AN ARTIFICIAL TRANSMISSION LINE

Thesis for the Degree of M. S.

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Wilbur Ray Vincent

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This is to certify that the

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An Artificial Transmission Line

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Wilbur Ray Vincent

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J A Strelzoff
Major professor

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AN ARTIFICIAL TRANSMISSION LINE

By

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Preface

Transmission lines play an extremely important part in our everyday lives. Power and all types of communication over short and long distances are carried over transmission lines. A thorough means of studying the characteristics of transmission lines could be available in every Electrical Engineering Laboratory.

It is the purpose of this paper to describe the design, calculations, and testing of a Lumped Artificial Transmission Line built by the author for use in the Electrical Engineering Laboratories of Michigan State College.

The author is indebted to Professor B. K. Osborn for his many suggestions concerning the design of the line and to Mr. Robert Nelson for his suggestions and short cuts in the laborious mechanical construction of the artificial line.

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CHAPTER I

Description of Artificial Lines and Their History

The principal purpose of an artificial line is to furnish an electrical model of a corresponding real transmission line. Thus the electrical behavior of the real line can be imitated by the model. The laboratory student can gain much valuable information concerning the behavior of transmission lines, especially in the behavior of long lines which are easily obtained in the artificial form but hard to study in their actual form.

In general, artificial lines can be classified in two ways.

1. Smooth lines
2. Lumpy lines

A smooth line is available in the Electrical Engineering laboratories at the present time for use of students. This line consists of parallel conductors wound upon long insulating tubes. Smooth lines have the advantage of imitating, exactly, the electric conditions of real lines for all frequencies and transient conditions. They are apt to be very large in physical size and hard to construct especially in a long line. Also it is rather difficult to obtain measurements upon this type of line.

A lumpy line is made by lumping together the values of capacitance, resistance, inductance, and conductance for several miles of a given line into a section. Lumpy lines are usually simpler to construct, more compact, more durable, and less expensive. It does not however, imitate the line for all frequencies and conditions. Measurements can easily be taken at several points along a lumpy line.

The first artificial line known to exist was constructed by C. F. Varley in 1862 for the study of submarine cables in England. This was a lumpy line consisting of alternate sections of resistance and capacitance. The first artificial line used in this country was built by M. I. Pupin in 1898 for use in the laboratories of Columbia University. This line consisted of distributed resistance, inductance, and capacitance. Many of the early lines are described in the literature along with the data obtained upon them.

The basic ideas used in the early artificial lines have not changed and are very similar to the line this paper describes. I do hope however, that the many refinements in construction and in the ease of taking readings will make it more adaptable to the study of present day transmission line problems.

CHAPTER II

Electrical Design

2.1 Choice of Circuit

When designing a lumped artificial line one has the immediate choice of several types of electrical structures. The line constants can be lumped together into a T section, π section, H section, II section or a lattice network. The type of section used is determined largely by the cost of building and the degree of accuracy.

It was decided to approximate as nearly as possible a pair of 104 mil wires spaced 12 inches. This is the usual open wire line used in telephone work.

A study of the materials at hand which were made available through government surplus and that which is listed in several manufacturers catalogues seemed to indicate that an H or balanced T section would allow us to build the best possible line in the most economical manner. This would allow us to use a block of high voltage precision mica condensors available in the surplus stock for the necessary capacitor. A standard size 5.3 mh. R.R. choke ℓ seemed the logical choice for the necessary inductance. Calculations shown later in the paper will show that the resistance of this coil is very close to that of the equivalent lumped line. Thus, it was not necessary to purchase resistors for this purpose. Also by using the standard 5.3 mh. R.F. choke the use of an inductor with an iron core was avoided. This means a line which more closely approximates the open wire original over a wider band of frequencies and one upon which transcients can be observed along with the possibility of using a carrier type transmission above the audio range of frequencies.

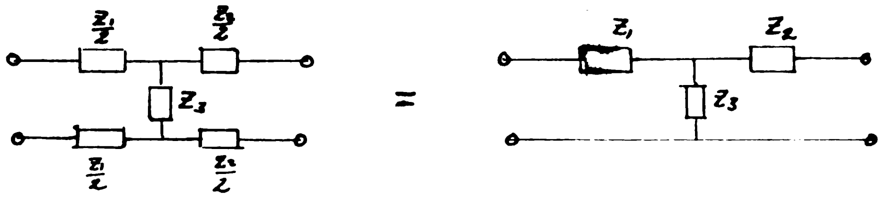
Measurement at the end of each section can easily be provided by a system of normaled jacks which are also available in the surplus stock. The operation of the jack system is evident from the circuit diagram which follows.

By using the H section as a unit, half sections which are inserted into the usual lumped line for measurement are eliminated. This makes the measurement of voltage and current a simple matter of plugging into the jacks at the end of the desired section.

Up to now I have inferred that the values used in a section of lumped line would be the sum of a certain number of miles of equivalent open wire. This seems to be a very logical answer, but are the Characteristic Impedance and Propagation Constant of the lumped section equal to that of the distributed line? The following derivations will show that for our purposes they are the same[3] and will point out the small error introduced by lumping the line constants into an H section.

2.2 Derivations

For convenience in the following derivations, the H section will be reduced to an equivalent T section.



1. $Z_{01} = Z_1 + Z_3$

2. $Z_{02} = Z_2 + Z_3$

3. $Z_{S1} = Z_1 + \dfrac{Z_2 Z_3}{Z_2 + Z_3} = \dfrac{Z_1 Z_2 + Z_2 Z_3 + Z_1 Z_3}{Z_2 + Z_3}$

4. $Z_{S2} = Z_2 + \dfrac{Z_1 Z_3}{Z_1 + Z_3} = \dfrac{Z_1 Z_2 + Z_2 Z_3 + Z_1 Z_3}{Z_1 + Z_3}$

Rearranging 1 and 2 and substituting into 3

$$Z_1 = Z_{01} - Z_3$$

$$Z_2 = Z_{02} - Z_3$$

$$Z_{S1} = \frac{Z_{01}Z_{02} - Z_{01}Z_3 - Z_{03}Z_3 + Z_3^2 + Z_{01}Z_3 - Z_3^2 + Z_{02}Z_3 - Z_3^2}{Z_{02}}$$

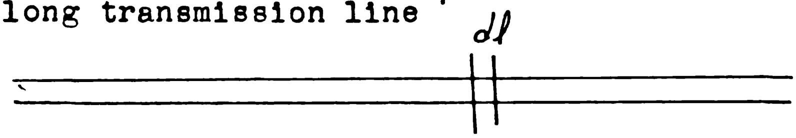
$$Z_{S1}Z_{02} = Z_{01}Z_{02} - Z_3^2$$

5. $Z_3 = \sqrt{Z_{02}(Z_{01} - Z_{S1})}$

6. $Z_1 = Z_{01} - \sqrt{Z_{02}\,(Z_{01} - Z_{s1})}$

7. $Z_2 = Z_{01} - \sqrt{Z_{02}\,(Z_{01} - Z_{s1})}$

Let us leave the lumped section at this point and find the values on Z_{01}, Z_{02}, Z_{s1}, and Z_{s2} for a distributed line. Considering a small portion $d\ell$ of a long transmission line[4]



8. $dI = -VY\,d\ell$

9. $dV = -IZ\,d\ell$

10. $\dfrac{dI}{d\ell} = -VY$

11. $\dfrac{dV}{d\ell} = -IZ$

12. $\dfrac{d^2 I}{d\ell^2} = -Y\dfrac{dV}{d\ell}$

13. $\dfrac{d^2 V}{d\ell^2} = -Z\dfrac{dI}{d\ell}$

Substitute 10 and 11 in 12 and 13

$$\frac{d^2I}{dl^2} = YZI$$

$$\frac{d^2V}{dl^2} = YZV$$

Which is a standard differential equation with the solution of the form

$$14. \quad I = A_1 e^{\gamma l} + B_1 e^{-\gamma l}$$

$$15. \quad V = A_2 e^{\gamma l} + B_2 e^{-\gamma l}$$

Solving for the constants of integration A_1, B_1, A_2, B_2,

$$\frac{dI}{dl} = \gamma A_1 e^{\gamma l} - \gamma B_1 e^{-\gamma l}$$

$$\frac{dV}{dl} = \gamma A_2 e^{\gamma l} - \gamma B_2 e^{-\gamma l}$$

$$-VY = \gamma A_1 e^{\gamma l} - \gamma B_1 e^{-\gamma l}$$

$$-IZ = \gamma A_2 e^{\gamma l} - \gamma B_2 e^{-\gamma l}$$

Considering the boundry conditions at the sending end of the line where $l = 0$, $V = V_s$ and $I = I_s$

$$I_s = A_1 + B_1$$

$$V_s = A_2 + B_2$$

$$-V_s Y = \gamma A_1 - \gamma B_1$$

$$-I_s Z = \gamma A_2 - \gamma B_2$$

Solving the four equations for A_1, B_1, A_2, and B_2

$$A_1 = \frac{1}{2}\left(I_s - V_s \frac{Y}{\gamma}\right) = \frac{1}{2}\left(I_s - V_s\sqrt{\frac{Y}{Z}}\right)$$

$$B_1 = \frac{1}{2}\left(I_s + V_s \frac{Y}{\gamma}\right) = \frac{1}{2}\left(I_s + V_s\sqrt{\frac{Y}{Z}}\right)$$

$$A_2 = \frac{1}{2}\left(V_s - I_s \frac{Z}{\gamma}\right) = \frac{1}{2}\left(V_s - I_s\sqrt{\frac{Z}{Y}}\right)$$

$$B_2 = \frac{1}{2}\left(V_s + I_s \frac{Z}{\gamma}\right) = \frac{1}{2}\left(V_s + I_s\sqrt{\frac{Z}{Y}}\right)$$

Calling $Z_0 = \sqrt{\frac{Z}{Y}}$

$$A_1 = \frac{1}{2}\left(I_s - \frac{V_s}{Z_0}\right)$$

$$B_1 = \frac{1}{2}\left(I_s + \frac{V_s}{Z_0}\right)$$

$$A_2 = \frac{1}{2}\left(V_s - I_s Z_0\right)$$

$$B_2 = \frac{1}{2}\left(V_s + I_s Z_0\right)$$

Substitute in 14 and 15

$$I = \frac{1}{2} I_s e^{\gamma l} - \frac{1}{2}\frac{V_s}{Z_0} e^{\gamma l} + \frac{1}{2} I_s e^{-\gamma l} + \frac{1}{2}\frac{V_s}{Z_0} e^{\gamma l}$$

$$V = \frac{1}{2} V_s e^{\gamma l} - \frac{1}{2} I_s Z_0 e^{-\gamma l} + \frac{1}{2} V_s e^{-\gamma l} + \frac{1}{2} I_s Z_0 e^{-\gamma l}$$

But

$$\frac{e^{x} + e^{-x}}{2} = \operatorname{Cosh} x$$

$$\frac{e^{x} - e^{-x}}{2} = \operatorname{Sinh} x$$

Therefore

16. $I = I_s \operatorname{Cosh} \gamma l - \frac{V_s}{Z_0} \operatorname{Sinh} \gamma l$

17. $V = V_s \operatorname{Cosh} \gamma l - I_s Z_0 \operatorname{Sinh} \gamma l$

Where l is measured from the sending end of the line, $\gamma = \sqrt{ZY}$ and $Z_0 = \sqrt{\frac{Z}{Y}}$.

A similar pair of equations could be developed by considering the boundry conditions at the receiving end of the line.

$$18. \quad I = I_r \cosh \gamma l + \frac{V_r}{Z_0} \sinh \gamma l$$

$$19. \quad V = V_r \cosh \gamma l + I_r Z_0 \sinh \gamma l$$

It might be well to sidetrack here for a moment to get a better picture of the quantity Z_0. Taking equation 17 and dividing by $\cosh \gamma l$ and letting $l \to \infty$

$$\frac{V}{\cosh \gamma l} = V_s - I_s Z_0 \frac{\sinh \gamma l}{\cosh \gamma l}$$

$$0 = V_s - I_s Z_0$$

$$Z_0 = \frac{V_s}{I_s} = \sqrt{\frac{Z}{Y}}$$

Z_0 is the impedance of an infinitely long line and is called the Characteristic impedance.

Now to return to the original aim of determining Z_{01} and Z_{s1} of a distributed line. Considering equations 18 and 19 for the open circuit case with $I_r = 0$

$$I = \frac{V_r}{Z_0} \sinh \gamma l$$

$$V = V_r \cosh \gamma l$$

$$Z_{oc} = \frac{E}{I} = Z_0 \frac{\cosh \gamma l}{\sinh \gamma l}$$

$$Z_{oc} = Z_0 \coth \gamma l$$

Considering the short circuit case with equations 18 and 19 where $V_r = 0$

$$I = I_r \cosh \gamma l$$

$$V = I_r Z_0 \sinh \gamma l$$

$$Z_{sc} = \frac{V}{I} = Z_0 \frac{\sinh \gamma l}{\cosh \gamma l}$$

$$Z_{sc} = Z_0 \tanh \gamma l$$

Substituting the values for 20 and 21 into equations 5, 6, and 7

$$Z_3 = \sqrt{Z_{02}(Z_{01} - Z_{s1})}$$

$$= \sqrt{Z_0^2 \coth \gamma l (\coth \gamma l - \tanh \gamma l)}$$

$$= \sqrt{Z_0^2 \frac{\cosh \gamma l}{\sinh \gamma l}\left(\frac{\cosh \gamma l}{\sinh \gamma l} - \frac{\sinh \gamma l}{\cosh \gamma l}\right)}$$

22. $$= \frac{Z_0}{\sinh \gamma l}$$

$$Z_1 = Z_2 = Z_{01} - Z_3$$

$$= Z_0 \coth \gamma l - \frac{Z_0}{\sinh \gamma l}$$

$$= Z_0 \left[\frac{\cosh \gamma l - 1}{\sinh \gamma l}\right]$$

$$= \left[\frac{\frac{e^{\gamma l} + e^{-\gamma l}}{2} - 1}{\frac{e^{\gamma l} - e^{-\gamma l}}{2}}\right]$$

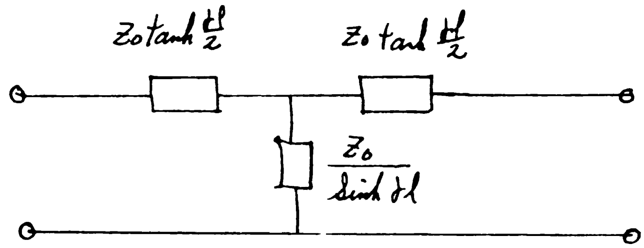
$$Z_1 = Z_0 \left[\frac{e^{\gamma l} - 2e^{-\gamma l}}{e^{\gamma l} - e^{-\gamma l}} \right]$$

$$= Z_0 \left[\frac{\left(e^{\frac{\gamma l}{2}} - e^{-\frac{\gamma l}{2}}\right)\cancel{\left(e^{\frac{\gamma l}{2}} - e^{-\frac{\gamma l}{2}}\right)}}{\left(e^{\frac{\gamma l}{2}} + e^{-\frac{\gamma l}{2}}\right)\cancel{\left(e^{\frac{\gamma l}{2}} - e^{-\frac{\gamma l}{2}}\right)}} \right]$$

$$\text{but } \tanh \frac{\gamma l}{2} = \frac{e^{\gamma l/2} - e^{-\frac{\gamma l}{2}}}{e^{\frac{\gamma l}{2}} + e^{-\frac{\gamma l}{2}}}$$

23. $Z_1 = Z_2 = Z_0 \tanh \frac{\gamma l}{2}$

Thus the equivalent T section for a length l of distributed line is



If $\frac{\gamma l}{2}$ is small we can use the following approximations

$$e^{p} \cong 1 + p \qquad e^{-p} \cong 1 - p$$

$$\sinh \frac{\gamma l}{2} \cong \tanh \frac{\gamma l}{2} \cong \frac{\gamma l}{2}$$

Thus

$$Z_1 = Z_2 = Z_0 \tanh \frac{\gamma l}{2}$$

$$\cong \frac{Z_0 \gamma l}{2}$$

$$\cong \frac{\sqrt{\frac{Z}{Y}}\sqrt{ZY}\, l}{2}$$

24. $$Z_1 = Z_2 = \frac{Z l}{2}$$

$$Z_3 = \frac{Z_0}{\sinh \gamma l} \cong \frac{Z_0}{\gamma l}$$

$$\cong \sqrt{\frac{Z}{Y}}\ \frac{1}{\sqrt{ZY}\, l}$$

25. $$Z_3 \cong \frac{1}{Y l}$$

And the series and shunt elements are merely those which would be obtained by lumping the distributed elements of impedance and admittance.

2.3 Calculation of Section Constants

The line constants for a pair of 104 mil wires spaced 12 inches are as follows:

R = 10.15 ohm per loop mile

L = .00367 henries per mile

C = .00835 micro farad per mile

G = .80 micro ~~ohm~~ mho per mile

For reasons described earlier in this paper the inductor used was a 5.3 mh. choke coil with a resistance of 14 ohm per coil. The following calculations in determining the lumped constants for the H section then became evident.

$$5.3 \times 4 = 21.2 \text{ mh/section}$$

$$\frac{21.2 \text{ mh/section}}{3.67 \text{ mh/mi}} = 5.78 \text{ miles/section}$$

$$C = 5.78 \times .00835 = .04825 \ \mu f/\text{section}$$

$$R = 10.4 \times 5.78 = 60.1 \ \Omega/\text{section}$$

$$R = \frac{60.1}{4} = 15.1 \ \Omega/\text{coil}$$

$$G = .8 \times 10^{-6} \times 5.78 = 4.62 \times 10^{-6} \text{ mho/section}$$

$$R_l = \frac{1}{G} = \frac{10^6}{4.62} = 216,000 \ \Omega/\text{section}$$

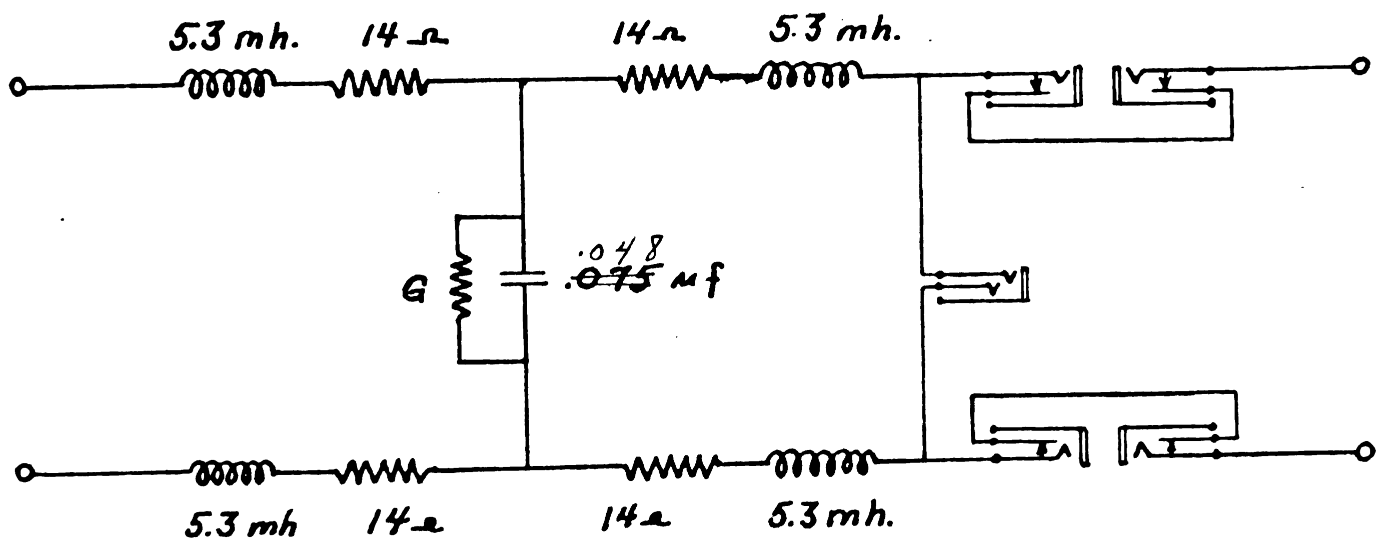
Several hundred dollars could be saved by using existing materials and for that reason the values actually used in the artificial line are slightly different from those calculated. The difference is very small however and the error introduced is also very small. The values used are listed.

R= 14 ohm per coil

L= 5.3 mh per coil

C= .048 micro farad per section

G= leakage of the insulation used in construction



Single "H" Section of Artificial Line

2.4 Error Introduced by Lumping

It is often important to know the limits of accuracy of a lumped line. That is how far are Z_0 and γl from that of the equivalent smooth line.

For the lumped H section line we have derived:

$$26. \quad Z_1 = \frac{l}{n}(R + j\omega L)$$

$$27. \quad Z_2 = \frac{l}{n}(G + j\omega C)$$

For a T section we have

$$28. \quad Z_0' = \sqrt{Z_1 Z_2 + \frac{Z_1^2}{4}} = \sqrt{Z_1 Z_2}\sqrt{1 + \frac{Z_1}{4 Z_2}}$$

For the smooth line

$$29. \quad Z_0 = \sqrt{\frac{R + j\omega L}{G + j\omega C}}$$

Substitute 26 and 27 in 28

$$Z_0' = \sqrt{\frac{R+j\omega L}{G+j\omega C}}\sqrt{1 + \frac{(R+j\omega L)(G+j\omega C)}{4}}$$

$$= Z_0 \sqrt{1 + \left(\frac{\gamma l}{2n}\right)^2}$$

We see that Z_0 differs from Z_0' by the factor

$$\sqrt{1 + \left(\frac{\gamma l}{2n}\right)^2}$$

This radical is easily expanded by the binomial therom which gives us

$$Z_0' = Z_0\left[1 + \frac{1}{2}\left(\frac{\gamma l}{2n}\right)^2 - \frac{1}{8}\left(\frac{\gamma l}{2n}\right)^4 + \cdots\right]$$

Simplified and neglecting higher order terms

$$Z_0' = Z_0(1 + \delta_3)$$

Where

$$\delta_z = \frac{1}{8}\left(\frac{l}{n}\right)^2 \cdot \gamma^2$$

$$= \frac{1}{8}\left(\frac{l}{n}\right)^2 (R + j\omega L)(G + j\omega C)$$

Since the error is largest at high frequencies where R is of little effect and G usually negligible we can write

$$29. \quad \delta_z \doteq -\frac{LC\omega^2}{8}\left(\frac{l}{n}\right)^2$$

Which to a very close approximation is the difference between Z_0' and Z_0.

Repeating the same line of attact we can find the error in the propogation constant introduced by lumping the line constants.

For the smooth line the propogation was expressed as

$$30. \quad \gamma l' = l\sqrt{ZY} = l\sqrt{(R + j\omega L)(G + j\omega C)}$$

For a series of lumped H sections

$$31. \quad \gamma n = n \, 2 \sinh^{-1}\sqrt{\frac{Z_1}{4Z_2}}$$

Substitute and in

$$\gamma l' = 2n \sinh^{-1}\frac{\gamma l}{2n}$$

Expanding the series for $\sinh^{-1}\frac{\gamma l}{2n}$

$$n\gamma = \gamma l\left[1 - \frac{1}{6}\left(\frac{\gamma l}{2n}\right)^2 + \frac{3}{40}\left(\frac{\gamma l}{2n}\right)^4 - \cdots\right]$$

$$= \gamma l(1 + \delta_y)$$

The error

$$\delta y = \frac{1}{6}\left(\frac{\theta l}{2n}\right)^2$$

Examination of the two errors shows us that The error in δ_z is of the opposite sign and three times as large as in δ_y . For a given Z_0 the error increases with frequency hence should be calculated for the highest frequency at which the line will be used. For a given frequency it increases as the square of the length and decreases as the reciprocal of the square of the number of cascaded sections.

The calculated error in this transmission line at 5000 cycles per second is

$$\delta_z = -3\delta_y = \frac{LC\omega^2}{8}\left(\frac{l}{n}\right)^2$$

$$= \frac{3.67 \times 10^{-3} \times .01835 \times 10^{-6} \times 39.4 \times 25 \times 10^6}{8}\left(\frac{231}{40}\right)^2$$

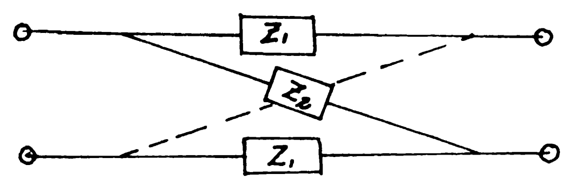
$$= .126$$

$$\% \text{ error in } Z_0 = \frac{.126}{640} \times 100$$

$$= .0197\%$$

2.5 The Lattice Network

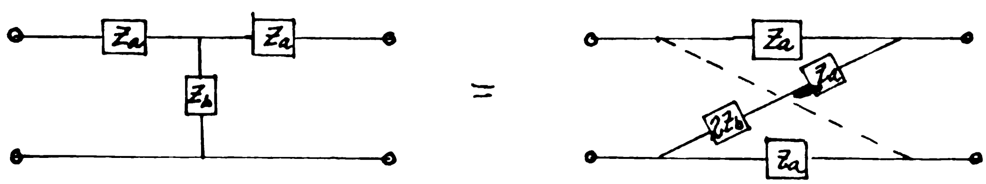
The Lattice or Bridge type structure[6] is the most general type of electrical network. Its design equations are simple and easy to handle. The characteristic impedance and propogation constant are derived from the following diagram and considerations which are used earlier in this paper.



$$Z_0 = \sqrt{Z_{oc} Z_{sc}} = \sqrt{Z_1 Z_2}$$

$$\tanh \frac{\gamma l}{2} = \sqrt{\frac{Z_{oc}}{Z_{sc}}} = \sqrt{\frac{Z_1}{Z_2}}$$

From the above equations we see that the Characteristic Impedance or the Propogation Constant can be varied without changing the other. This is not possible in either the T or H structure and is a decided advantage when designing general structures. Also networks can be formed which do not have an equivalent T or π structure. This will be evident upon inspecting the following conversion of a T to a lattice network which is based upon the fact that the open and short circuit impedances must be equal.[7]



From the above equivalence, the proper values for the elements to be used in an equivalent section of artificial line can be calculated as follows.

$$Z_1 = Z_a$$

$$Z_2 = Z_a + 2Z_b$$

$$Z_1 = R + j\omega L =$$

where $R = 56\,\Omega$

$L = 10.6\,mh.$

$$Z_2 = R + j\omega L + 2\frac{1}{j\omega C}$$

where $C = .045\,\mu f$

CHAPTER III

Mechanical Design

Rack and panel type of construction was decided as being the most desirable from many standpoints. A standard 7' steel cabinet was available through government surplus which made a very neat appearing and convenient container for the artificial line.

Aluminum panels were used to facilitate accurate drilling of the panels for the mounting of the jacks. Mounting and shielding panels are made of No. 16 sheet iron painted black. The panel designs are shown in the following drawings and the assembled panels are shown in the accompanying photographs. The panels are designed so that complete shielding is obtained between each section.

The placement of parts in the H section are shown in the panel assembly photograph. The photograph also shows the mica condensor assembly each of which is made up of six separate condensors mounted together with threaded brass rod. The total condensor assembly being mounted on a bakelite strip.

Parts List

1 ea. Standard 7' Relay Rack Cabinet•

10 ea. 7" x 1/8" Standard Relay Rack Panels-Aluminum

2 ea. 3" x 1/8" Standard Relay Rack Panels-Aluminum

2 ea. 3' x 8' No. 16 Sheet Iron

8 ea. 3' Lengths of 1/8" Brass Rod

2 gross 8-32x½ Brass Machine Screws

2 gross 8-32 Brass Nuts

1 gross 6-32x½ Brass Machine Screws

1 gross 6-32 Brass Nuts

40 ea. 3/8" Rubber Gromments

166 ea. 2 Circuit Normaled Jacks•

41 ea. 3 Circuit Jacks•

3 ea. 2 Circuit Double Plugs

2 ea. 3 Circuit Plugs•

160 ea. 5.3 mh. 14 ohm Choke Coils

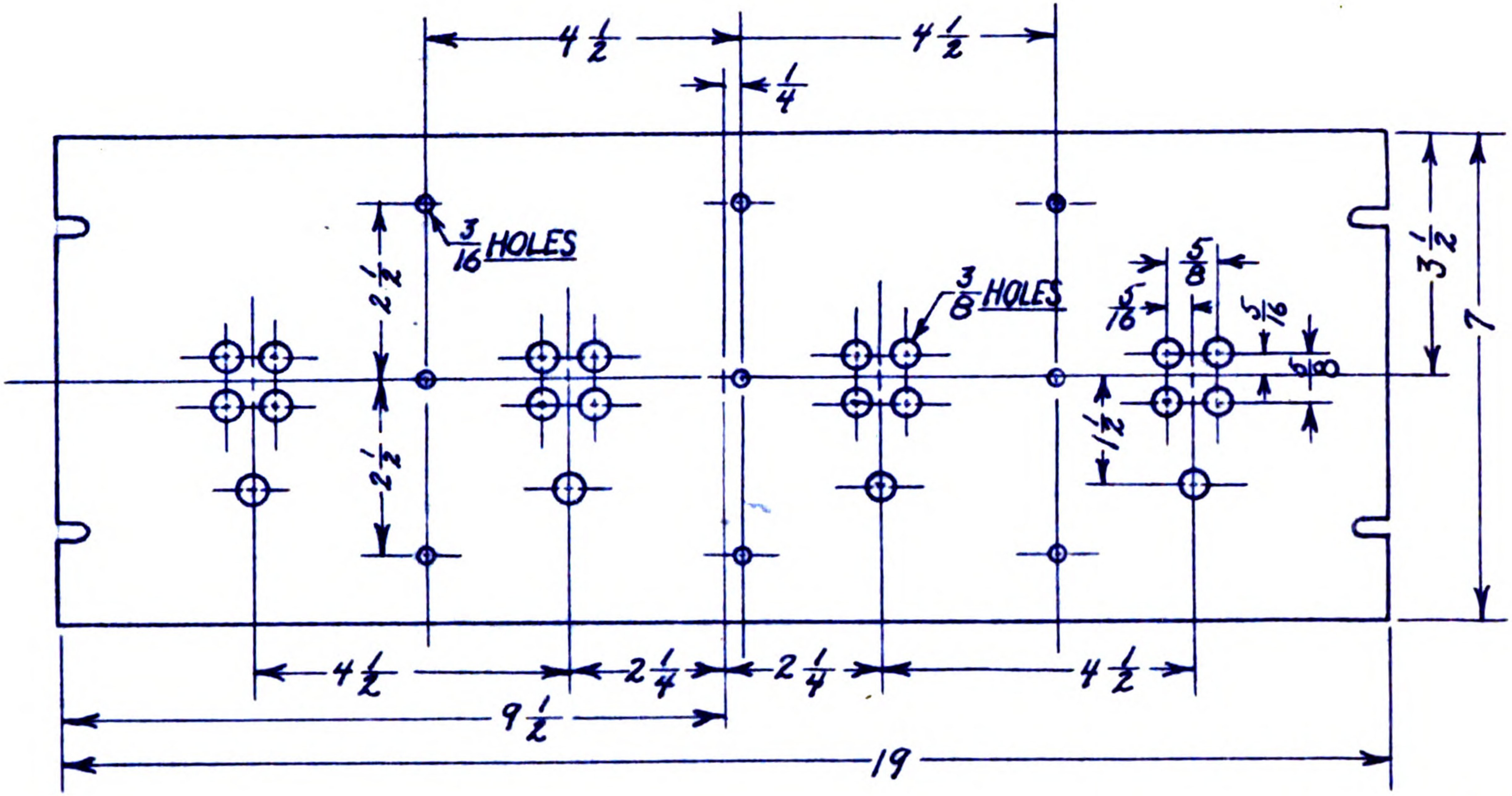
120 ea. .015 uf 1200 volt, 2% Mica Condensors•

120 ea. .001 uf 600 volt, 2% Mica Condensors•

40 ea. Bakelite Mounting Strips•

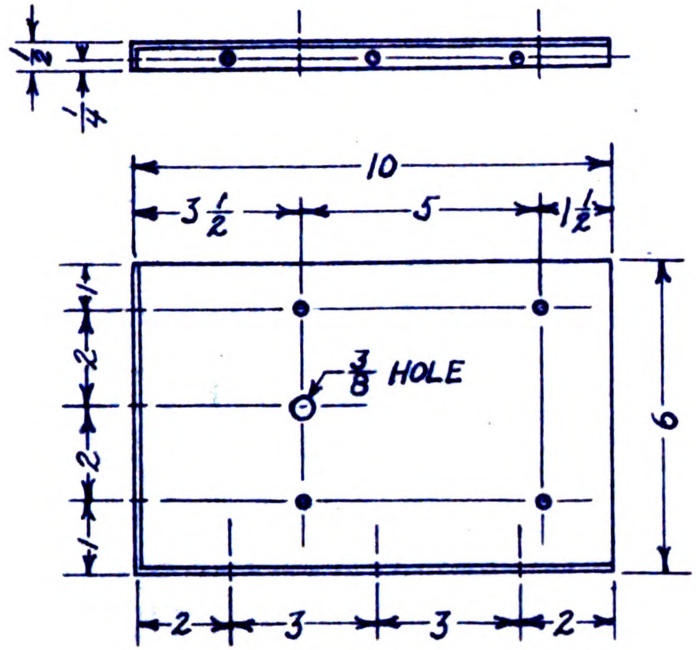
80 ea. Stand-off Mountings, 1" •

• Available from present Government Surplus Stocks



Front Panel

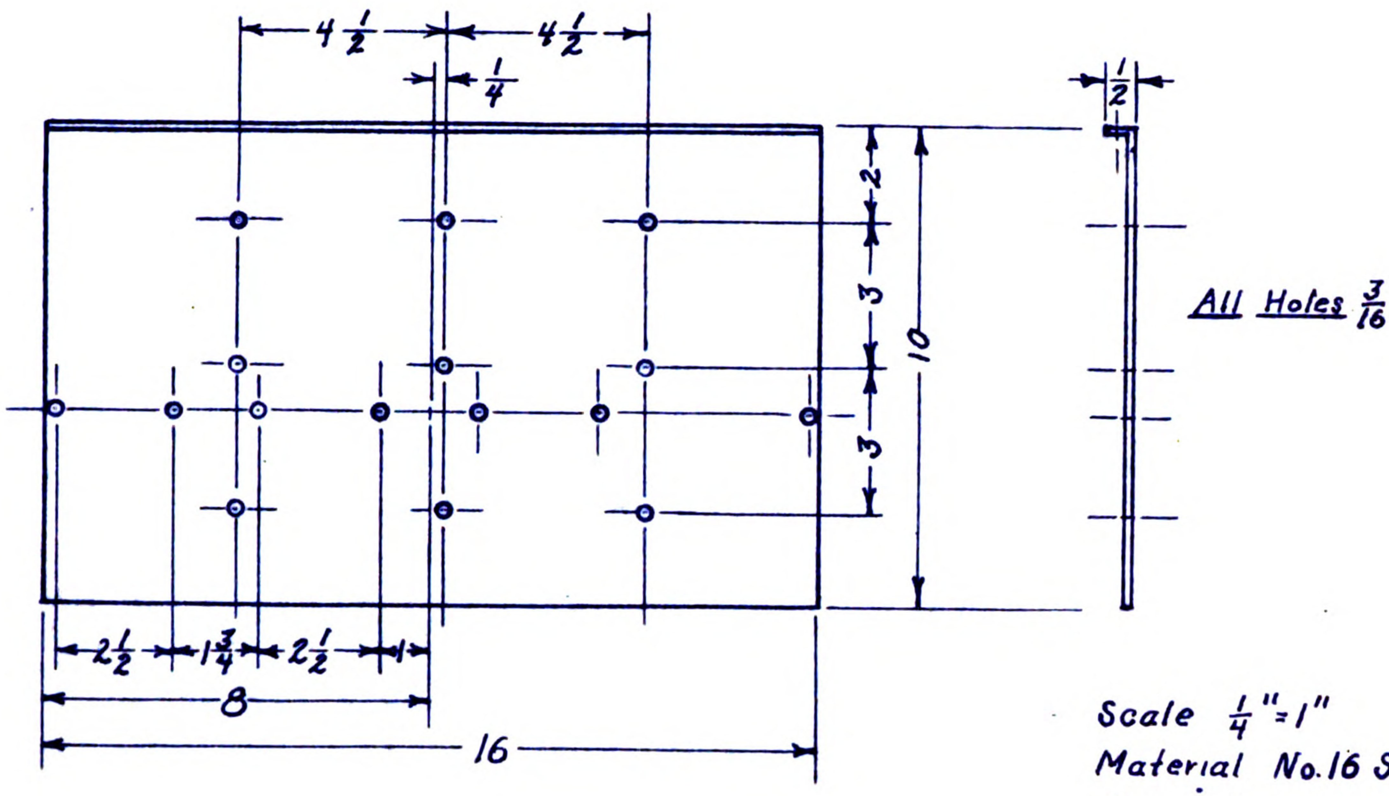
Scale $\frac{3}{8}$" = 1"
Material $\frac{1}{8}$" Aluminiu
Needed 10



All Holes $\frac{3}{16}''$

Scale $\frac{1}{4}'' = 1''$
Material No. 16 Sheet Iron
Quanity 30

Mounting Panel

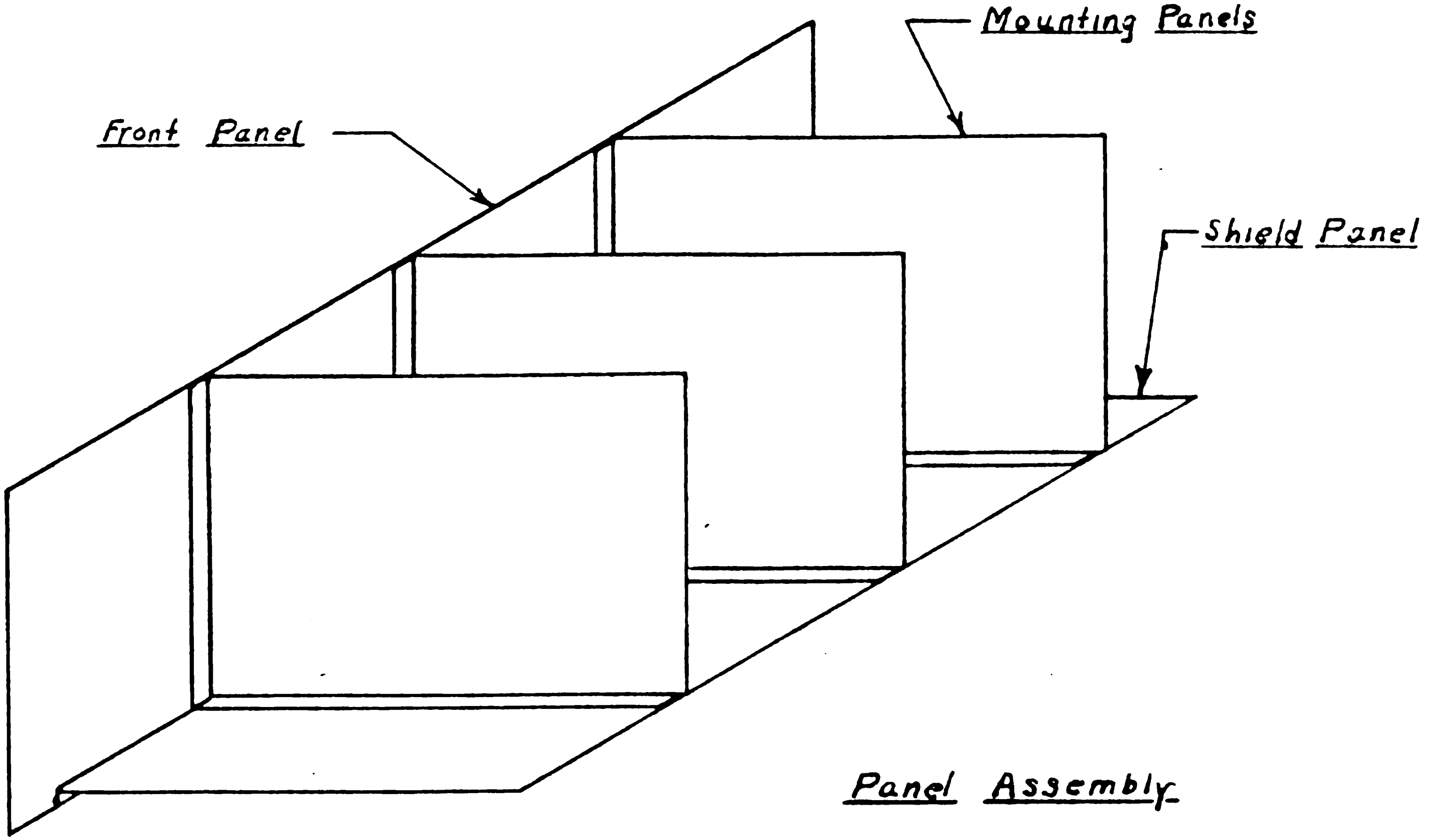


Shield Panel

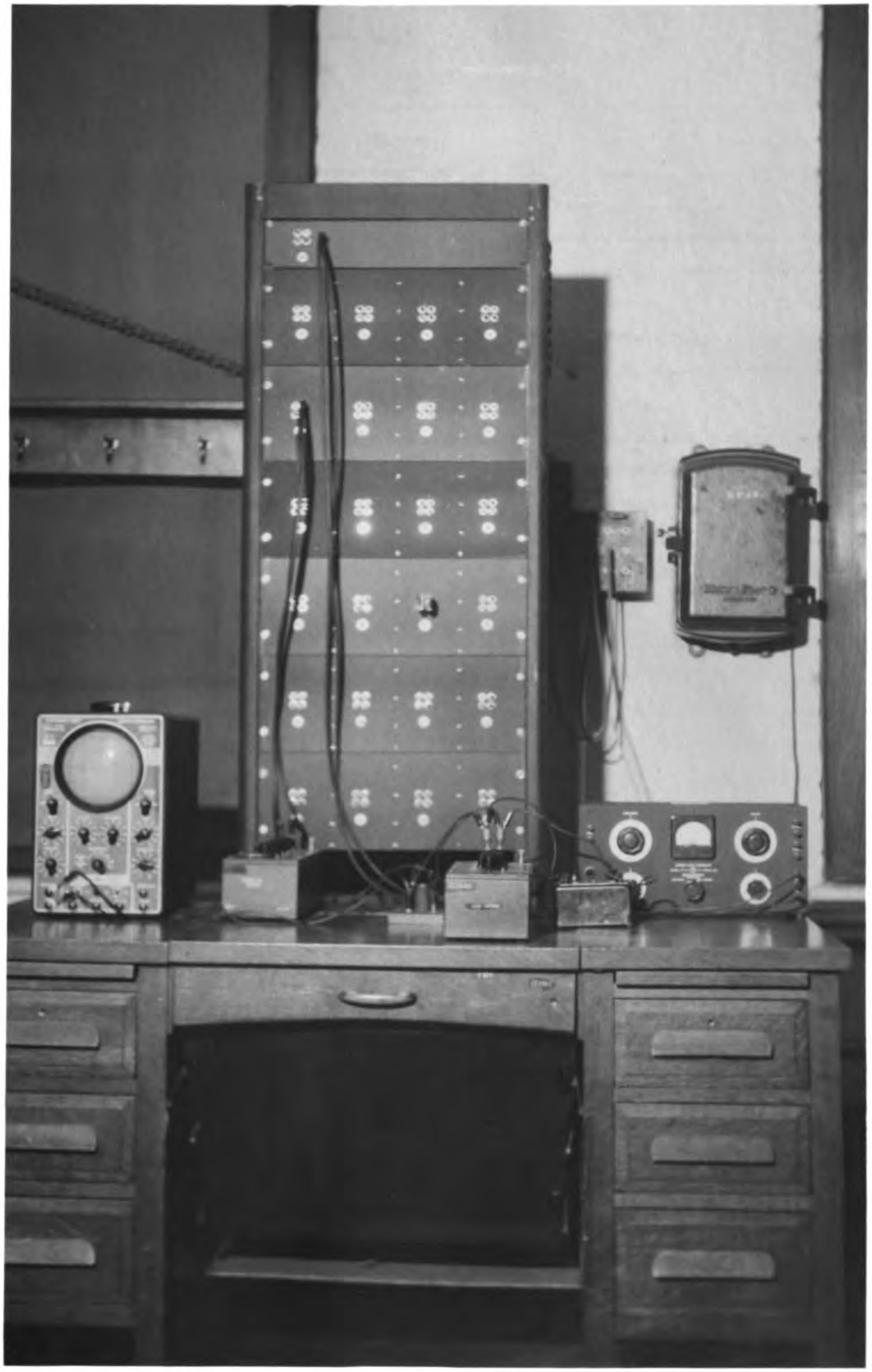
Scale 1/4" = 1"

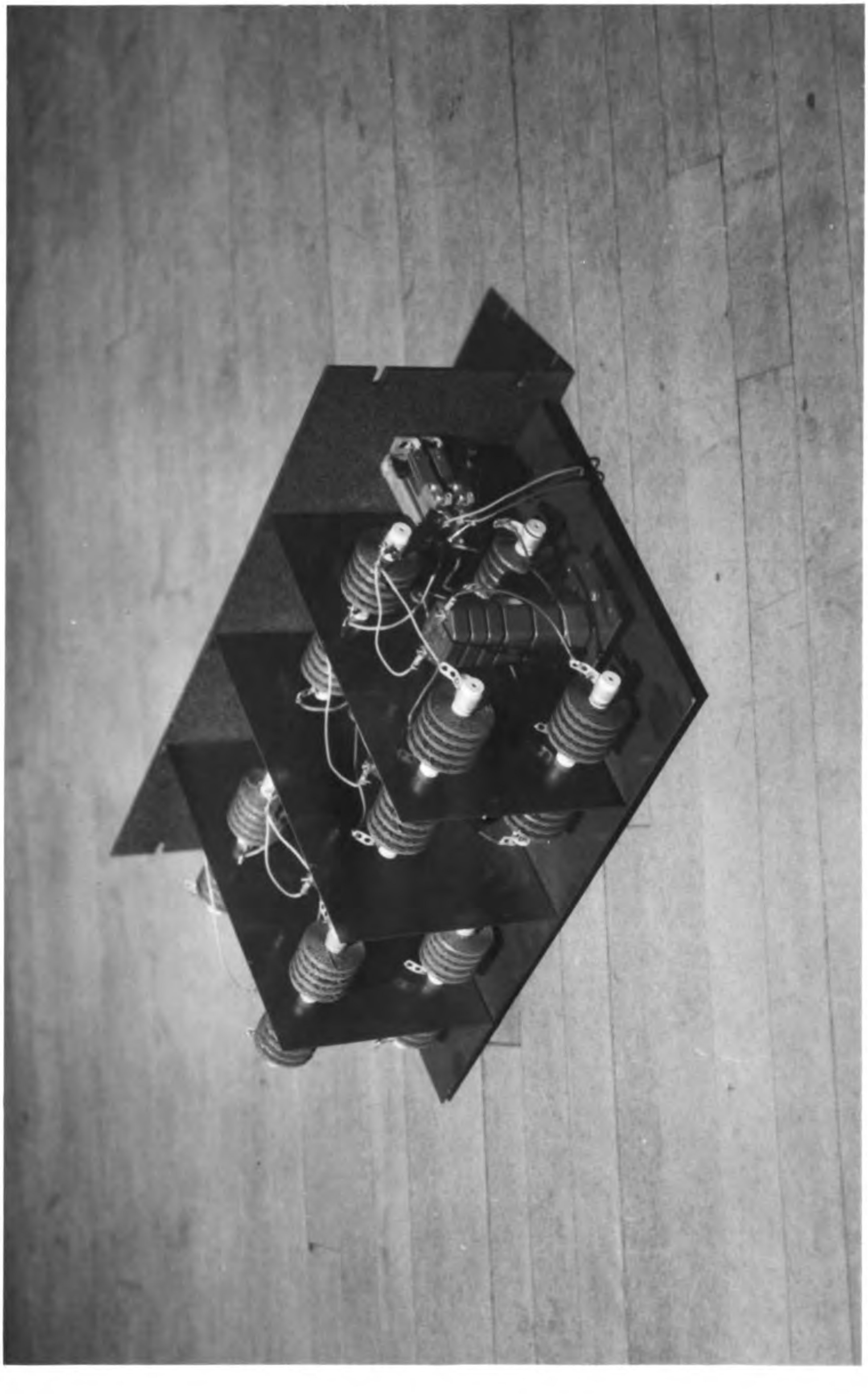
Material No. 16 Sheet Iron

Quanity 10



Panel Assembly





CHAPTER IV

Tests and Results

4.1 Voltage and Current Measurements

The following data show the results of voltage and current measurements at the end of each section[8] for various frequencies under open and short circuit values of termination. The resulting standing waves are clearly shown.

Possibly more data than necessary has been taken to show this result but it is all included here to show that there are no discontinuities or irregular operation points on the line.

Voltage and Current Measurements

f=500 cps.

Section	Open Circuit			Short Circuit		
	I_1	I_2	V	I_1	I_2	V
0	32.0	32.0	25.0	28.0	28.0	25.0
1	29.0	29.0	27.0	30.6	30.6	22.0
2	25.0	25.0	28.8	32.5	32.5	19.0
3	21.2	21.2	30.0	34.0	34.0	16.0
4	17.3	17.3	32.0	36.0	36.0	13.0
5	13.3	13.3	33.0	37.2	37.2	10.0
6	9.0	9.0	33.6	38.0	38.0	6.3
7	4.5	4.5	33.8	38.5	38.5	3.2
8	0.0	0.0	34.0	39.5	39.5	0.0

Voltage and Current Measurements

f=796 cps.

Section	Open Circuit			Short Circuit		
	I_1	I_2	V	I_1	I_2	V
0	79.0	79.0	25.0	12.1	12.1	25.0
1	73.5	73.5	33.0	15.8	15.8	23.0
2	66.4	66.4	41.0	19.0	19.0	21.0
3	58.1	58.1	47.8	23.3	23.3	18.0
4	48.0	48.0	51.5	26.0	26.0	15.0
5	37.0	37.0	58.0	28.2	28.2	12.0
6	25.1	25.1	62.0	30.0	30.0	8.0
7	12.9	12.9	64.5	31.2	31.2	4.0
8	0.0	0.0	65.0	31.9	31.9	0.0

Voltage and Current Measurements

f=1200 cps.

Section	Open Circuit			Short Circuit		
	I_1	I_2	V	I_1	I_2	V
0	79.0	79.0	25.0	12.0	12.0	25.0
1	83.0	83.0	14.0	6.4	6.4	25.8
2	81.8	82.0	13.8	7.2	7.2	25.0
3	75.2	75.1	30.9	13.0	13.0	23.6
4	66.5	66.5	44.2	18.6	18.5	20.2
5	54.0	54.0	53.0	24.2	24.2	16.3
6	38.8	38.8	58.0	28.8	28.8	11.7
7	20.0	20.0	62.0	31.1	31.1	6.0
8	0.0	0.0	63.0	32.2	32.2	0.0

Voltage and Current Measurements

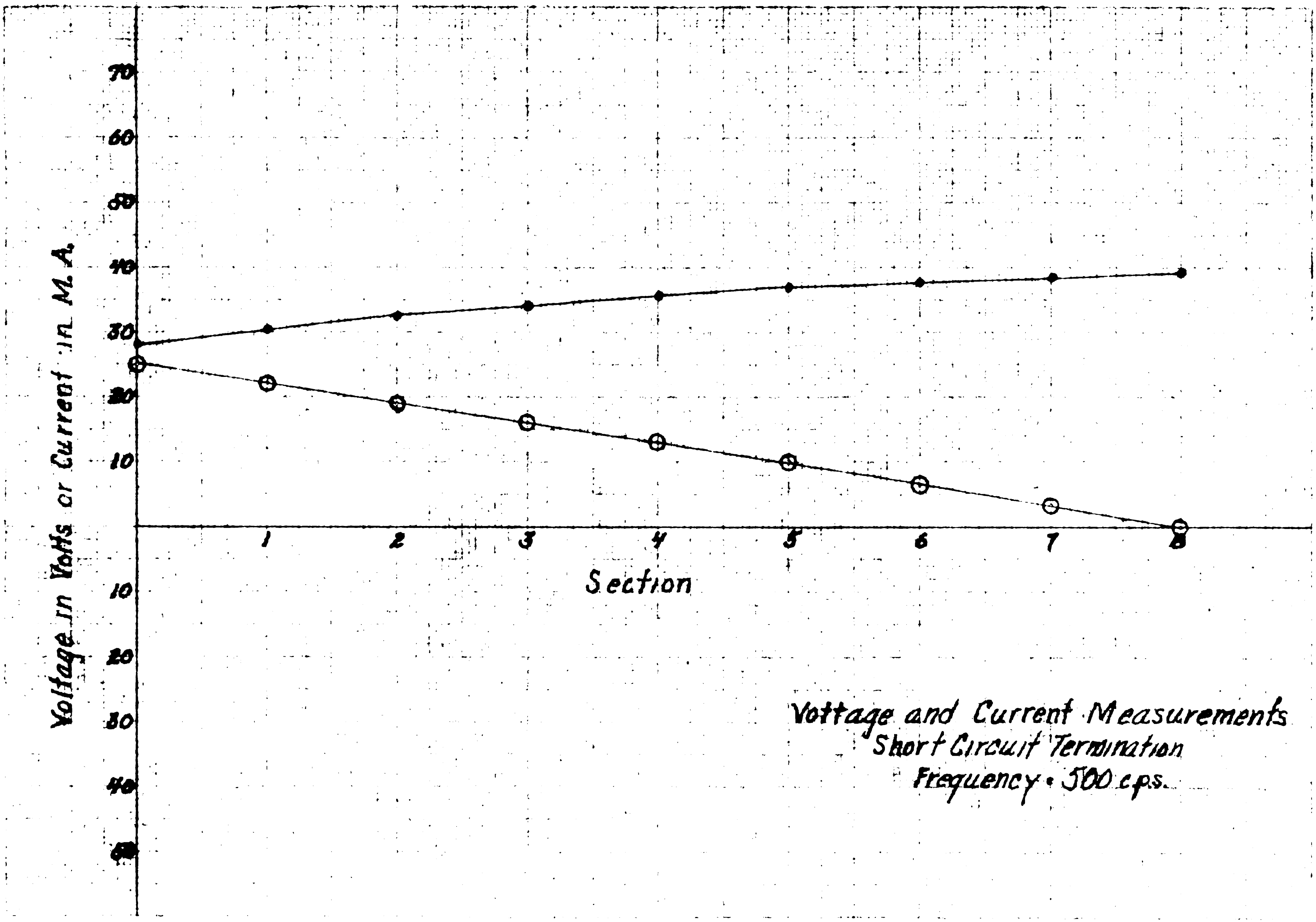
f=2500 cps.

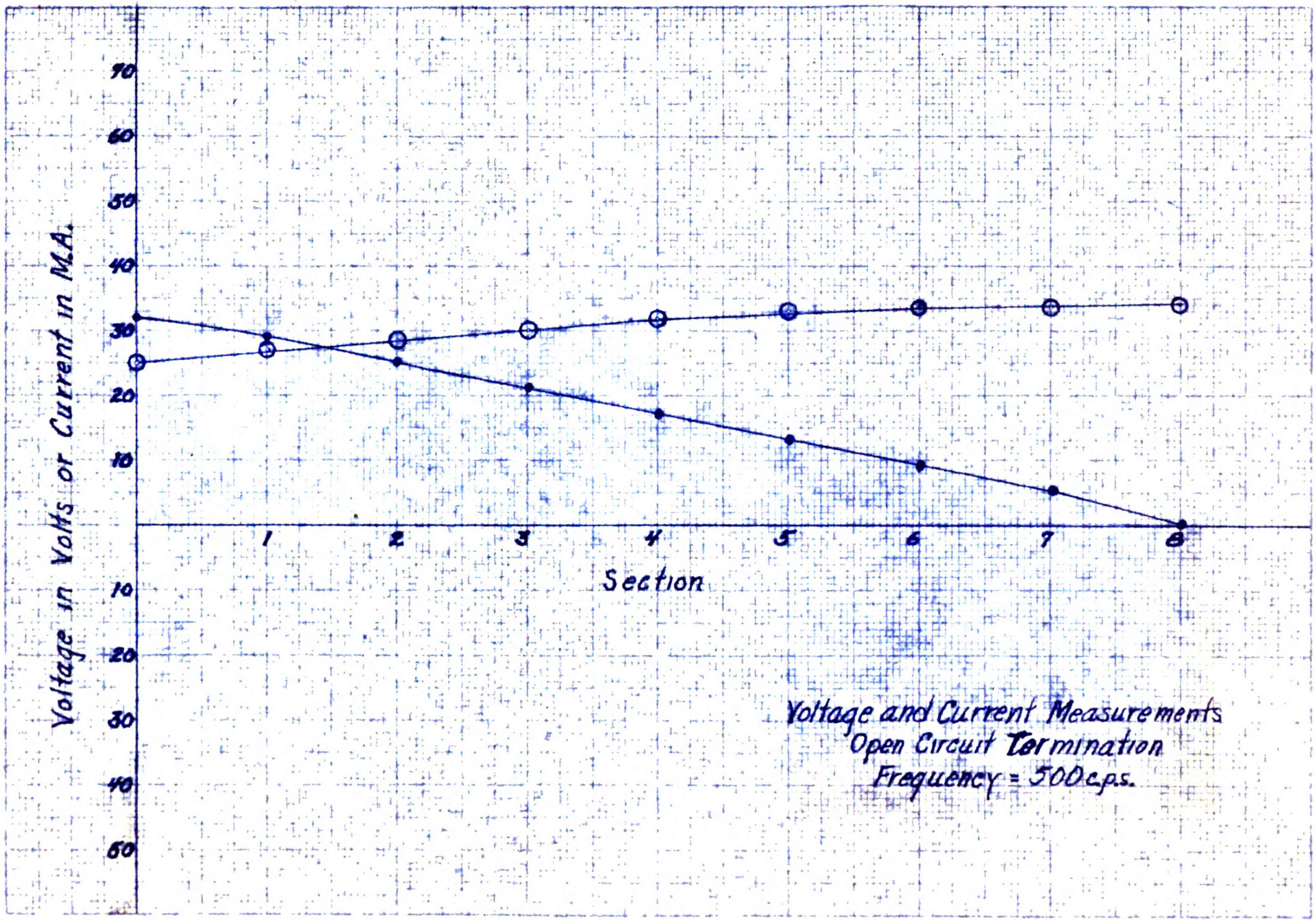
Section	Open Circuit			Short Circuit		
	I_1	I_2	V	I_1	I_2	V
0	31.8	31.8	25.0	32.2	32.2	25.0
1	14.9	14.9	33.0	42.5	42.6	12.0
2	11.5	11.5	34.0	43.1	43.1	9.0
3	28.7	28.6	26.0	34.0	33.9	21.0
4	40.0	40.1	13.0	17.7	17.7	30.5
5	43.0	43.0	4.0	5.7	5.7	33.0
6	36.2	36.2	18.0	24.0	24.0	27.9
7	20.1	20.1	29.0	37.2	37.3	12.9
8	0.0	0.0	33.8	42.0	42.0	0.0

Voltage and Current Measurements

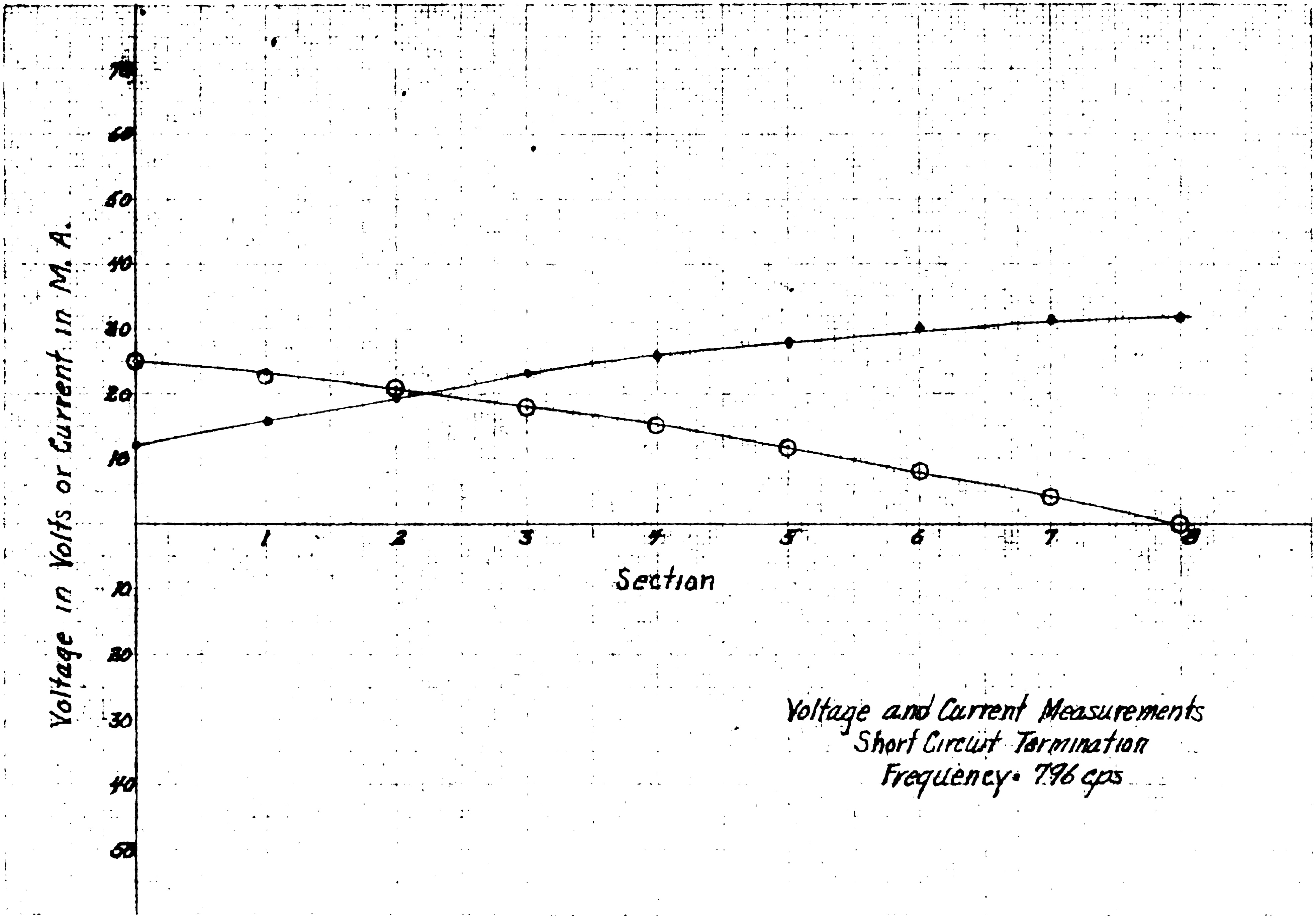
f=3500 cps.

Section	Open Circuit			Short Circuit		
	I_1	I_2	V	I_1	I_2	V
0	33.4	33.4	25.0	34.0	34.0	25.0
1	45.2	45.3	9.0	11.3	11.3	34.0
2	38.0	38.0	19.0	26.0	26.0	29.0
3	14.7	14.7	31.8	42.2	42.2	12.0
4	17.4	17.4	30.8	41.2	41.3	12.0
5	39.0	39.0	15.5	22.0	22.0	29.0
6	43.0	42.8	6.2	8.9	8.9	32.0
7	28.2	28.0	24.5	34.0	34.0	20.2
8	0.0	0.0	31.5	43.0	43.0	0.0

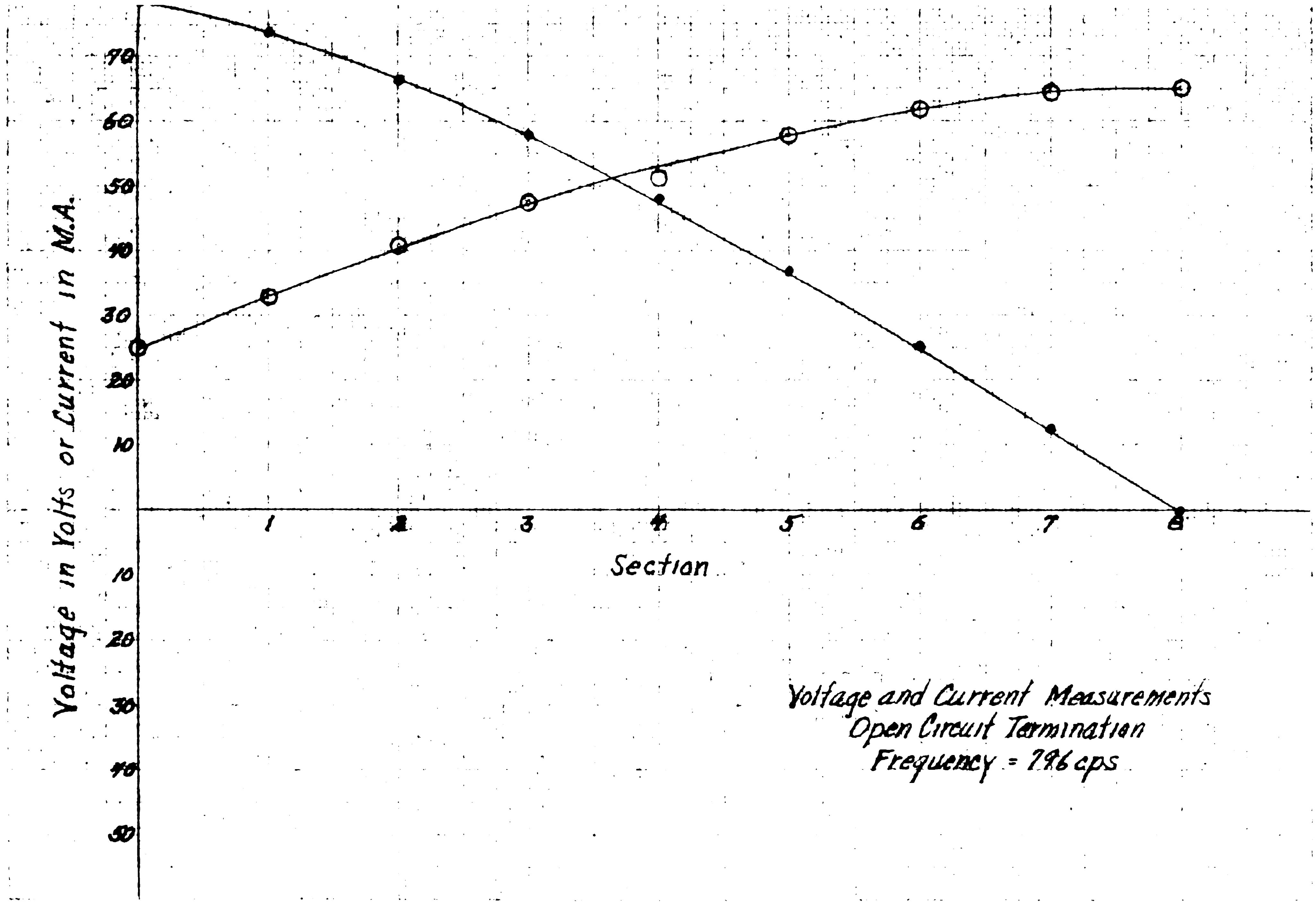

Voltage and Current Measurements
Short Circuit Termination
Frequency • 500 c.p.s.
Voltage in Volts or Current in M.A.
Section
70
60
50
40
30
20
10
10
20
30
40
50
1
2
3
4
5
6
7
8

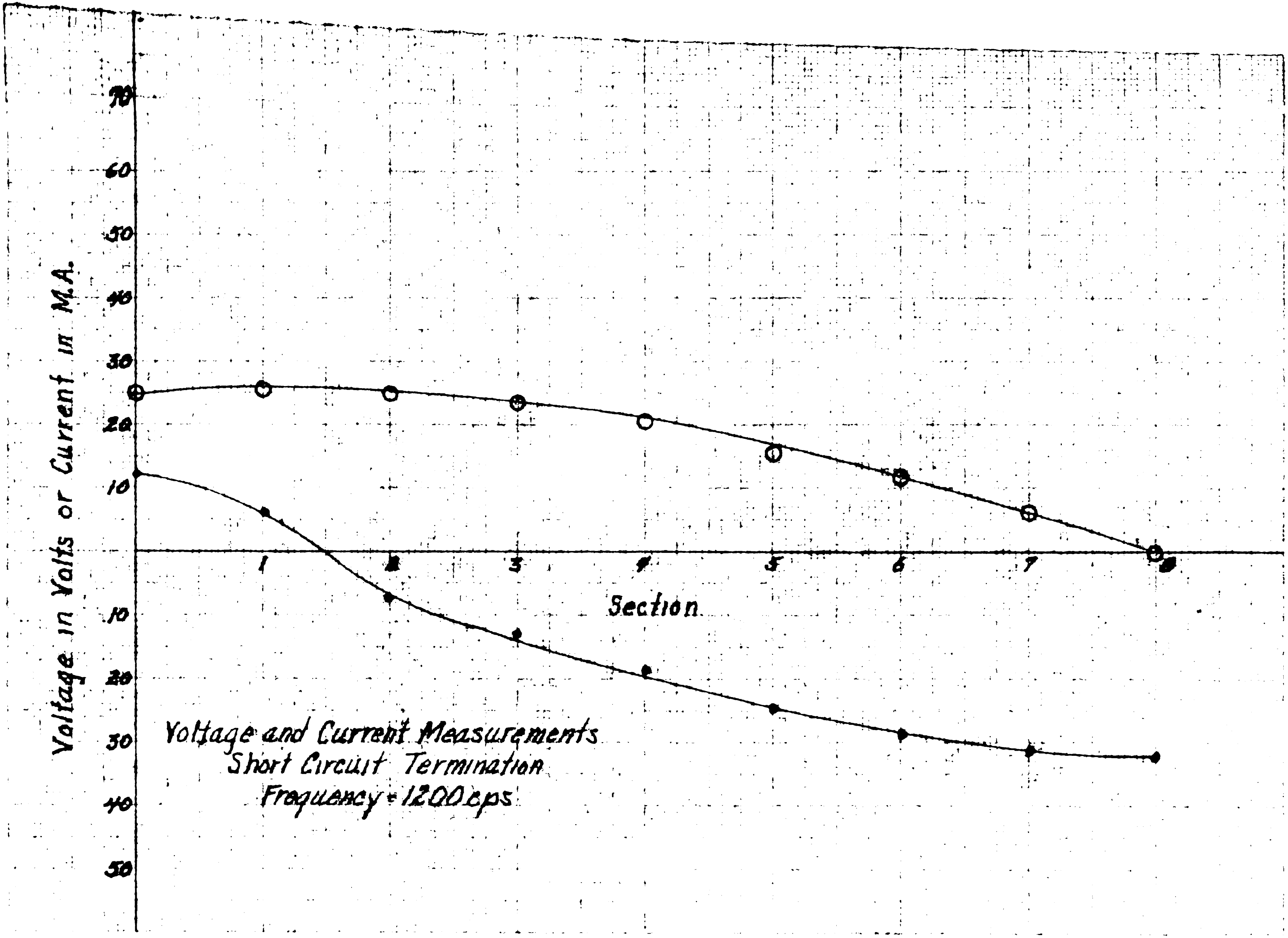


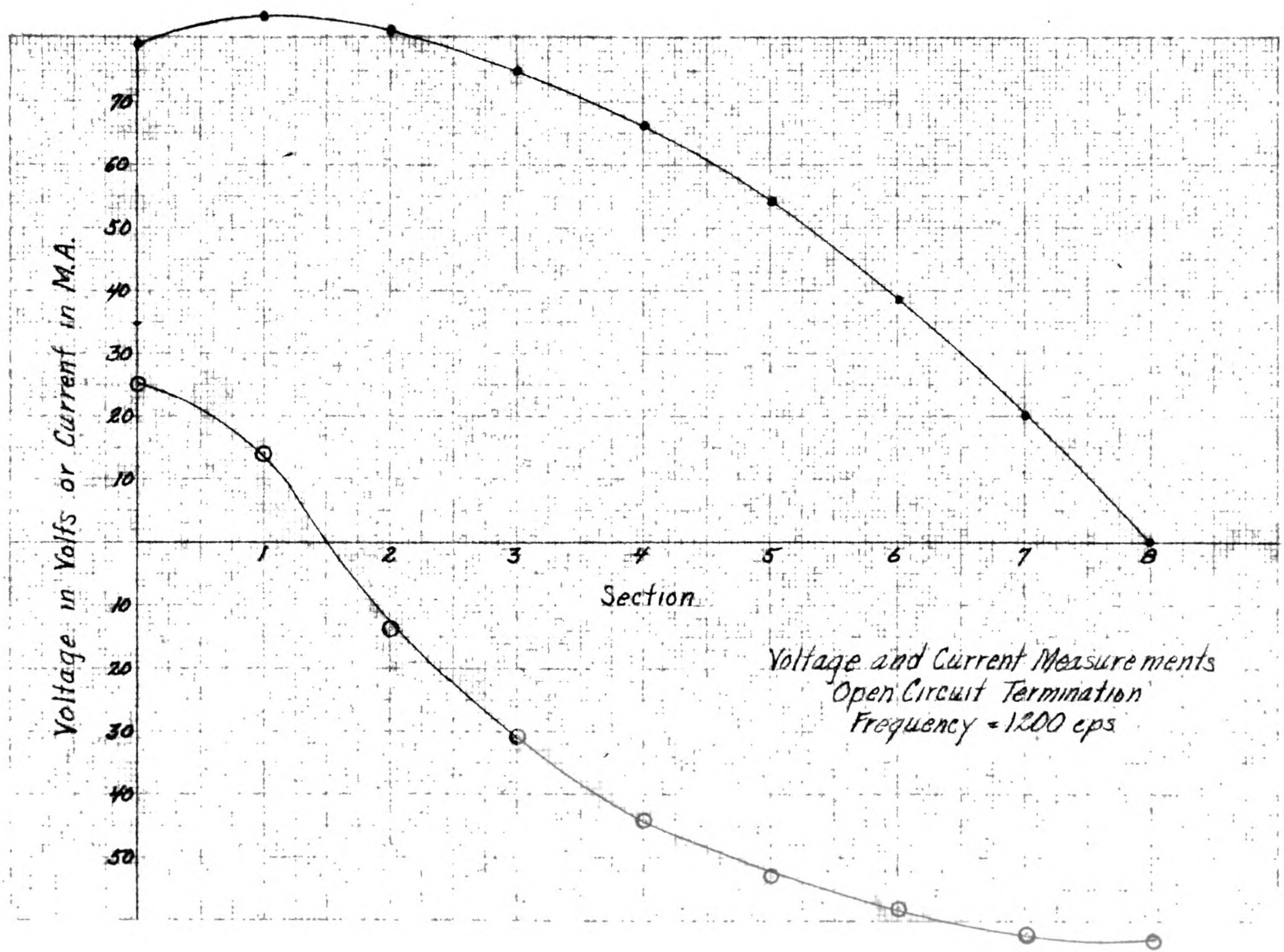
Voltage and Current Measurements
Open Circuit Termination
Frequency = 500 c.p.s.

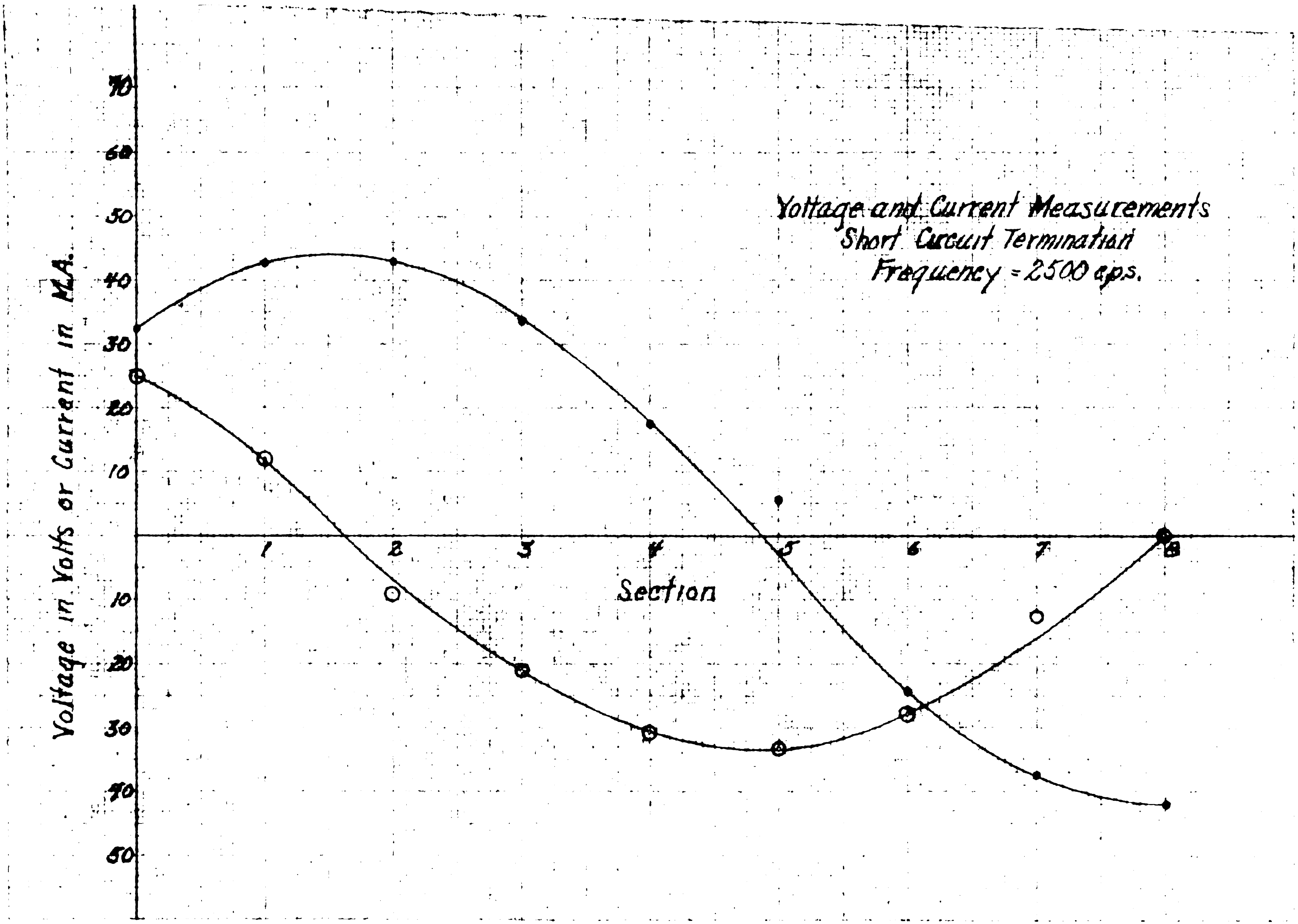


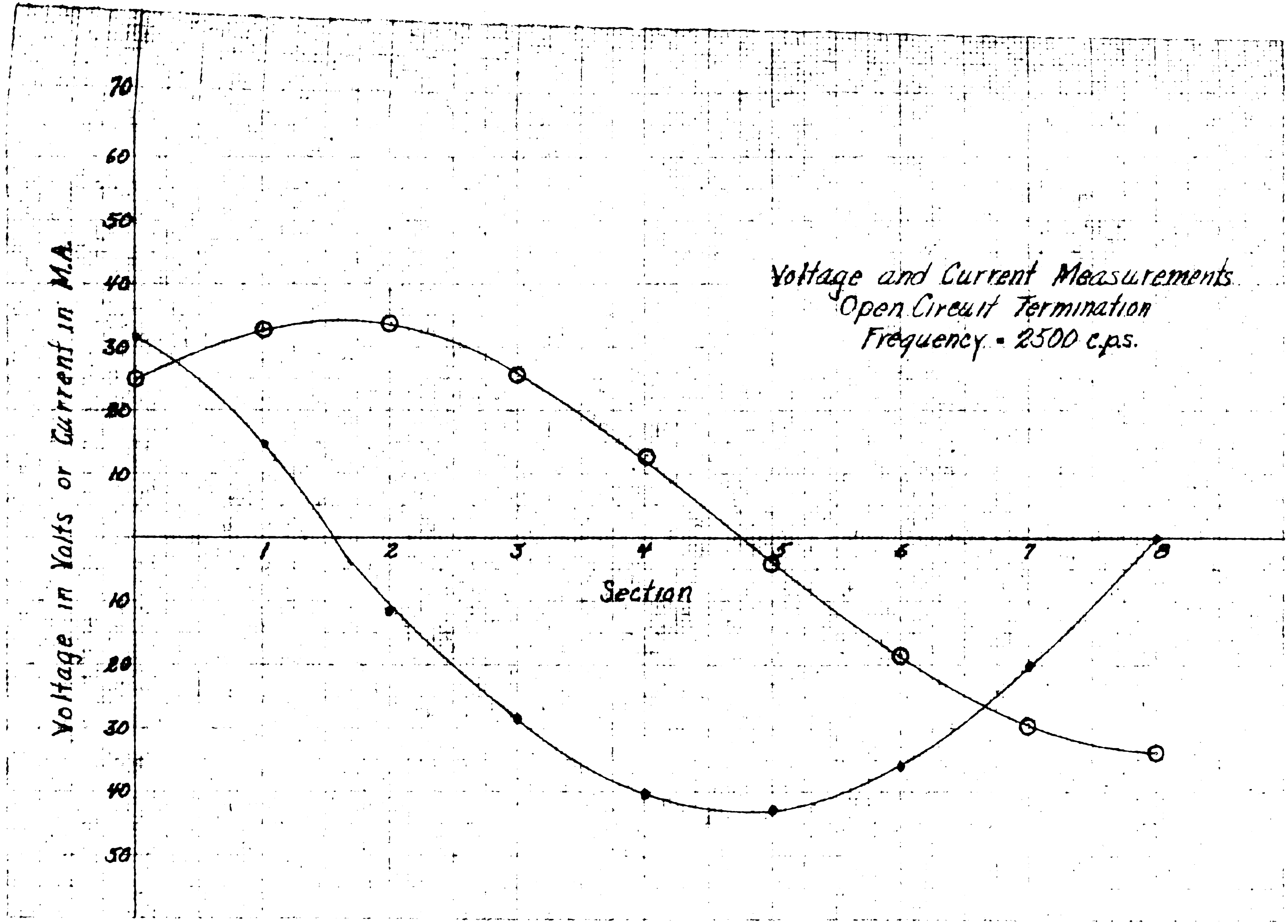
Voltage and Current Measurements
Short Circuit Termination
Frequency = 796 cps


Voltage in Volts or Current in M.A.
70
60
50
40
30
20
10
10
20
30
40
50
1
2
3
4
5
6
7
8
Section
Voltage and Current Measurements
Open Circuit Termination
Frequency = 796 cps

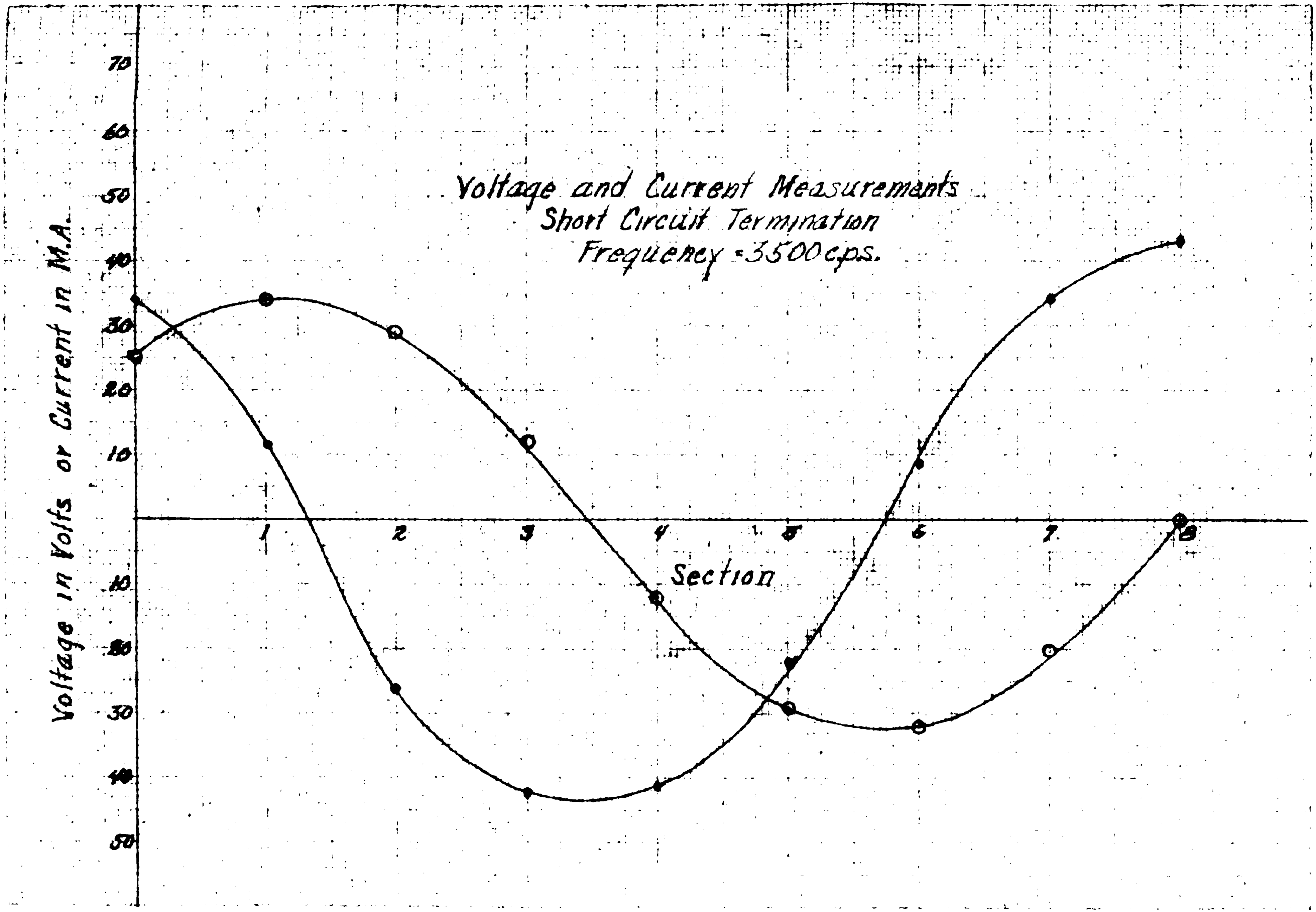

Voltage in Volts or Current in M.A.
70
60
50
40
30
20
10
10
20
30
40
50
1
2
3
4
5
6
7
8
Section
Voltage and Current Measurements
Short Circuit Termination
Frequency = 1200 cps

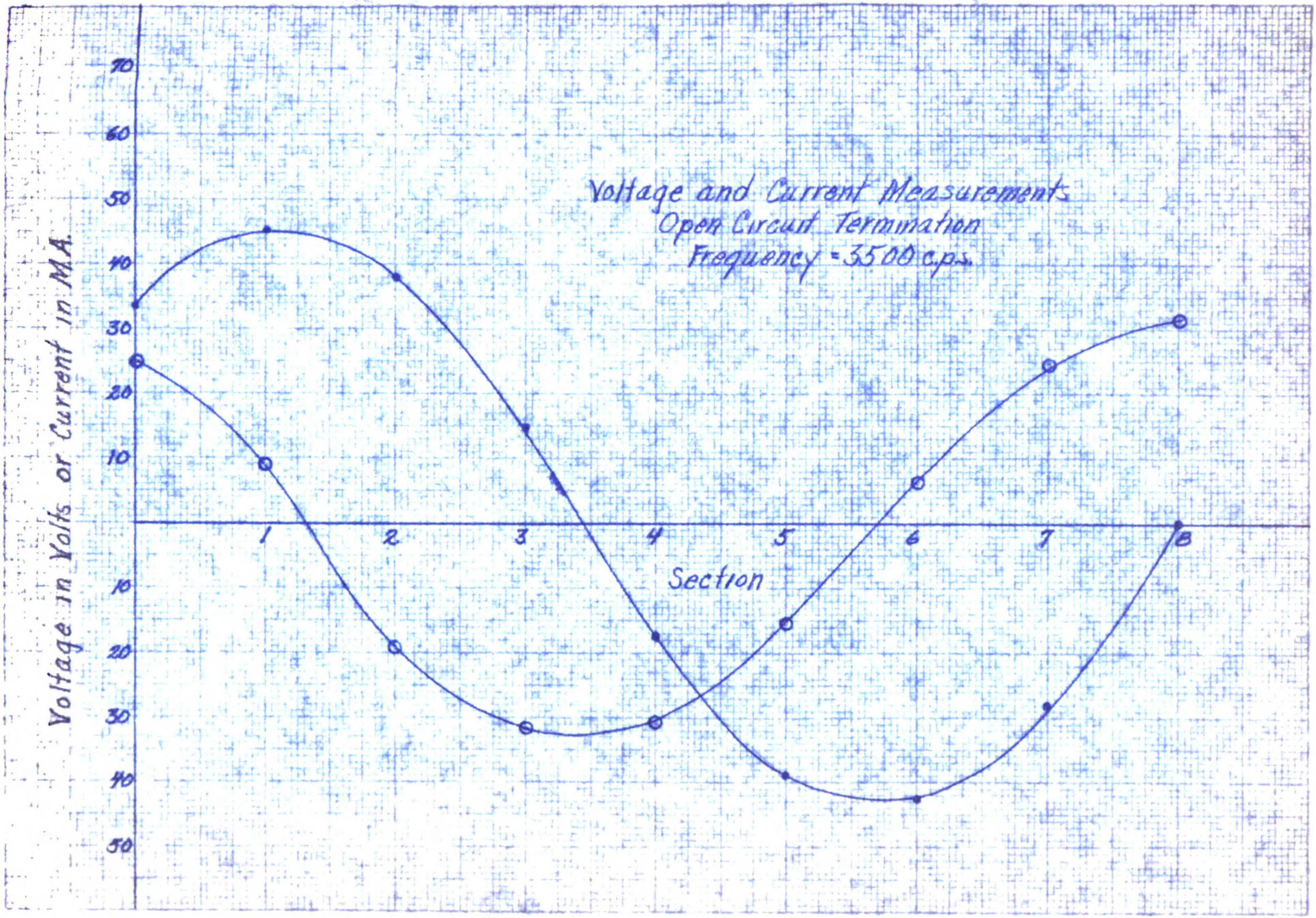

Voltage and Current Measurements
Open Circuit Termination
Frequency = 1200 cps
Voltage in Volts or Current in M.A.
Section
70
60
50
40
30
20
10
10
20
30
40
50
1
2
3
4
5
6
7
8


Voltage and Current Measurements
Short Circuit Termination
Frequency = 2500 cps.
Voltage in Volts or Current in M.A.
70
60
50
40
30
20
10
10
20
30
40
50
1
2
3
4
5
6
7
8
Section



Voltage and Current Measurements
Open Circuit Termination
Frequency = 2500 c.p.s.
Voltage in Volts or Current in M.A.
70
60
50
40
30
20
10
10
20
30
40
50
1
2
3
4
5
6
7
8
Section


Voltage and Current Measurements
Short Circuit Termination
Frequency = 3500 cps.
Voltage in Volts or Current in M.A.
70
60
50
40
30
20
10
10
20
30
40
50
1
2
3
4
5
6
7
8
Section


Voltage and Current Measurements
Open Circuit Termination
Frequency = 3500 c.p.s.
Section
Voltage in Volts or Current in M.A.
70
60
50
40
30
20
10
10
20
30
40
50
1
2
3
4
5
6
7
8

4.2 Impedance Data and Curves

The following data was taken to determine how R and X vary with frequency for the open and short circuit cases. From this data Z_0 is calculated for many frequencies and also the angle of Z_0 .

The constants were measured with a standard bridge circuit which balances the R and L of the line. The circuit of Figure a) being used when the line is capacitive in nature and that of Figure b) when the line is inductive in nature.

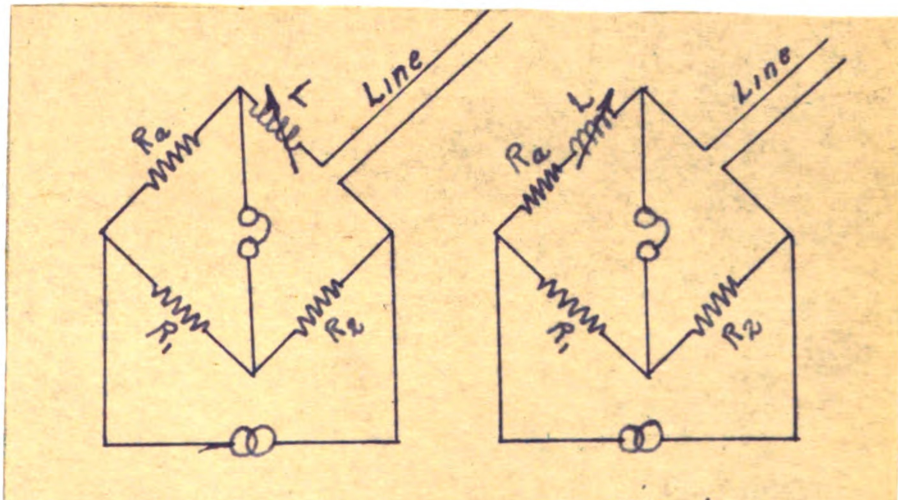


Fig. a Fig. b

A very good idea of the value of the Characteristic impedance can be obtained by first calculating the characteristic impedance of one of the H sections.

$$Z_0 = \sqrt{\frac{Z}{Y}} = \sqrt{\frac{R + j\omega L}{G + jB}}$$

$$= \sqrt{\frac{56 + j\,2\pi \times 796 \times 24.3 \times 10^{-3}}{0 + j\,2\pi \times 796 \times .048 \times 10^{-3}}}$$

$$= 706 \angle -14.4^\circ$$

Z_o Calculations for Eight Sections

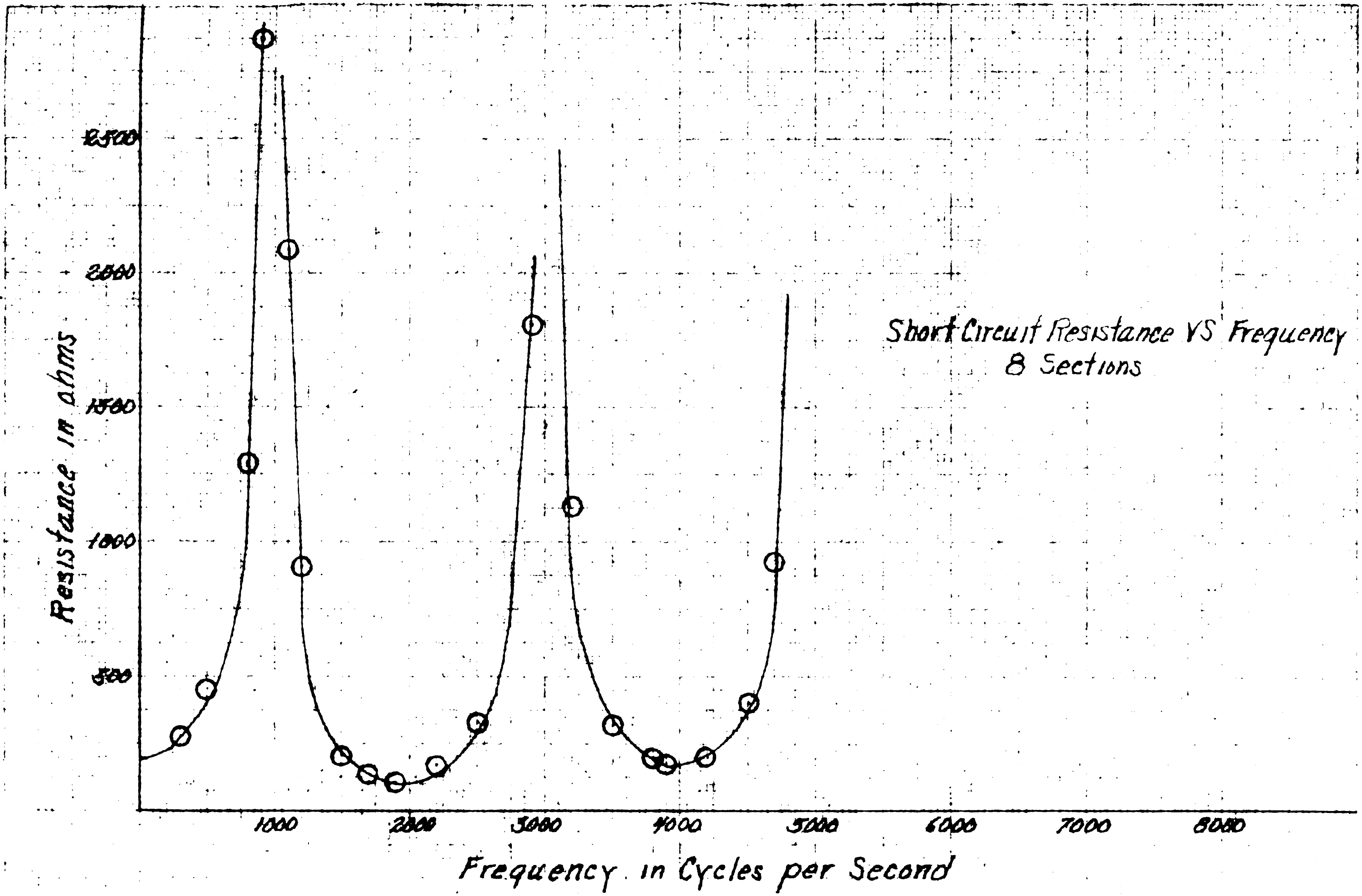
freq.	$Z_{oc} \times Z_{sc}$	Z_o	θ
300	1440 x 454	805	-15.5°
500	722 x 804	740	-12.9°
796	282 x 1940	740	-8.7°
900	180 x 2970	730	-7.8°
1000	-	-	
1100	191 x 2820	735	-5.3°
1200	268 x 1791	695	-3.3°
1500	736 x 722	730	-5.7°
1700	1305 x 387	710	-6.3°
1900	2640 x 172	674	-7.3°
2000	-	-	
2200	1895 x 264	694	-4.7°
2500	726 x 704	716	-3.0°
2900	214 x 2060	664	-3.7°
3000	-	-	
3200	278 x 1651	677	-0.2°
3500	669 x 672	670	+0.1°
3800	1523 x 262	633	0.6°
3900	2195 x 196	654	0.3°
4000	-	-	
4200	1395 x 313	652	1.5°
4500	528 x 790	646	1.9°
4700	305 x 1341	640	0.9°

Open Circuit Measurements for Eight Sections

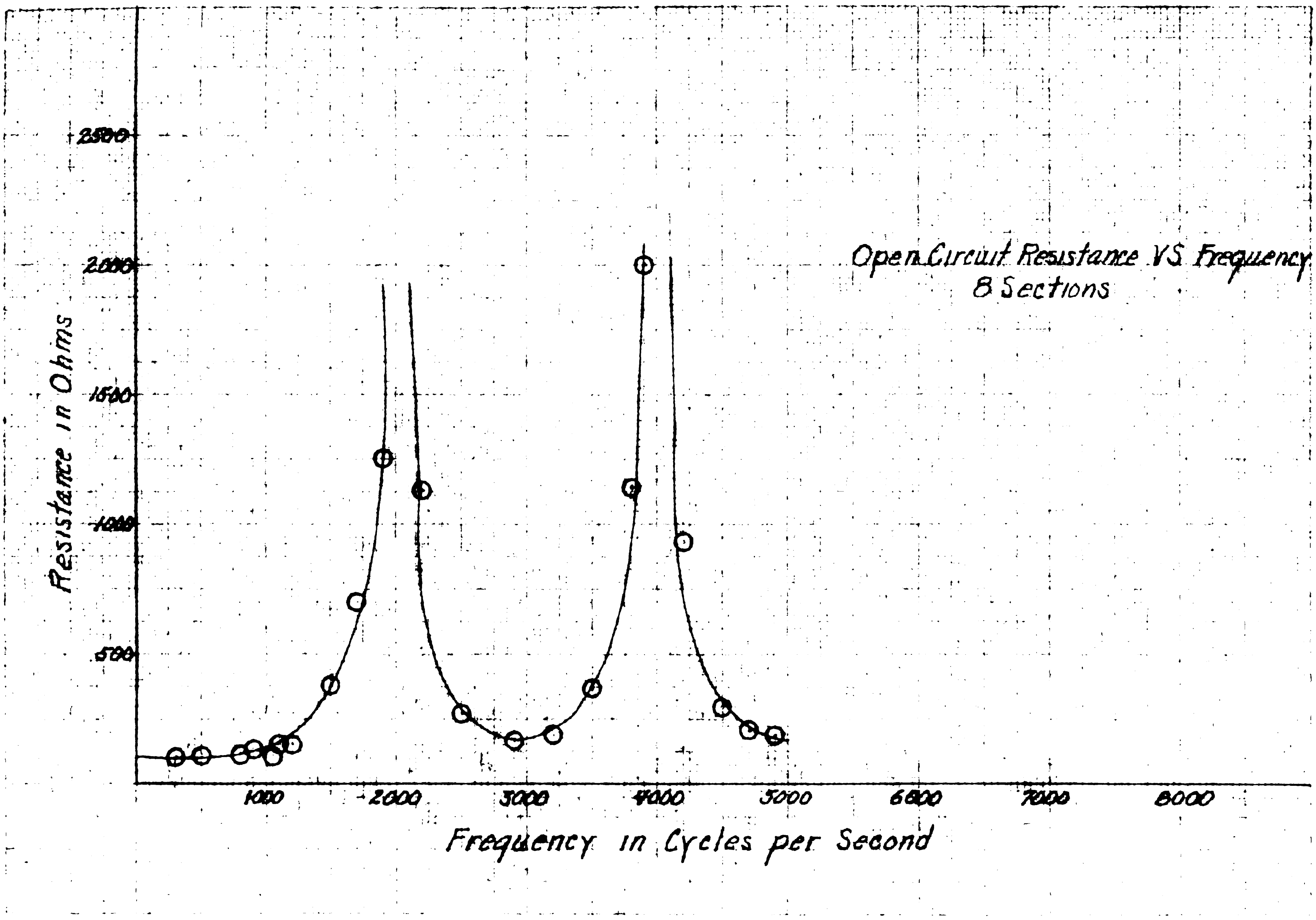
freq.	R	L_{mh}	Z	Z_{mag}	Z_{arg}
300	105	760	105 -j1430	1440	-82.2°
500	110	225	110 - j720	722	-81.3°
796	118	51	118 - j256	282	-65.3°
900	128	23	128 - j126	180	-44.7°
1000	127	2	127 - j13	128	-5.8°
1050	110	6	110 + j40	117	19.7°
1100	162	15	162 + j100	191	31.6°
1200	159	29	159 + j215	268	53.6°
1500	336	68	336 + j635	736	62.2°
1700	706	103	706 +j1100	1305	57.2°
1900	2256	115	2256 +j1370	2640	31.3°
2200	1133	110	1133 -j1520	1895	-53.2°
2500	274	43	274 - j672	726	-67.9°
2900	172	7	172 - j127	214	-36.4°
3200	190	10	190 + j202	278	46.8°
3500	320	26	320 + j587	669	61.4°
3800	1140	42	1140 +j1008	1523	41.4°
3900	2006	37	2006 + j892	2195	24.0°
4200	934	38	934 -j1000	1395	-46.8°
4500	300	15	300 - j435	528	-55.4°
4700	220	7	220 - j211	305	-43.8°
4900	190	2	190 - j62	200	-17.9°

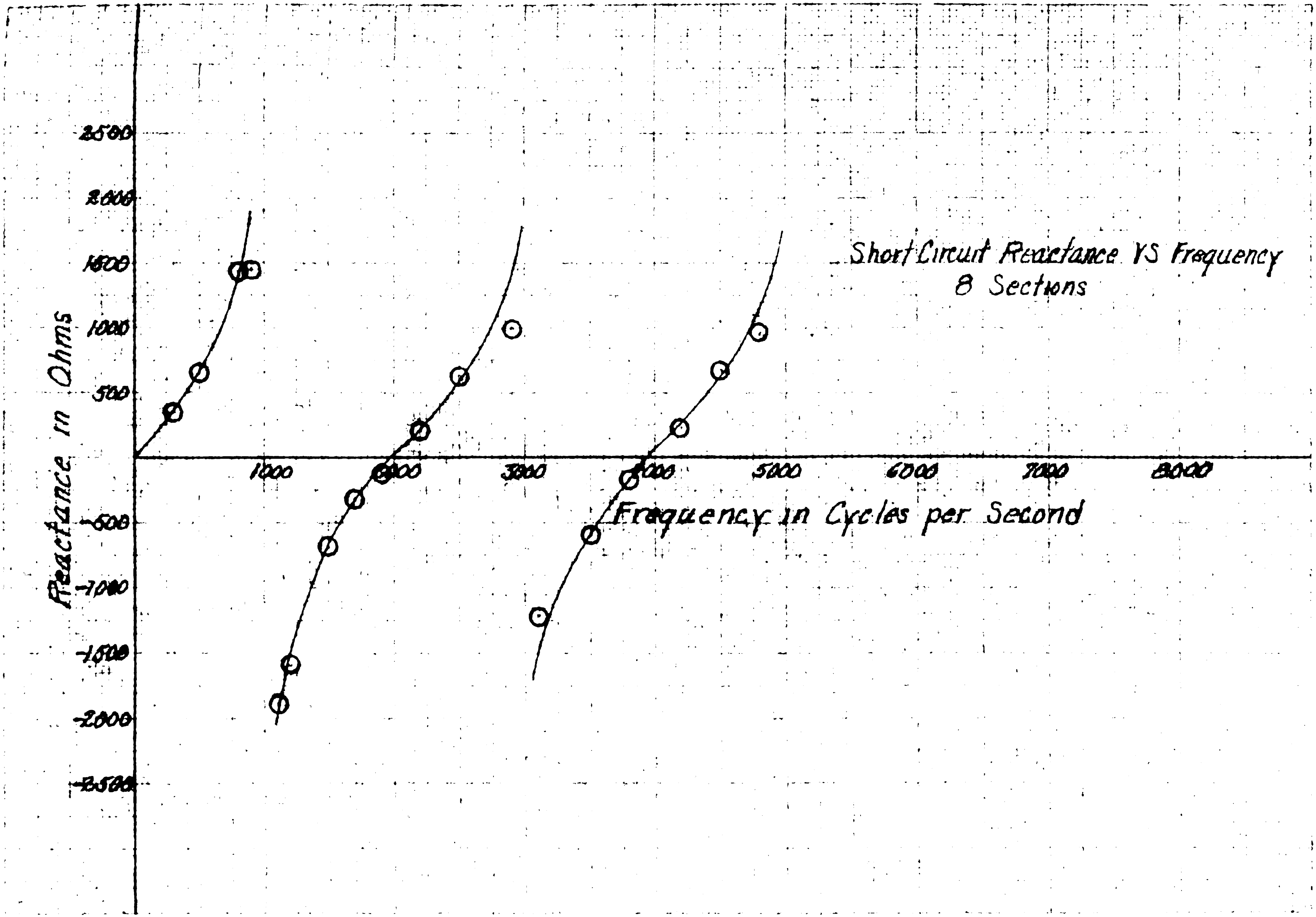
Short Circuit Measurements for Eight Sections

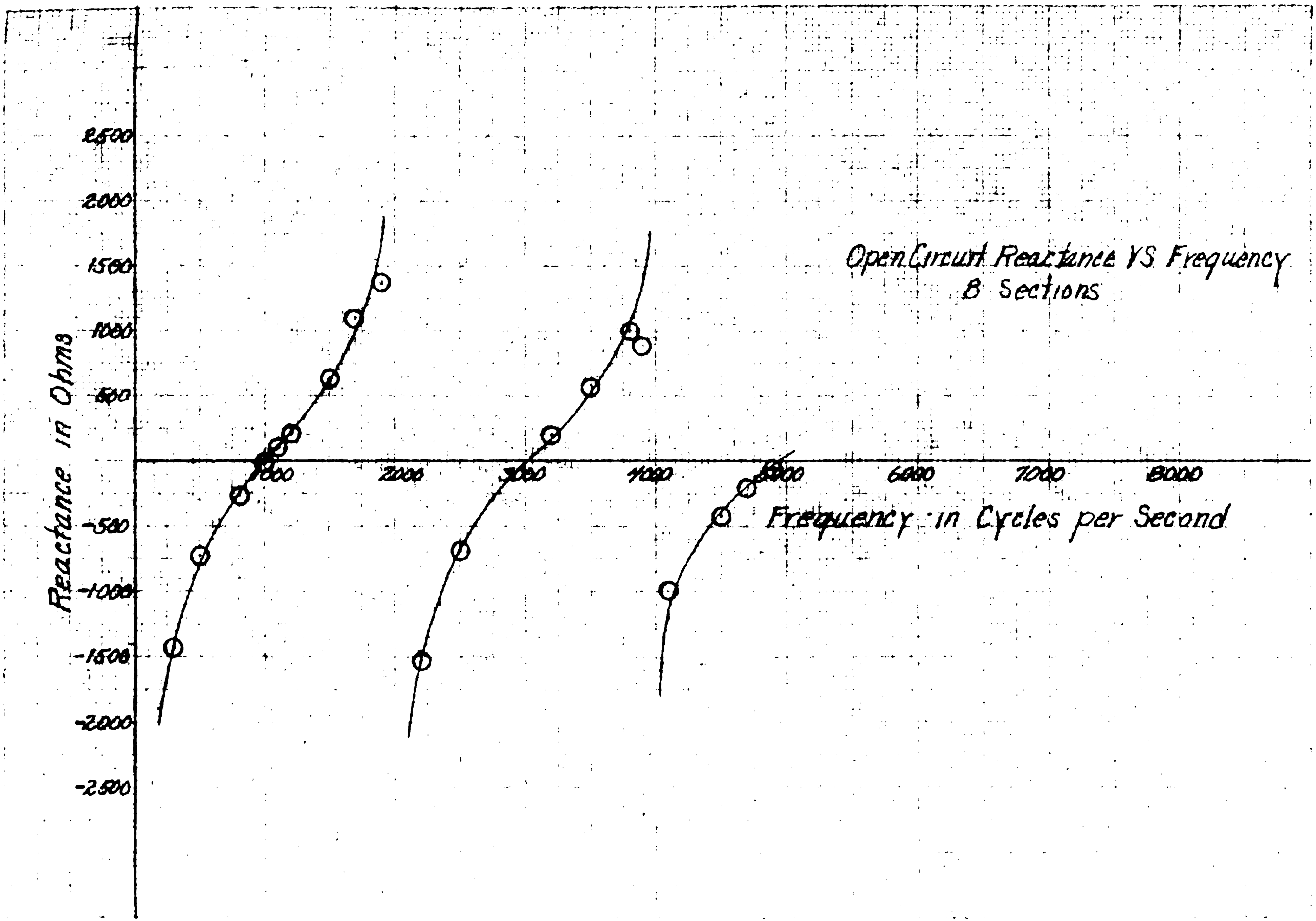
freq	R	L_{mh}	Z	Z_{mag}	Z_{arg}
300	285	188	285+ j354	454	51.2°
500	455	212	455 + j662	804	55.5°
796	1295	288	1295 +j1440	1940	48.0°
900	2585	240	2585 +j1450	2970	29.2°
1000	-	-			
1100	2090	277	2090 -j1890	2820	-42.1°
1200	915	211	915 -j1590	1791	-60.1°
1500	204	74	204 - j692	722	-73.6°
1700	134	35	134 - j364	387	-69.8°
1900	117	10	117 - j120	172	-45.8°
2000	-	-			
2200	171	14	171 + j202	264	49.8°
2500	331	40	331 + j628	704	62.0°
2900	1806	55	1806 +j1000	2060	29.0°
3000	-	-			-
3200	1124	60	1124 -j1210	1651	-47.1°
3500	320	27	320 - j591	672	-61.6°
3800	200	7	200 - j169	262	-40.2°
3900	180	3	180 - j 78	196	-23.5°
4000	-	-			
4200	202	9	202 + j239	313	49.8°
4500	406	24	406 + j680	790	59.2°
4700	936	33	936 + j960	1341	45.7°



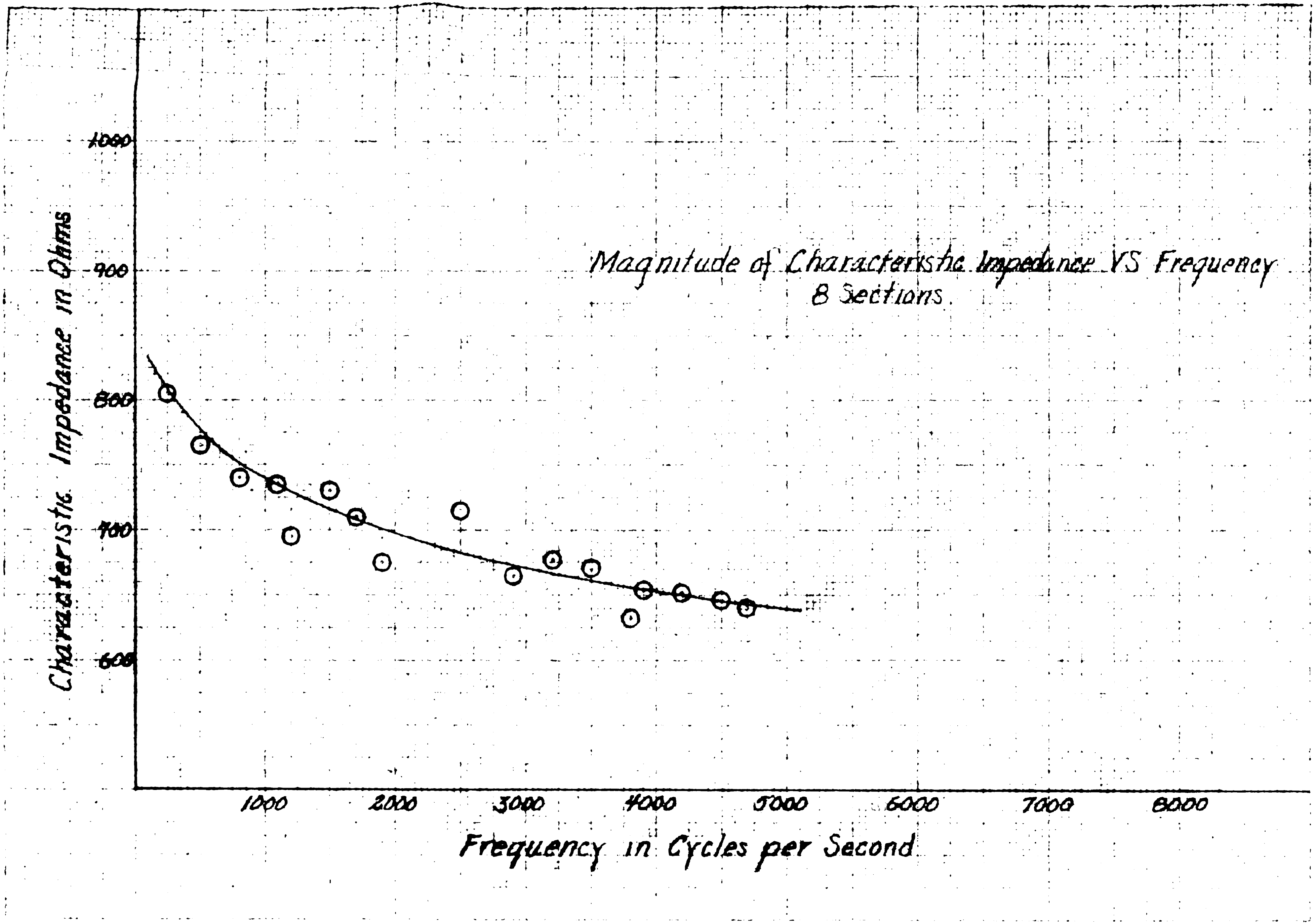
Short Circuit Resistance VS Frequency
8 Sections
Resistance in ohms
2500
2000
1500
1000
500
1000
2000
3000
4000
5000
6000
7000
8000
Frequency in Cycles per Second


Open Circuit Resistance VS Frequency
8 Sections
Resistance in Ohms
2500
2000
1500
1000
500
1000
2000
3000
4000
5000
6000
7000
8000
Frequency in Cycles per Second

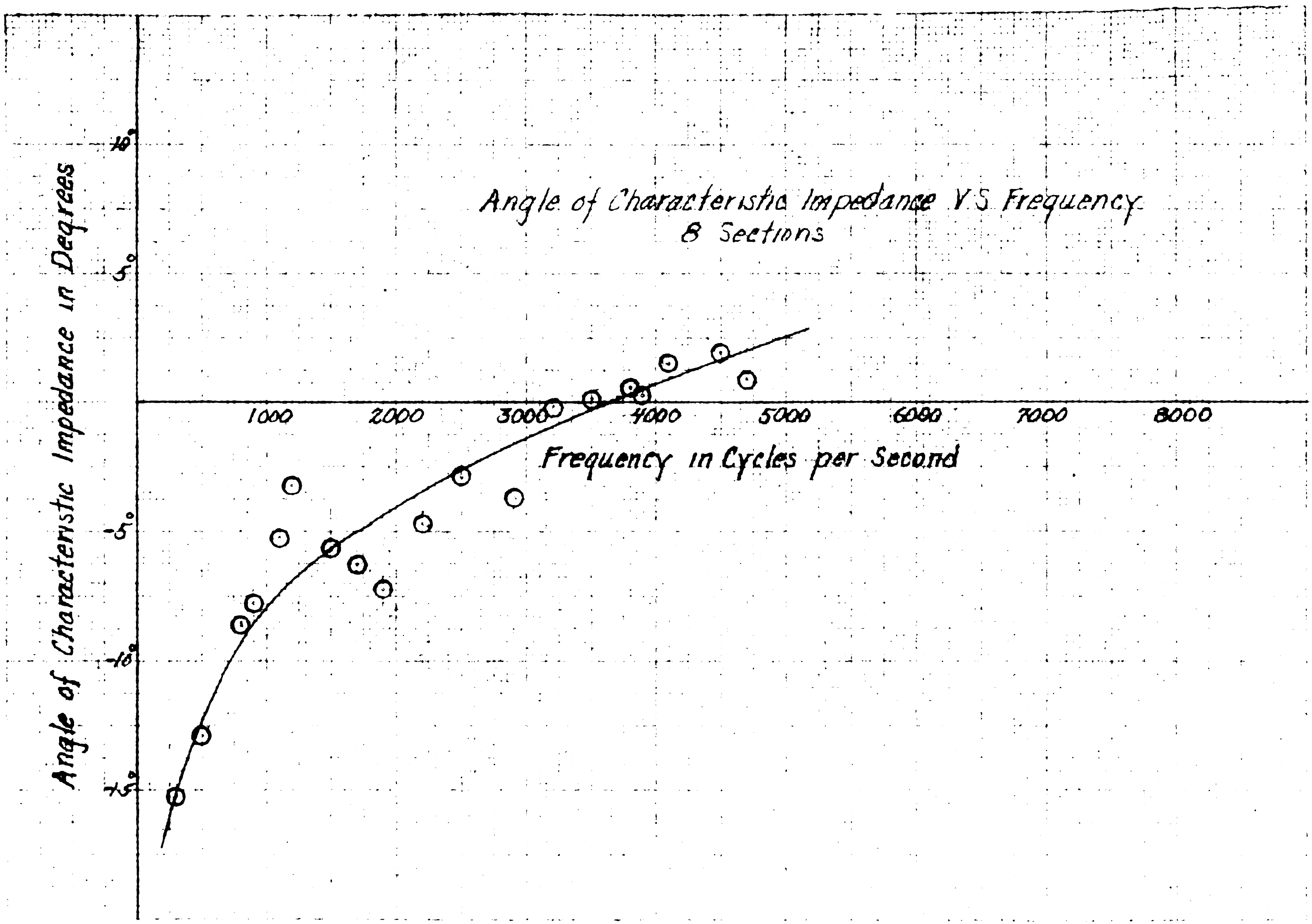

Short Circuit Reactance VS Frequency
8 Sections
Reactance in Ohms
Frequency in Cycles per Second
2500
2000
1500
1000
500
-500
-1000
-1500
-2000
-2500
1000
2000
3000
4000
5000
6000
7000
8000



Open Circuit Reactance VS Frequency
8 Sections
Reactance in Ohms
2500
2000
1500
1000
500
-500
-1000
-1500
-2000
-2500
1000
2000
3000
4000
5000
6000
7000
8000
Frequency in Cycles per Second



Magnitude of Characteristic Impedance VS Frequency
8 Sections
Characteristic Impedance in Ohms
1000
900
800
700
600
1000
2000
3000
4000
5000
6000
7000
8000
Frequency in Cycles per Second


Angle of Characteristic Impedance V.S Frequency
8 Sections
Angle of Characteristic Impedance in Degrees
10°
5°
-5°
-10°
-15°
1000
2000
3000
4000
5000
6000
7000
8000
Frequency in Cycles per Second

4.3 Determination of the Line Constants from Impedance Measurements

Often it is desirable to obtain the constants of an unknown line. A very convenient method[9] of doing this is from the impedance data gathered in section 4.2. The following set of calculations will then determine the line constants. They are used here also as a check upon the impedance measurements since we know their actual values.

at $f = 796$ cps

$$Z_{oc} = 282 \angle -65.3^\circ$$

$$Z_{sc} = 1940 \angle 48^\circ$$

$$Z_0 = \sqrt{Z_{oc} Z_{sc}} = \sqrt{282 \times 1940 \angle}$$

$$= 740 \angle -8.65^\circ$$

$$\tanh \gamma l = \sqrt{\frac{Z_{sc}}{Z_{oc}}} = \sqrt{\frac{1940 \angle 48^\circ}{282 \angle -65.3^\circ}}$$

$$= 2.62 \angle 56.6^\circ$$

$$= 1.442 + j\,219$$

$A = 1.442$

$B = 2.19$

$A^2 + B^2 = 2.08 + 4.78$

$= 6.86$

$$\tanh 2\alpha l = \frac{2A}{1+A^2+B^2} = \frac{2.884}{7.86}$$

$= .368$

$2\alpha l = .387$

$\alpha l = .193$

$$\alpha = \frac{.193}{8}$$

$= .0241$ / section

$$\tan 2\beta l = \frac{2B}{1-(A^2+B^2)} = \frac{4.38}{-5.86}$$

$= .818$

$2\beta l = 140^\circ 43' = 140.717^\circ$

$\beta l = 70.3585^\circ = 1.225$ rad.

$$\beta = \frac{1.225}{8}$$

$= .1532$ rad/section

$$\gamma = \alpha + j\beta = .0241 + j.1532$$
$$= .1555 \angle 80.7^\circ$$

$$Z = Z_0 \gamma = 740 \angle -8.65^\circ \times .155 \angle 80.7^\circ$$
$$= 114.7 \angle 72.15^\circ$$
$$= 36.2 + j\,109$$

$R = 36.2$ ohms/section

$L = \frac{109}{\omega} = 21.78$ mh/section

$$Y = \frac{\gamma}{Z_0} = \frac{.1555 \angle 80.7^\circ}{740 \angle -8.65^\circ}$$
$$= .000210 \angle 89.35^\circ$$
$$= .0000034 + j.000210$$

$G = 3.4$ μ mho/section

$C = \frac{210 \times 10^{-6}}{\omega} = .042$ μf/section

$\lambda = \frac{2\pi}{\beta} = \frac{6.28}{.1532} = 41$ sections

$V = \frac{\omega}{\beta} = \frac{6.28 \times 796}{.1532} = 32{,}600$ sections/sec.

	Computed Values	Actual Values	% error
R	36.2 Ω	36.0	.55%
L	21.78 mh	21.2	2.77%
C	.042 uf	.048	12.5%
G	3.4×10^{-6} mho	?	?

4.4 Location of Faults

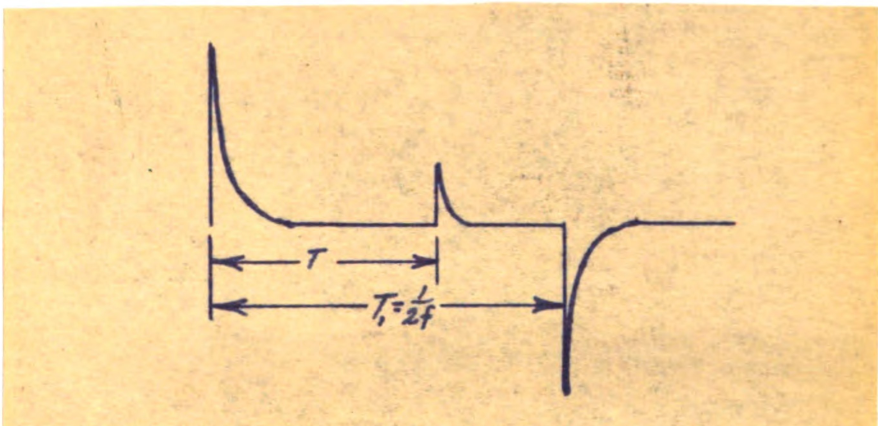
The usual method of location of fault on a transmission by accurate bridge measurements is not discussed here due to lack of time and space. This method is well known however and there is no reason to believe that it would not work nicely with the artificial line.

Another more usual method of location faults[10] was used however. This method is employed very little if at all at the present time, however its great advantages seem to warrant widespread future use in all types of transmission lines.

Briefly the method consists of sending a very sharp pulse type signal down the transmission line. If the line is terminated in the Characteristic Impedance, the pulse is dissapated and reflections are not present. However, if the line is not properly terminated or a fault exists, a pulse is reflected back to the start of the line.

With a series of repeating pulses, an Oscilloscope can be placed across the line showing the applied pulses sweeping across the screen just as in viewing a sine wave. If reflections are present, they will be shown displaced from the sending pulse by an amount proportional to the distance of the fault causing the reflection.

If the frequency of the pulse is known, and the apparent velocity of the wave on the line is known, the distance to a fault is very easily calculated from measurements taken upon the oscilloscope screen. A very complete knowledge of the type of fault which exists is also known.



Ideal Oscilloscope Trace

From the above diagram the time to the reflected wave can easily be found since T_1 is known from f.

Perhaps the best way to find the apparent velocity of the line is to place a discontinuity on the line at a known distance and measuring the time and hence the velocity from $v = f\lambda$. Knowing this, the fault can be located by

$$2\ell = \frac{v}{f} = vt$$

$$\ell = \frac{vt}{2}$$

On the following page is a circuit diagram of this method of determining line faults. The source of pulses comes from a square wave which is differentiated by the R-C combination. The 650 ohm 6db pad is placed in the circuit so that Z_g is more nearly matched to Z_o. This prevents another reflection from occuring if a wave comes back toward Z_g. The following pictures were taken from the screen of a standard 5" DuMont oscilloscope. A plate type camera with an auxillary lens to permit close-up foucing was used to take the pictures with an exposure of approximately 2 seconds on Super XX film.

Picture a) is that of a normal line. The slight waves or uneveness of the pulse are believed to be small reflections caused by lumping the line constants. By expanding the vertical axis of the oscilloscope greatly, 8 uneven places occur at approximately the right distance to account for this fact when 8 sections of line were used.

Picture b) is that of an open-circuited line on the eighth section. The reflected wave is clearly seen.

Picture c) is that of a short circuited line on the eighth section. The reflection is of the opposite polarity to that of the open circuit but is in exactly the same place and of the same form.

Picture d) is of a normal line but with two 50 ohm

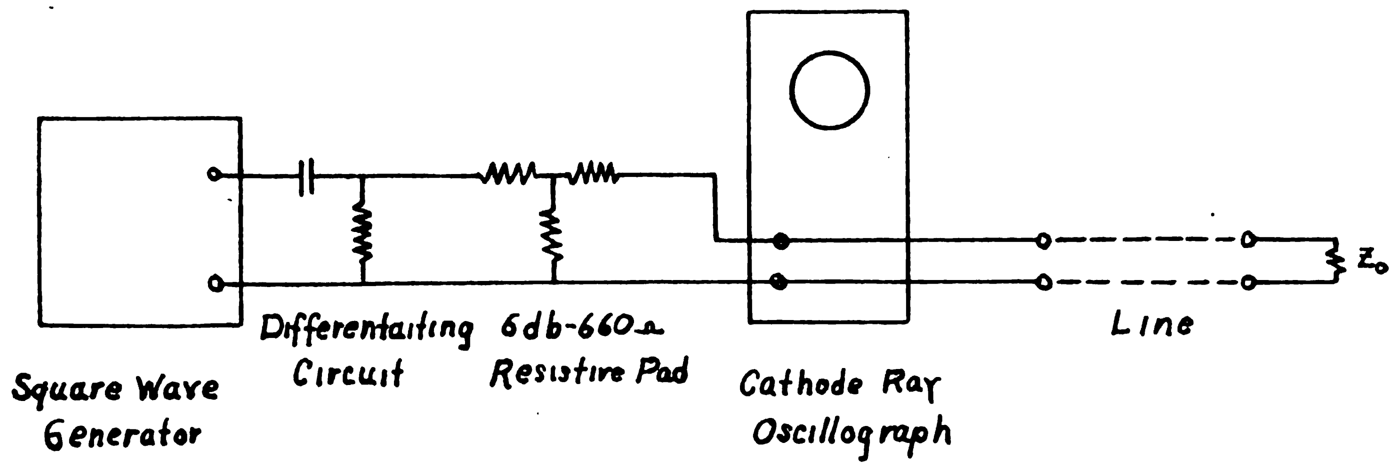
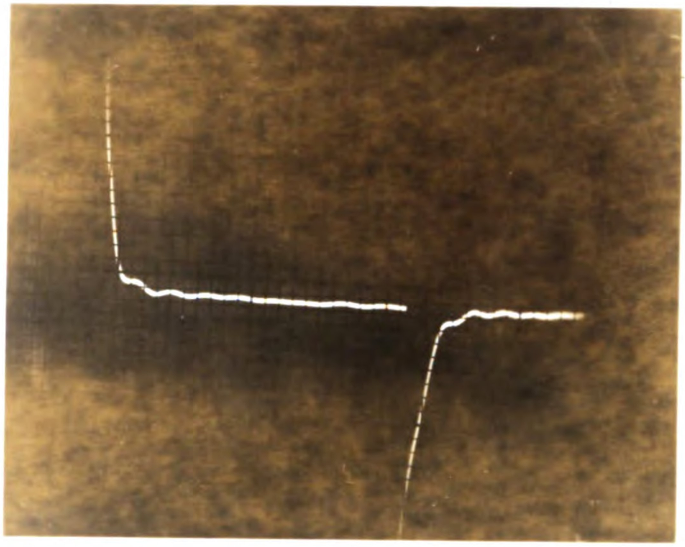
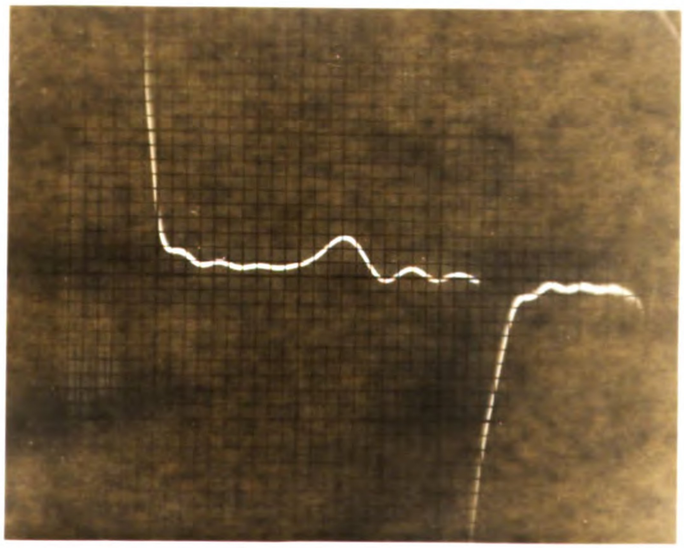


Diagram of

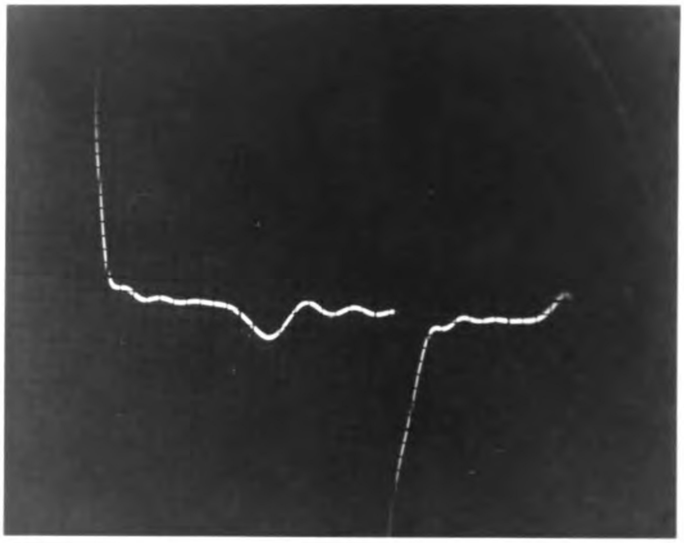
Location of Line Faults by a Pulse Technique



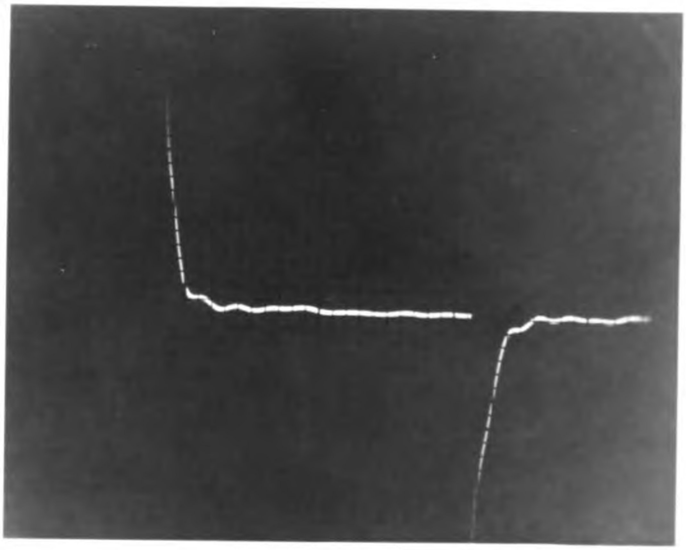
Normal Line



Open Circuit on Section No. 8



Short Circuit on Section No. 8



100-Ω Resistance added on Section No. 6

resistors inserted into the line at the end of the sixth section. Compare this photograph with that of the normal line and the reflection caused by the resistors is easily seen.

The calculations to determine the placement of the resistors follow.

From Photo 4, the apparent velocity of propogation is

$$v = \frac{l}{t} = 16 \times 1000 \times \frac{24}{14}$$

$$= 27,420 \text{ sections/sec}$$

$$l = \frac{vt}{2} = \frac{27,420}{2} \times \frac{11}{232} \times \frac{1}{1000}$$

= 5.94 sections Calculated

6.00 sections actual

1% error

With very simple equipment and a little practice this method of determining line or cable faults is quite accurate and informative. For the best results the following things should be tabulated on the lines to be tested.

1. Velocity of propogation of the line
2. A normal picture of the line

Another use for this type of testing of transmission lines is that of correctly terminating the line. Observation of the oscilloscope while varying the terminating impedance at the end of eight sections of line would show a very definite reflection if the terminating impedance was varied 5% from Z_0. A simple test like this would easily and quickly eliminate the echo effect caused by reflection in the transmission of pictures by wire.

4.5 Square Wave Testing

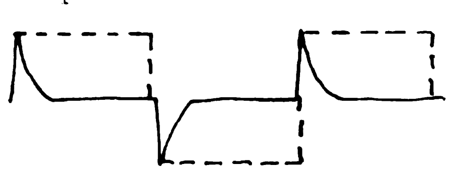
The frequency response of a circuit can easily and quite accurately be determined by Square Wave Testing. A Fourier analysis of a square wave gives the following result

$$e = \frac{4}{\pi}\left(\cos t - \frac{1}{3}\cos 3t + \frac{1}{5}\cos 5t - \frac{1}{7}\cos 7t + \cdots\right)$$

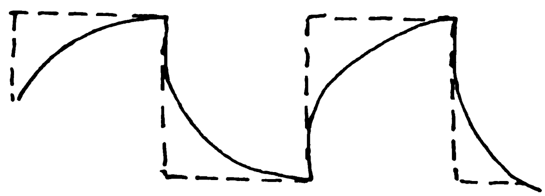
Since the square wave contains almost every conceivable frequency, it can be applied to a network and the distortion of the wave observed on an oscilloscope. Proper interpretation of this output wave will then determine the frequency response of the network.

Time does not permit an accurate analytical analysis of square wave testing in this paper, however a very good idea of the frequency response of a network can be made observing the output wave and comparing with the wave form known to exist in the extreme cases. Also, several sources list pictures[11] of waves with which an unknown can be compared to obtain an idea of the frequency response.

If a square wave is applied to a network with poor low frequency response, the output will be similar to the following where the dotted line is the square wave input.



If a poor high frequency response is present, the output wave will be similar to the following.



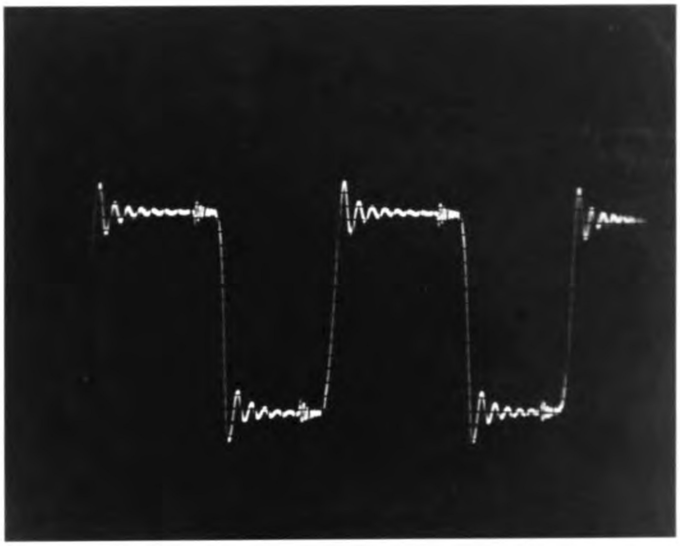
Many times it is desirable to observe both the input and output waves on the oscilloscope at the same time as shown in the above drawings. This is accomplished by the use of an electronic switch which rapidly applies first one voltage then the other so that they both appear on the y axis.

The accompanying photographs show the square wave response for 8 sections of artificial line for frequencies of 500 and 2000 cycles per second.

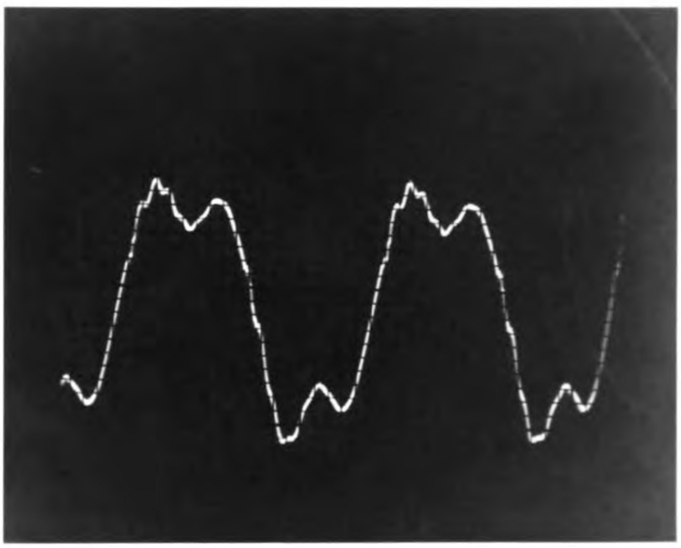
The 500 cycle per second photograph shows the characteristic of excellent low frequency response. High frequency deficiencies are not apparent. The small oscillation at the peak of the wave is due to a peak in the response curve or a rapid cut off frequency. Since our H section is also one of a low pass filter, we can expect a cutoff frequency to occur. The frequency can be measured from the photograph by a proportion.

$$\frac{500}{21} = \frac{1}{f}$$

$f = 10,500$ cycles per second



500 Cycles per Second



2000 Cycles per Second

The frequency of a cut-off calculated from filter theory is as follows and shows very good agreement with that actually found.

$$f_c = \frac{1}{\pi}\sqrt{\frac{1}{LC}}$$

$$= \frac{1}{\pi}\sqrt{\frac{1}{21.2 \times 10^{-3} \times .048 \times 10^{-6}}}$$

$$= 10{,}300 \text{ cycles/sec}$$

The second smaller oscillation at first appears to be of doubtful origin. I believe this oscillation to be caused by a reflection of the initial surge back toward Z_g and a consequent reflection back into the line. Z_g was not matched to the line while square wave testing and this error in carrying out the experiment I feel is certain to be the cause of this unexpected oscillation. The dismantling of the artificial line to install slightly different inductances prevented taking further data to fully account for this phenomenom.

The 2000 cycle per second photograph shows a definite high frequency deficiency in the output wave. This is determined from the slanted vertical slopes. The oscillation is still evident by the rough peak but is not quite so easily calculated. A more involved analytical treatment[12] would give the frequency however.

CHAPTER V

Conclusion

This paper does not intend to be a complete works on transmission lines. It describes the design, construction, and testing of an Artificial Transmission Line to be used in the Laboratories of the Electrical Engineering Department of Michigan State College. The theory presented has been used to justify the calculation of the elements used and to explain the results of the tests.

It was intended to construct 40 sections of artificial line which would be the equivalent of 231 miles of a pair of 104 mil wires spaced 12". However, considerable difficulty was experienced in obtaining delivery of the necessary inductors. Eight sections were constructed with the available coils which made 46 miles of equivalent open wire line. Tests were run on the completed 8 sections.

Since we were unable to obtain a complete order of 160 coils similar to those used in the first 8 sections, it is necessary to replace the coils used in these sections with a type which could be obtained in sufficient quantity to complete the line. The coils used had 9 ohms resistance and those available in sufficient quantity have 14 ohms resistance per coil.

This new coil will offer a closer approximation to the resistance of an equivalent amount of open wire.

All tests taken on the line agree with the expected results very closely. The entire characteristics of the equivalent open wire line are not available at the present time so that an absolute check cannot be made. The checks available are quite satisfactory though.

The mechanical construction of the line lends itself very well to measuring the electrical effects. Faults of different kinds can easily be placed on the line for future laboratory students to find.

Several additional tests could be applied to the artificial line. Time did not permit their being used in this paper but will be mentioned for possible future use. A few are Determination of the Phase-shift [13] Along the Line, Location of Faults by the Impedance [14] Method, further investigation of the Location of Faults by the Pulse Technique described in this paper. The line seems to be very well adapted to the study of transient effects within the limitation of the voltage breakdown point of the condensers used.

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