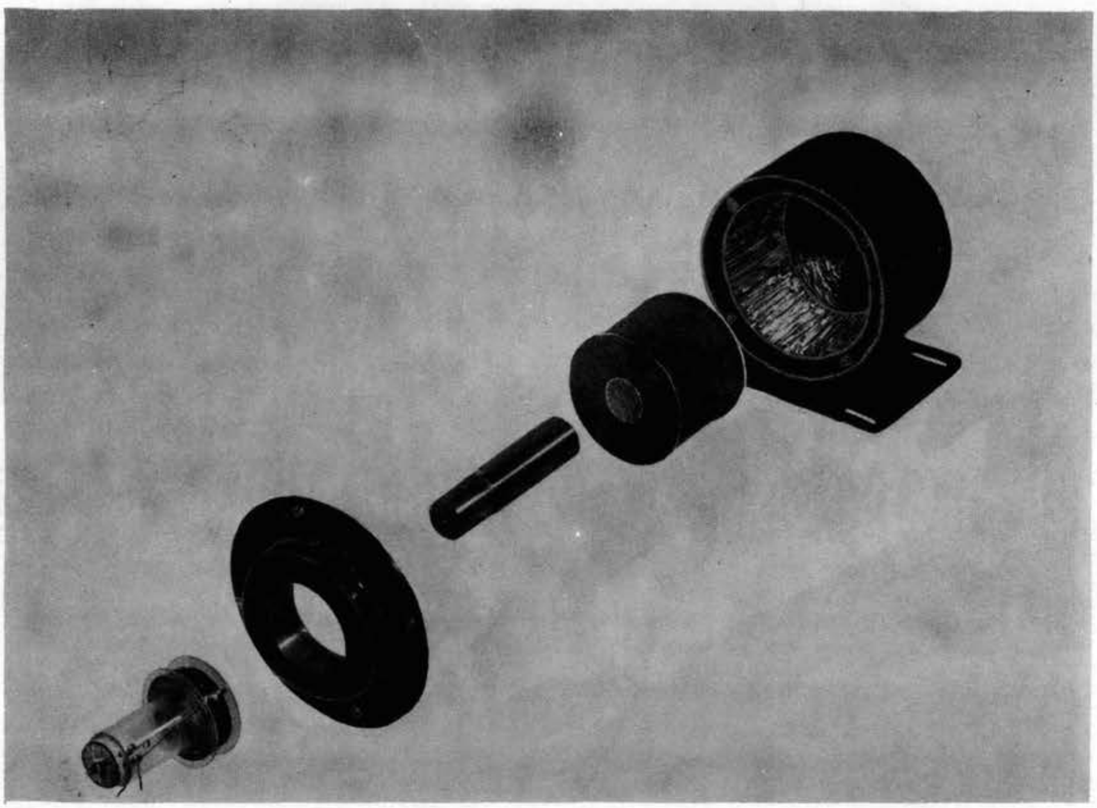


Figure 13. Exploded View of Concentric Oscillating Electromagnetic Generator.

and generating coil. The coil, shown in Figure 14, slides back and forth on the pole piece with harmonic motion.

The d-c electromagnet produces a flux density of approximately 1650 gauss and the coil has 500 turns of number 23 wire. The generator develops approximately 7 volts rms at a frequency of 20 cycles per second. The advantages of the concentric design is that little leakage flux exists and each element of wire in the coil cuts the same amount of flux at the same instant of time.

Figure 14. Generating Coil for the Concentric Oscillating Generator.

The Electrical Power Factor Analogy

In an electrical system consisting of a prime mover driving a generator, which in turn delivers electrical power to a load, the power factor of the load is often corrected to a higher value by the use of a parallel capacitor. The reason for correcting the power factor is to reduce the heat losses of the generator. This requires the prime mover to do less work for the same amount of power consumed by the load. It is proposed that when the mass of the mechanical system associated with the oscillating generator is resonated with the compliance of the springs, less power input will be required by the prime mover. This situation is exactly analogous to that of the power factor correction of an electrical system. In the analogous mechanical system, less friction loss will be produced in the prime mover system if the mechanical load is made resonant by the application of springs.

In order to illustrate more fully the analogy between the mechanical case and its electrical equivalent, an example is introduced at this point. The electrical system and its mechanical counterpart as shown in Figure 15, and 16 respectively.

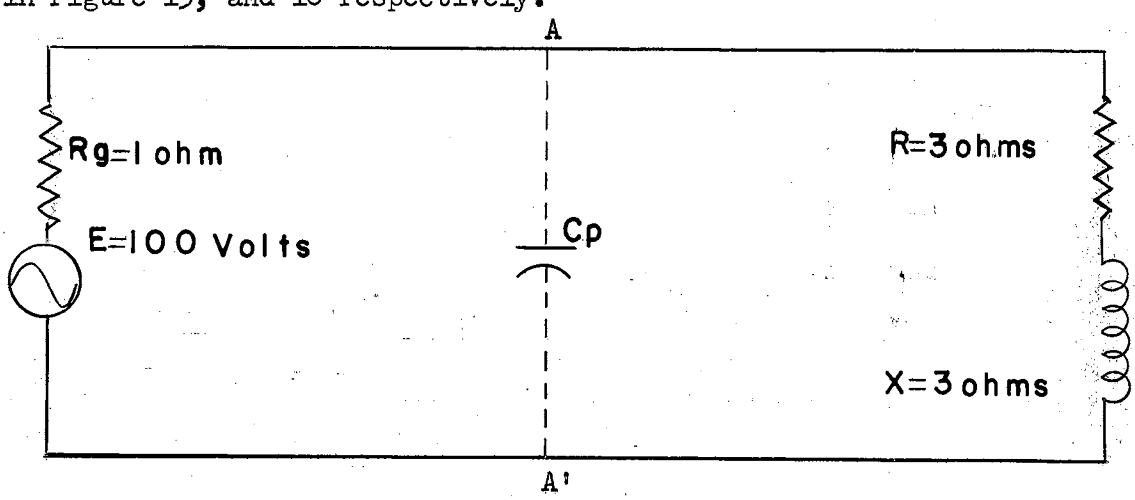


Figure 15. Equivalent Electrical Circuit to a Mechanical System Having Mass and Friction.

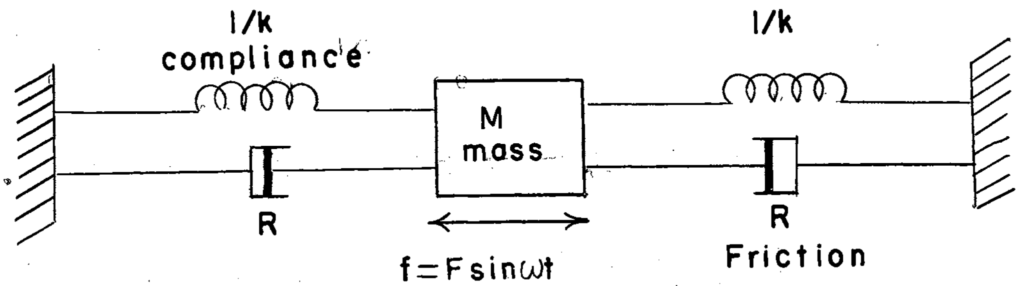


Figure 16. A Mechanical System Resonated by Means of Springs.

The generator in Figure 15 produces an internal emf of 100 volts and has an internal resistance of 1 ohm.

The total impedance to the flow of current is

$$Z_t = R_t + jX_t = 4 + j3 = 5\angle 36.9^\circ \text{ ohms} \tag{8}$$

and resulting current flow is

$$I = \frac{E}{Z} = \frac{100 + j0}{4 + j3} = 16 - j12 = 20\angle 36.9^\circ \text{ amperes} \tag{9}$$

The true power delivered to the load is

$$P_{load} = I^2 R_L = (20)^2 (3) = 1200 \text{ watts} \tag{10}$$

and the heat loss in the generator is

$$P_g = I^2 R_g = (20)^2 (1) = 400 \text{ watts} \tag{11}$$

The power factor of the load is

$$pf = \cos \theta \tag{12}$$

where

$$\begin{aligned} \theta &= \tan^{-1} X/R \\ \theta &= \tan^{-1} 3/3 \\ \theta &= 45^\circ \end{aligned} \tag{13}$$

hence

$$pf = \cos 45^\circ = .707 \text{ lagging} \tag{14}$$

In order to correct the power factor of the load a capacitor is installed across the load at points AA' in Figure 15.

The susceptance of the load will be

$$B_L = \frac{X}{Z^2} = \frac{3}{3^2+3^2} = -j0.166 \text{ mho} \tag{15}$$

and the susceptance of the correcting capacitor will be

$$B_C = B_L = -j0.166 \text{ mho} \tag{16}$$

The capacitance of such a capacitor can be readily computed from equation (9). This will have a quadrature component of current, which is leading, that is equal to the quadrature component of the load current, which is lagging. Thus the total current delivered by the generator will be smaller. This is illustrated in the vector diagram in Figure 17.

Since the capacitor is in parallel with the load, the current through the load will not be changed and thus the true power delivered to the load will remain the same. However, the generator current will be smaller. The I^2R_g heat loss will require less power from the prime mover since the generator current has decreased. The new generator current, after the capacitor is installed, will be equal to the inphase component of the load current or 16 + j0 amperes.

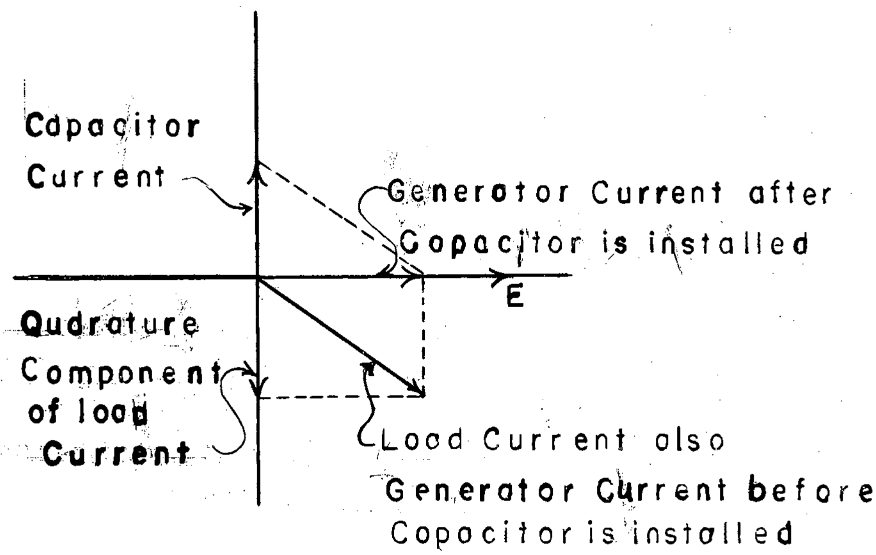


Figure 17. Vector Diagram Showing the Effect of Correcting the Power Factor of the Electrical Circuit to Unity.

Therefore, the power loss in the internal resistance of the generator is

$$P'_g = (I')^2 (R_g) = (16)^2 (1) = 256 \text{ watts} \tag{20}$$

as compared to 400 watts.

The total power delivered by the generator would now be 1456 watts as compared to the 1600 watts previously obtained. The installation of the capacitor has thus increased the efficiency from a value of 75 per cent to 82.5 per cent.

The example shows that the efficiency of the system can be improved by the correction of the electrical power factor. Similarily, the mechanical power factor can be improved by addition of springs to the oscillating coil and the adjustment of the springs so that the mechanical resonant frequency corresponds to the frequency of motion of the generating coil. Actually, a maximum gain in efficiency of 11 per cent was obtained in the experimental generator by using the mechanical resonance principle. The details of this experiment appear in Chapter VI.

Mechanical Resonance

In a forced vibrating system,[1] such as the case of the oscillating coil generator with springs attached, the natural resonant frequency depends upon the mass of the oscillating coil and the compliance of the springs. When the external driving force, which produces the forced vibration, is exactly in step with the natural frequency, the frequency of the free vibration is said to be in resonance with the driving force. If no friction were present, and the motion of the system was unrestricted, the amplitude of the resonant vibration would become infinite. This is illustrated in Figure 18.

In a practical machine, friction is always present, therefore, the resonant amplitude builds up until the rate of energy dissipation becomes just as large as the rate of energy supplied through the driving force. If the driving force were removed, the vibration would continue

[1]Arthur L. Kimball, Vibration Prevention in Engineering (New York, and London, 1932), p. 3.

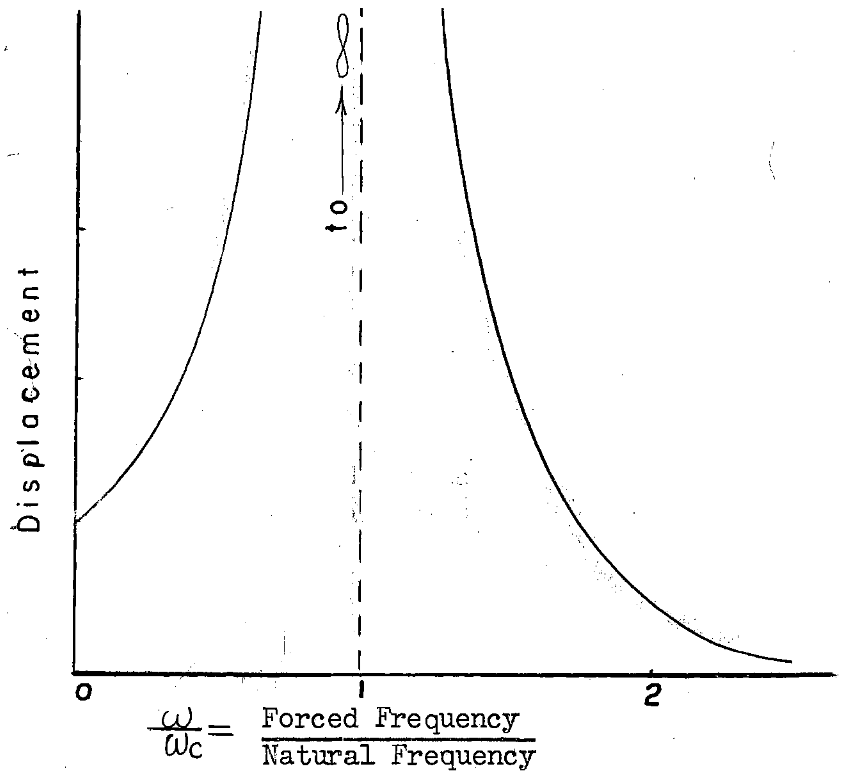


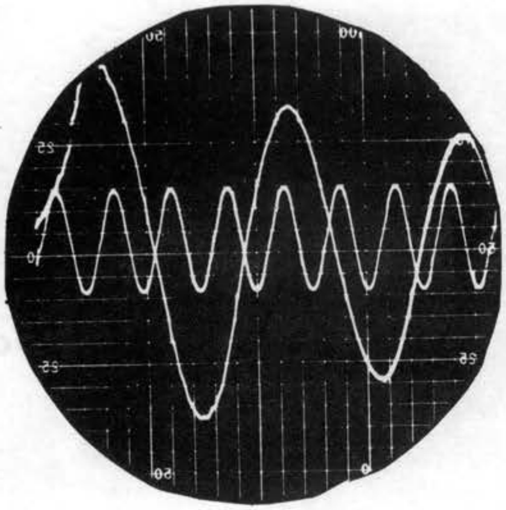
Figure 18. Amplitude of Resonant Vibration Without Friction.

at the same frequency with a slowly damped amplitude until it no longer existed. Oscillograms showing the damping effect at various loads on the experimental generator are shown in Figure 19.

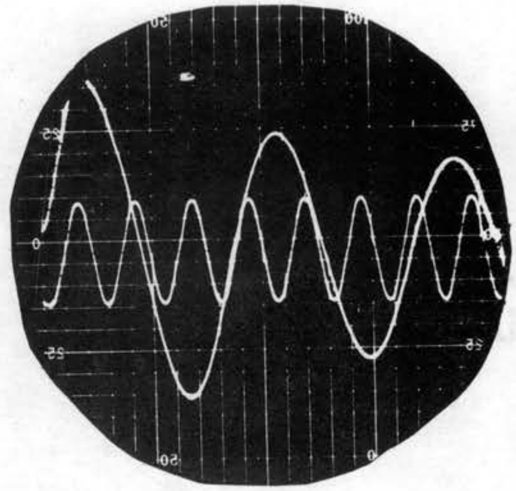
In Figure 16, the mass, compliance and friction represent the mechanical system of the oscillating electromagnetic generator with springs attached. If the coil of the generator were delivering power to an electrical load, it could be represented in the diagram by additional friction.

The motion of the system shown in Figure 16 can be expressed as

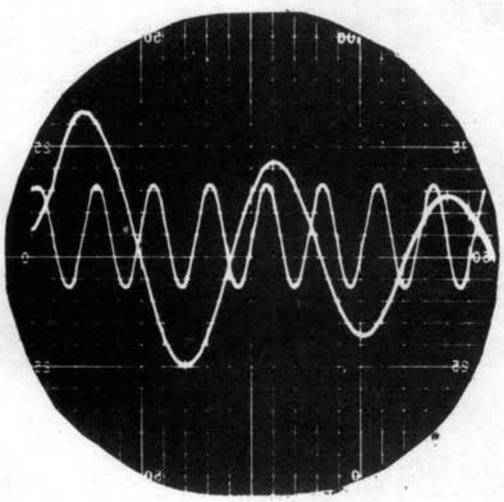
$$M\frac{dv}{dt} + Rv + k\int v\,dt = F\sin\omega t \qquad (21)$$



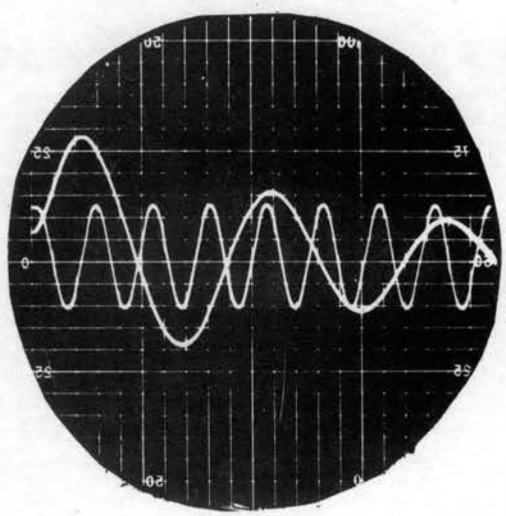
(a) $R_L = \infty$



(b) R_L = 100 ohms



(c) R_L = 25 ohms



(d) R_L = 10.7 ohms

Figure 19. Oscillograms Showing Damping Effect of Output Waveform at Various Electrical Loads.

or taking into effect the additional effective friction when the electrical load is applied to the generator, the equation becomes

$$M \frac{dv}{dt} + (R - \delta)v + k\int v\, dt = F \sin \omega t \ , \tag{22}$$

which has a complete solution when resonant of

$$v = \frac{F \sin(\omega t + \psi_1)}{\sqrt{R^2 + (\omega M - \frac{k}{\omega})}} + \frac{F\sqrt{k/M}\ \varepsilon^{\frac{-Rt}{2M}} \sin(\omega t + \psi_2)}{\omega\sqrt{R^2 + (\omega M - \frac{k}{M})^2}} \ . \tag{23}$$

where

$$\psi_1 = 90° - \tan^{-1} \frac{4\omega M}{R} \ ;$$

$$\psi_2 = \tan^{-1} \frac{(-2\omega M)}{R} - \tan^{-1} \frac{(-4\omega M)}{R} \ ,$$

$$\omega = \sqrt{\frac{k}{M} - \frac{R^2}{4M^2}} \ ,$$

δ = friction due to an electrical load

Since it is not desired to analyze the transient response of such a system, Equation 23 can be reduced to

$$v = \frac{F}{\sqrt{R^2 + (\omega M - \frac{k}{\omega})^2}} \sin(\omega t + \psi_1) \ . \tag{24}$$

The resonant frequency of this system is

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{M} - \frac{R^2}{M^2}} \ , \tag{25}$$

which is 20 vibrations per second in the experimental model.

CHAPTER VI

EXPERIMENTAL RESULTS

Calibration of the Prime Mover

The prime mover for the experimental oscillating electro-magnetic generator was a 1/6-horsepower, 120-volt, shunt-wound, direct-current motor. A standard prony brake test[1] was performed on the prime mover at a speed of 1200 revolutions per minute in order to obtain directly the calibration curve shown in Figure 20.

The test was made with the motor connected to the generator but with no electrical load on the generator. Therefore, all windage and friction losses, with the exception of extra friction losses when the generator was loaded, were included as losses in the motor prime mover. The motor output for a given motor current was then considered identical to the generator input.

Physical Properties of the Generator

The generator housing, electromagnet, pole piece, and a coil had a combined volume of 0.1302 cubic feet and a weight of 42.6 pounds. The coil had 500 turns of number 23 enameled copper wire wound on a Lucite plastic form. The coil weighed 0.66 pounds and had a resistance of 5.38 ohms. A photograph of the generator with springs attached is shown in Figure 21. The maximum power output of 1.314 watts for the generator occurred with a load resistance of 10.7 ohms. A complete graph showing power output and efficiency appears in Figure 22.

[1]Vladimir Karapetoff and Boyd C. Dennison, Electrical Laboratory Experiments (New York, 1936), p. 202.

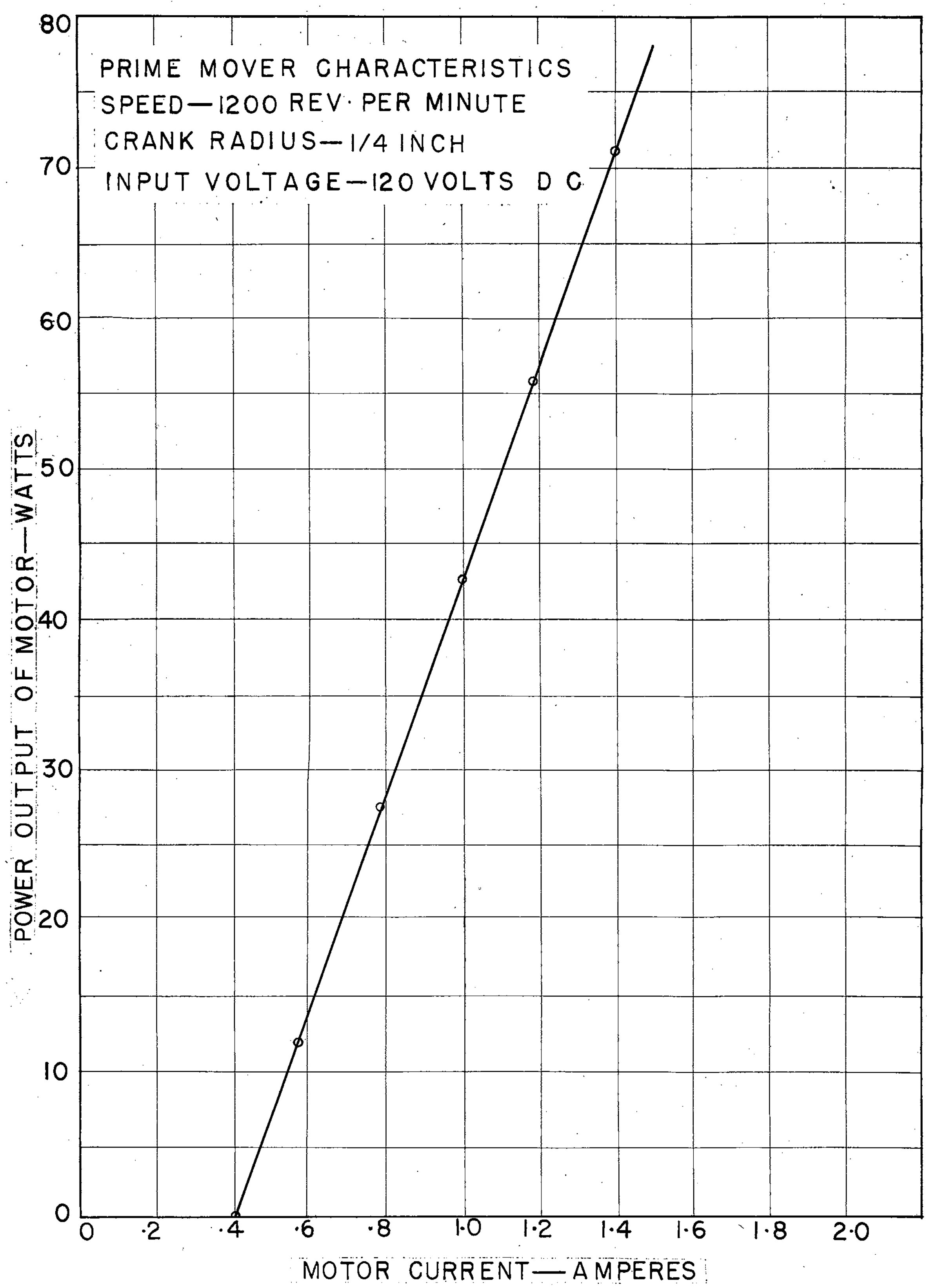


Figure 20. Prime Mover Calibration Curve

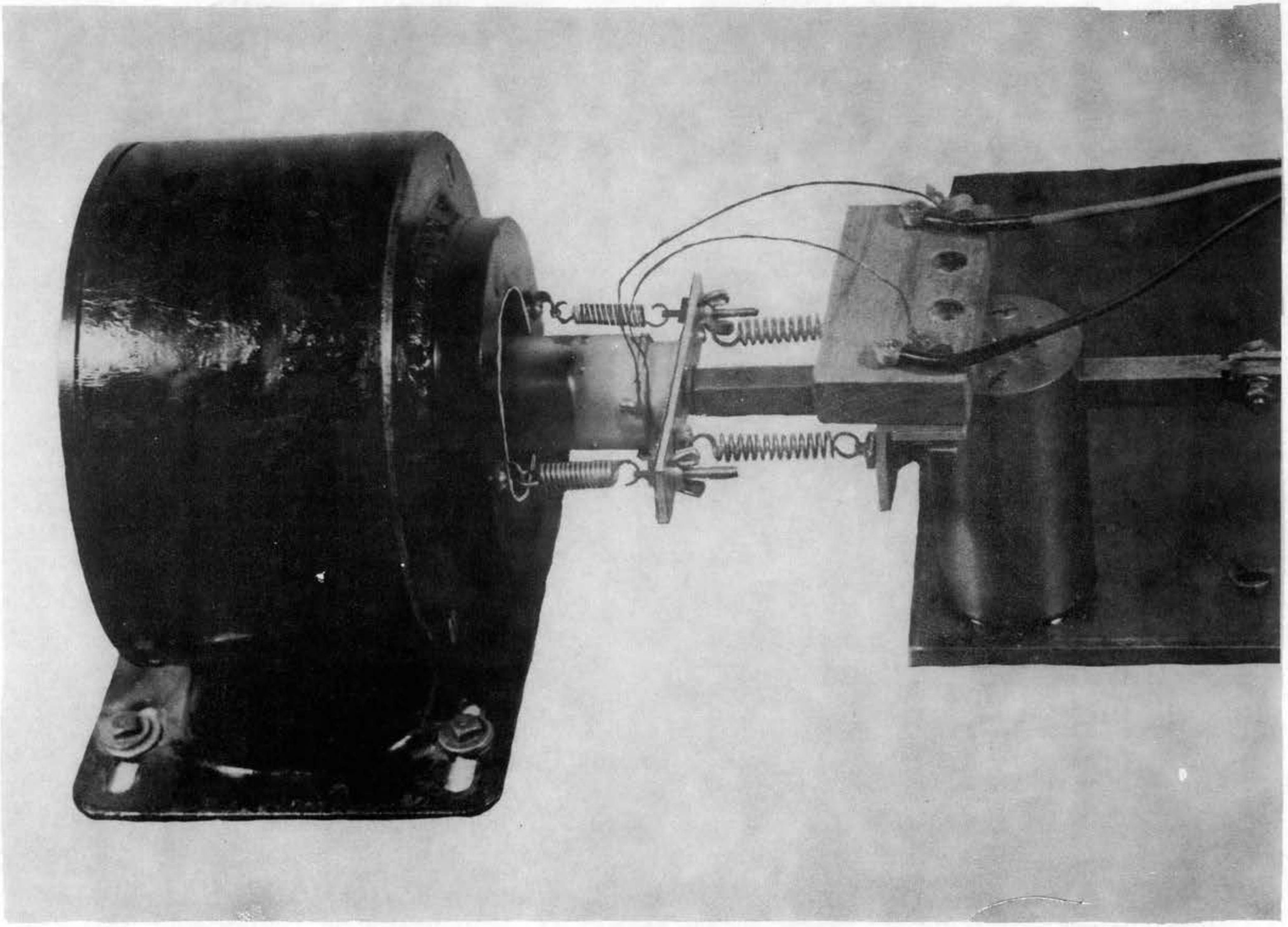


Figure 21. Experimental Generator with Spring Attached.

As a matter of interest, the volume of the generator is 0.098 cubic feet per watt or 98 cubic feet per kilowatt. The generator has a weight of 32 pounds per watt or 1.6 tons per kilowatt. These figures are quite large compared to conventional system. However, it must be pointed out that no attempt was made to minaturize the generator as the primary objective was to construct a workable model without regard to size or weight. It is believed that weight and volume measurements of a generator of this type could be reduced by a considerable amount by utilizing proper design techniques.

Power Output and Efficiency of the Generator

The oscillating electromagnetic generator had an internal impedance of $Z_t = 5.38 + j9.26$ ohms. It should therefore produce a maximum power output at a load of 10.7 ohms. This can easily be verified by inspecting the graph in Figure 22 which shows the maximum power output of the generator to be 1.314 watts. It may be noted that the power output with and without the springs attached is the same. This is to be expected since the load voltage and current is the same. However, it may also be noted in Figure 22 that the higher efficiency is the result of smaller losses in the system due to the resonant properties of the system. Actually, when mechanical resonance is present, less power is dissipated in the friction of the system. Therefore, the motor can deliver the same amount of horsepower to the generator but at the same time draw less current from the 120 volt d-c source.

Analysis of Results

The experimental data gathered as a result of the tests performed on the oscillating electromagnetic generator indicated that its

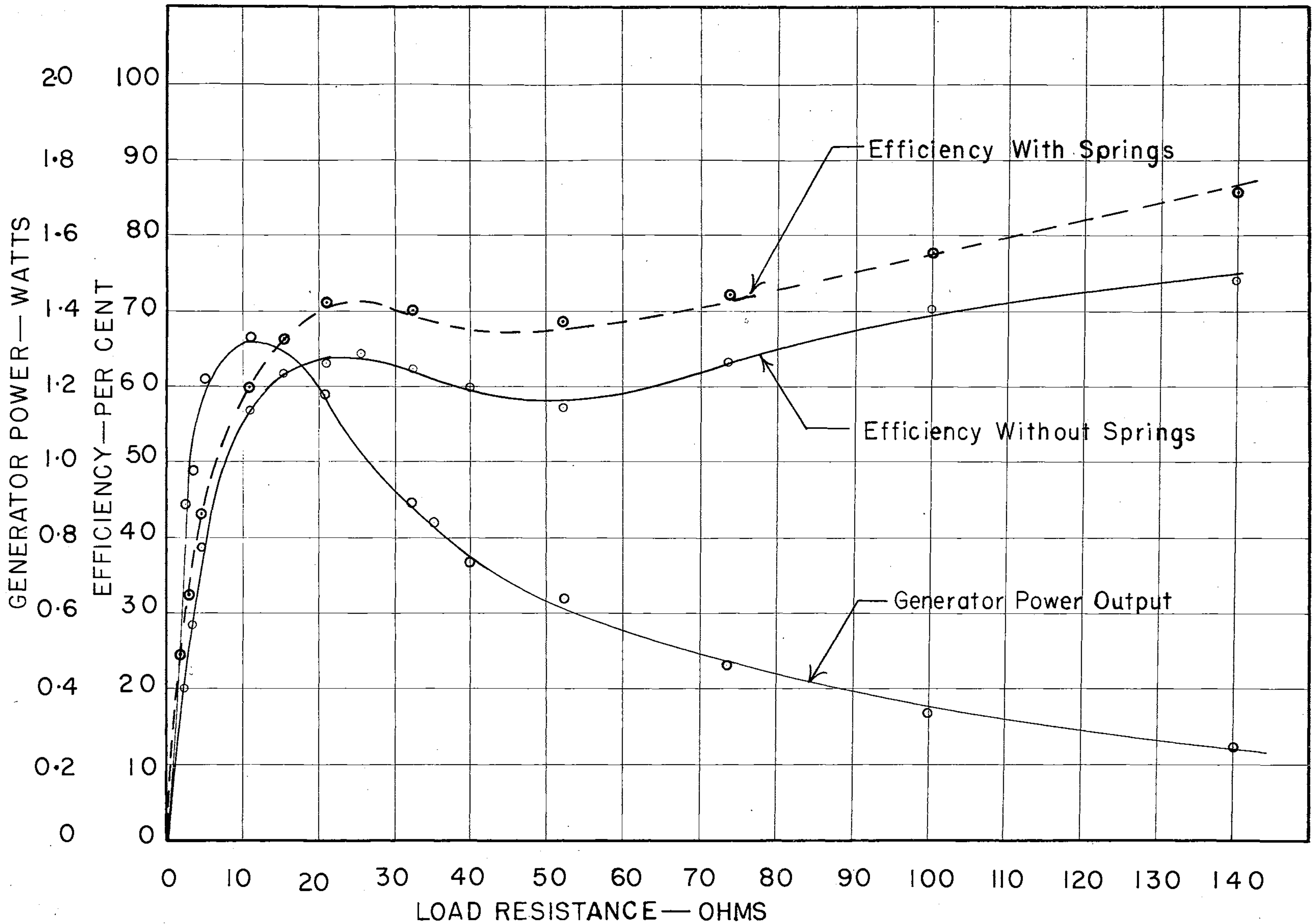


Figure 22. Power Output and Efficiency Curve.

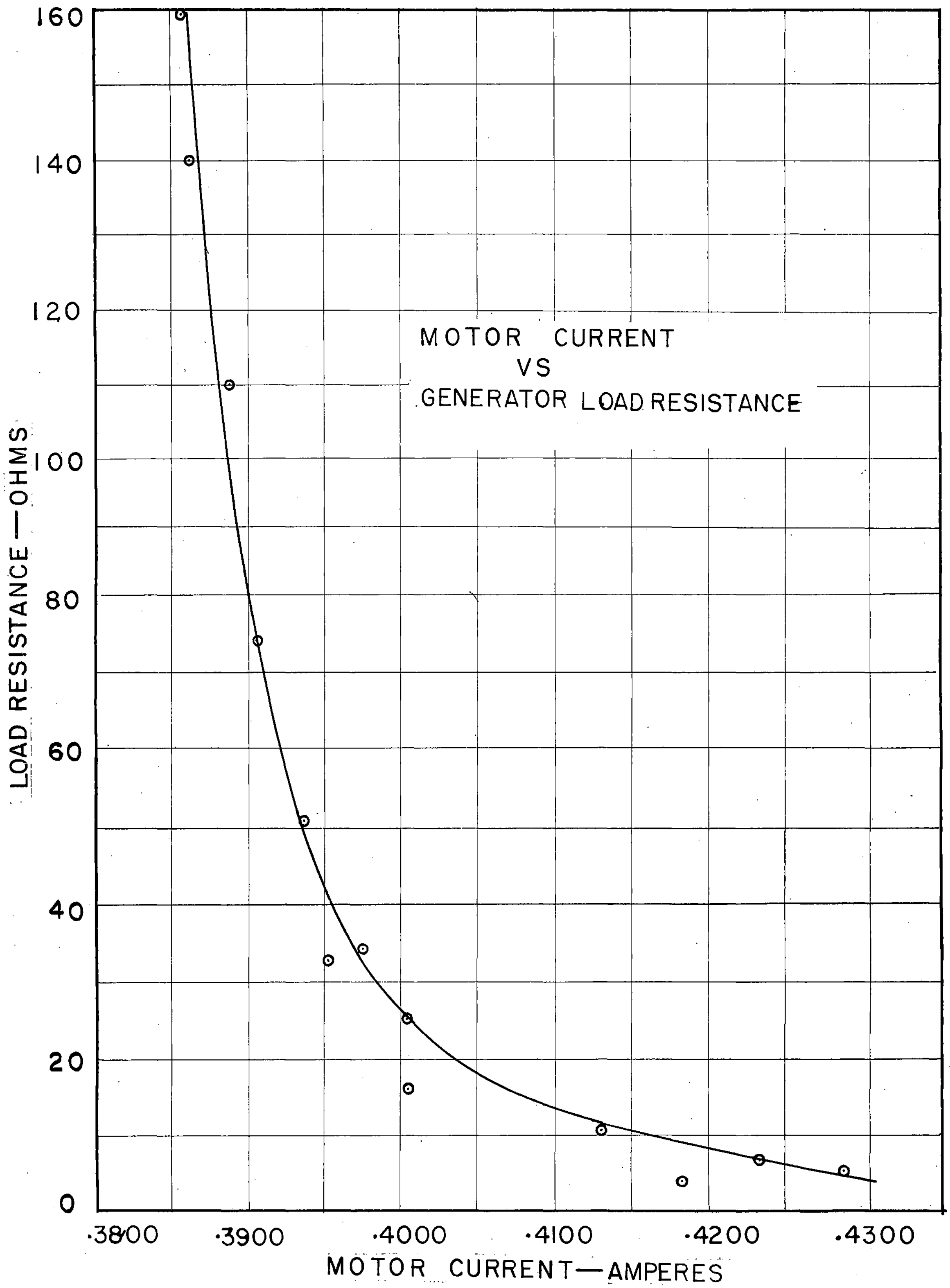


Figure 23. Prime Mover Current-Load Resistance Curve.

performance at a frequency of 20 cycles per second would produce usable power. Although it would seem that a device of this nature would be large (98 cubic feet per kilowatt), it is believed that a version using selected components and good design techniques could be made much smaller and lighter for the same power output.

In order to improve its efficiency, the mechanical resonance principle was employed in the testing of this generator. The application of mechanical resonance resulted in an improvement of maximum efficiency of 11 per cent. This bears out the theory of the analogy of the mechanical and electrical system that was advanced in Chapter V.

The analysis of the wave form generated by this machine shows that the wave form approximates a sine wave with an effective value of 69.5 which compares favorably with the value 70.7 per cent for a true sine wave. The voltage wave form is shown in Figure 24.

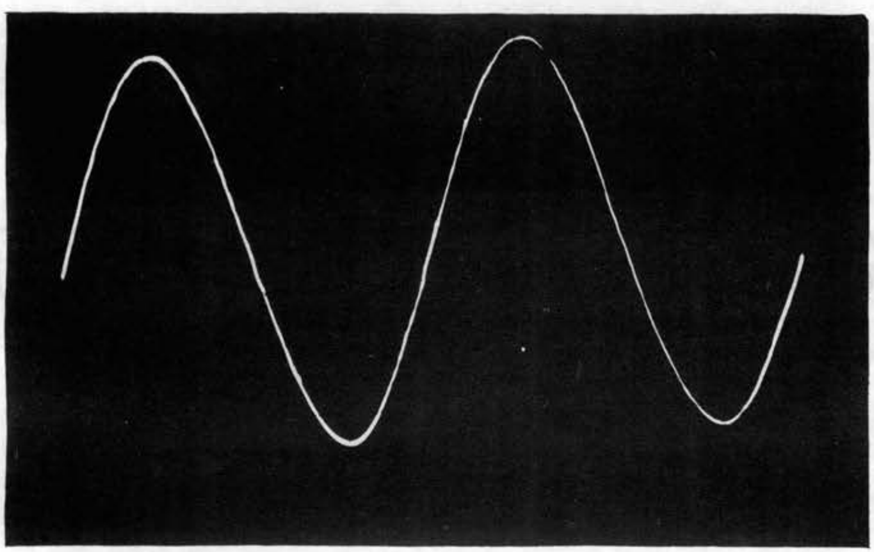


Figure 24. Voltage Wave Form of Experimental Generator

CHAPTER VII

SUMMARY AND CONCLUSIONS

Summary

The primary objective of this thesis was the investigation of the method of generating electrical power by the use of the oscillating electromagnetic principle. The three variations studied were the electromagnet, the permanent magnet and the variable reluctance systems. The oscillating generator using an electromagnet was considered in more detail because it permitted more favorable experimental possibilities. Materials were readily available for the construction of a generator of this type. The other two methods were discussed in some detail, however, generators of these designs were not constructed as time and component parts were not available.

During the testing period of the oscillating electromagnetic generator, the principle of mechanical resonance was applied with the thought in mind of increasing the efficiency of the generator. The results indicated that a maximum of eleven per cent efficiency was gained when this idea was incorporated in the experimental model. The experimental model was rather bulky and would require more space than similar rotating devices: No attempt was made to minaturize any of the components as the emphasis was primarily on the design and testing of a workable machine.

The testing of the experimental machine enabled the author to determine two factors that are of primary importance. First, the machine can develop usable power, and second, the efficiency of the machine can be improved by the use of the mechanical resonance principle which is analogous to the correction of the power factor in an electrical system. Based upon the findings of this investigation, it is believed that practical machines using the oscillating principle can become a reality.

Conclusions drawn from the information gathered in the investigation of the permanent magnet generator are that this generator offers possibilities as an unconventional power source. It has the advantage of having a self contained magnetic field and lends itself to minaturization quite readily. The basic design presented in this thesis is intended for experimental purposes. Further study of this generator would no doubt lead to many refinements resulting in volume and weight reductions per kilowatt of power output.

The variable reluctance generator would not be limited to a small voltage output due to the larger generator coil that can be used with this device. Moreover, low frequency oscillations would not necessarily be a limiting factor in this type generator. One disadvantage of this device would be the tricky design problem of establishing the maximum air gap for optimum conditions.

Recommendations for Further Study

The procedures and methods outlined in this thesis should prove useful to those engaged in further research on this type of power generator. Considerable work is yet to be done on the permanent magnet and variable reluctance generators, especially from the experimental standpoint. In order to reach definite conclusions on these generators it is recommended that a model of each device be constructed on the order of those outlined in this thesis so that definite conclusions can be reached on each machine.

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016	Bibliography; in subject division by number after decimal point. Example: 016.6 = 600 = Physical Sciences, Bsmt.
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100--199	Social Sciences, 4 W
200--299	Humanities, 3 W
300--369	Social Sciences, 4 E
370--379	Social Sciences, 4 SW
380--399	Social Sciences, 4 E
400--499	Humanities, 3 W
500--559	Physical Sciences, Basement W
560--599	Biological Sciences, 1 NW
600--609	Physical Sciences, Basement S
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