THESIS

A Report on Artificial Transmission Lines with an original Design.

by

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Pasadena, California

1917

The purpose of this paper is to describe the designs of a few of the artificial power transmission lines now in use in some of the engineering colleges and universities in this country as laboratory apparatus for undergraduate instructional experiments, as well as for research, and to design a line for the Electrical Engineering Laboratory at Throop College.

The lines herein reported on are of both types: the smooth line type, and the "Lumpy" type. In the first type the chief advantage is that it can be operated without a change of electrical dimensions at all frequencies within a reasonable range, making it possible to obtain oscillographic records of surges and transcient conditions in the same manner as they might occur on actual lines. The "Lumpy" type has to have its electrical dimensions corrected for lumpiness at frequencies beyond a certain limit. On the other hand the Lumpy Artificial Line is a great deal easier to build and maintain in a good operating condition, than is the smooth line, which is hampered in both respects by the large active condenser surface required. The lines considered will be reported on in the following order: The Artificial Transmission Line at Union College; The Artificial Power-Transmission Line at Harvard University; The Artificial Transmission line at the University of Washington; Characteristics of the Artificial Transmission Line at Massachusetts Institute

I. ARTIFICIAL TRANSMISSION LINE AT UNION COLLEGE.'

The method selected for securing a smooth artificial line was as follows: Wire of a suitable diameter was wound on glass tubes or cylinders which were lined with tinfoil. In this way any relation desired between resistance, inductance and capacity was obtained by selecting the proper length and size of wire to go with the proper size of glass cylinder. Each section of line as built represents a half-mile line of No 1/0 B.& S. guage copper wire spaced at five feet, and has the following constants: resistance, 0.25 ohms; inductance, 0.001 henries; capacity, 0.007 microfarads.

In designing the section the following formula was used to find the inductance:

$$L = 4 \ {}^2r^2n^2 \times 2.54/1 \times 10^9$$

in which

L = inductance in henries.

r = radius of winding in inches.

n = number of turns.

1 = length of coil in inches.

The capacity was found in a similar manner:

$$C = 4.54 \times 1 \ r \ k/2 \ d \times 9 \times 10^5$$

in which

' From Trans. A.I.E.E. Vol. XXX. p. 245.

C = capacity in farads.

l = length of glass cylinder.

r = radius of glass cylinder.

d = thickness of glass.

k = specific inductive capacity of glass.

= 4.5 (shown by test to be high.)

The most practicable design required a cylinder six inches in diameter, one-eighth inch thick, and four and one-half feet long, would with 240 turns of No. 8 B.& S. guage copper wire -- three inches at each end being left free of winding. Substituting these values in the above formulae gave L = 0.00104 henries, and C = 0.00748 micro-farads. (0.00748 x 10^{-6}F.). The resistance of the 240 turns of wire is 0.24 ohms. With these constants each unit represents one-half mile of No. 00 B.& S. guage wire (copper) spaced at five to six feet.

Because the weight of each unit was high (40 pounds) a rack of heavy construction was required, and as the floor space was limited these racks were constructed as high as possible. Each rack was designed to hold 100 tubes or sections, ten in a row each way.

Considerable difficulty was encountered in winding the wire on the tubes, as they were easily broken. Finally the wire was wound on wooden forms, six and one-fourth (6 1/4") inches in diameter; 230 turns were used (equivalent to 240 turns on the glass cylinder). After being loosened and removed from the forms the solenoids, or coils of wire, were slipped over the tube. Copper strips for connections were used in fastening the coil ends to the tube: first one end was made fast by means of several turns of one inch tape; the wire was then distributed and tightened and the other end made secure by taping.

Even more troublesome was the task of lining the tubes with the tinfoil. The tinfoil was pasted to sheets of raw-hide fiber 40 mils thick and 54 inches long by 17.5 inches wide. In order to prevent eddy currents, slits were cut six inches apart, alternately, half way across the sheet. Small copper leads were soldered to one end of the tinfoil (one lead per section). Later these leads were soldered to a bus of No. 8 B.& S. guage bare wire which was attached to the frame of the rack by means of porcelain insulators. After being placed inside of the tube, the tinfoil was held out firmly against the tube by using three phosphor-bronze (expansion) rings. As these rings held the tinfoil against the tube, thereby decreasing the air gap between the glass and tinfoil, the electrostatic capacity of each unit was greatly increased.

The most important objection to this form of line is its high first cost and maintainence or upkeep charge.

II. ARTIFICIAL POWER-TRANSMISSION LINE AT HARVARD UNIVERSITY. '

The artificial line herein described is of the "Lumpy" type, in sections designed to represent 49.7 miles of 3/0 A.W.G. aluminum stranded conductors, 0.47 inches in diameter (over strands), suspended parallel, on towers or poles, and spaced at 90.5 inches centers. The corresponding linear constants per wire mile are:

Resistance at 25° C. -------- 0.537 ohms.
Linear Inductance (L) ------- 1.995 millihenries.
Capacity (C) --------------- 15.00 millimicrofarads.

The type of line section as originally constructed was a T-line, but it was later changed to a   -line.

It was desired that the inductance coils of the unit should have little or no mutual inductive action. Closed circular solenoids, if properly wound, would have no external magnetic field and consequently would be devoid of mutual inductive action. For mechanical reasons a square form was adopted, the unit being made up of four coils wound on wooden forms which were securely fastened so as to make a closed magnetic circuit. By assembling the coils in the form of an anchor ring in building up the unit,

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' From the Electrical World, Feb. 17, 1912.

their internal magnetic flux is relatively feeble but in order to minimize the mutual indictive action of adjacent units the coils of each line were mounted on a shelf in vertical planes alternately perpendicular to each other, the even-numbered coil units being parallel planes, while the odd-numbered ones were in a plane at right angles to the former. The internal diameter of each component coil was 2.16 inches, the external diameter was about 2.87 inches, while the length was 7.88 inches. Each coil was made up of 1190 turns of #19 d.c.c. wire the covered diameter of which was 45 mils. After each coil was wound it was immersed in molten paraffin wax. The weight of each main coil, after being assembled was 18.5 lbs., while the weight of copper used in the entire line was approximately 370 lbs

The average resistance of main coil or unit was 24.6 ohms at 25° C., making the resistance of each line of ten units 246 ohms, and giving a nominal linear resistance of 0.495 ohms per wire mile at 25° C.

The average inductance of each unit was approximately 90 millihenries, making the total inductance of each line of ten units 0.90 henries. The nominal linear constant represented was 1.82 millihenries per wire mile.

The condensers were made up of tinfoil and paraffin paper set in a tinned iron box 7.9 inches by 2.2 inches by 5.6 inches; the space between the condenser and box was filled with paraffin wax. The average capacity was 0.75

microfarads or 15.1 millimicrofarads per wire mile. The definite power loss of these condensers at a given voltage corresponds to a small nominal linear leakage in the actual line.

At ordinary frequencies the correction factor of this line is 0.07% increasing, however, with increased frequencies so that at 200 cycles per second it has to considered in making the calculations based on any readings taken at that or higher frequencies.

III. THE ARTIFICIAL TRANSMISSION LINE AT THE UNIVERSITY OF WASHINGTON.'

This line consists of twenty units connected in series. Each unit is complete in itself and represents approximately ten miles of power-transmission lkne. It can be adjusted to practically any spacing up to 120 inches, to any size wire up to No. 4/0 hard drawn copper, and may be converted into a standard telephone line by inserting a 50-ohm non-inductive resistance between each unit.

The line is of the "lumpy" type, similar to the artificial line at Harvard University, the condensers being connected at the middle point of inductance of each unit. Protection is provided for the condensers against excessive voltage, under resonant conditions, by means of a suitable spark gap.

In order to fulfil the requirements of a unit adjustable to represent any power-transmission line up to 200 miles in length at different spacings and of different sizes of hard-drawn copper wire up to No. 4/0; the linear constants must be adjustable within the following limits:

Resistance, minimum value	=	2.59 ohms.
Inductance, " "	=	0.021 henries.
Capacity,	=	0.1 to 1.0 m.f.

The allowable resistance of each coil in the unit was found by dividing the minimum resistance by four (2.59/4 = 0.65 ohms.). By selecting No. 14 A.W.G. copper wire the length per coil was limited to 257 feet. Allowance was made for the resistance of connecting wires by using only 250 feet of wire for each coil. The high resistance required to represent lines of the smaller conductors is obtained by moving the short circuit clamp on the loop of "Advance" resistance wire.

The inductance is obtained by using four short air-core solenoids connected in series and arranged in a square. By using Brook's formula the dimensions of each coil were obtained, all the coils being similar. As constructed the dimensions are:

' From Electrical World, June 12, 1915.

Mean radius ------------------ 2.20 inches.

Length of coil --------------- 2.15 inches.

Thickness of winding --------- 0.60 inches.

Length of wire ------------- 250. feet.

Number of turns ------------ 216

(Eight layers of 27 turns each.)

It was found that with the coils arranged in a square the mutual inductance was approximately 8.0% of the total-self-induction of each unit. Variations in the inductance is obtained by providing one coil with taps at each quarter of the total number of turns, and by mounting one coil so that it can be rotated thru 180^{0}.

The average maximum inductance for the whole line is 0.0213 henries for each unit. Some of the units when measured differed slightly, varying from 0.022 to 0.0197 henries.

The capacity is obtained from type 21-AA, standard telephone condensers guaranteed to stand 1000 volts. Each unit is provided with ten 1 m.f. condensers connected in series, with taps brought out at the 5th, 6th, 7th, 8th, 9th and 10th condenser. Each complete unit was calibrated and the results were tabulated for use when connections are made for any of the many tests desired.

Of all the lines considered this type is the easiest and cheapest to construct; there is also practically no maintenance charges or upkeep to take care.

IV. ARTIFICIAL TRANSMISSION LINE AT THE MASSACHUSETTS INSTITUTE OF TECHNOLOGY. '

The artificial transmission line at the Massachusetts Institute is electrically equivalent to 800 miles of single-phase 500,000 circular mil copper conductor spaced at ten foot centers, or it may be used as a 700 mile three-phase line with conductors spaced in an equilateral triangle. By proper changes in the connections shorter lines may be represented. The line is made up of thirty sections housed in a cabinet 12 feet long, 5 feet 6inches high, and 2 feet deep, each unit occupying a compartment 20 inches long by 12 inches high. The line inductance is provided by eight coils (per section) centered on a circular axis, each coil being of No. 12 wire wound to a diameter of 7 inches and a width of 1 inch. By this method mutual inductance effects are secured. The capacity is secured by a condenser mounted on the side of each compartment. A great many combinations of resistance, inductance and capacity may be secured and studied if the proper connections are made.

' From the Electrical World, May 2, 1914.

DESIGN OF AN ARTIFICIAL POWER-TRANSMISSION LINE FOR THROOP COLLEGE.

In order that the Senior Electricals might get a more comprehensive insight into the physical phenomena, and understand what actually takes place in the transmission system, it was considered that an Artificial Line was necessary.

After having studied all of the designs used by other Engineering Institutions it was decided that the "Lumpy" type would fulfill the conditions of low first cost, low maintenance, ease construction, and adjustability. The ten-mile unit was selected as a sufficiently close approximation to the uniformly distributed line constants of actual power-transmission lines, for ordinary frequencies.

As it will be desireable to study many standard transmission lines, the variations of line constants will vary over a wide range, consequently standard lines were chosen as the starting point. The voltages considered varied from 44,000 to 200,000 volts.

The corresponding standard spacings are given in Table I; the corresponding standard length of line is found by dividing the voltage by 1000 (i.e., a drop of 1000 volts is allowed per mile).

Line resistance. In order to meet the requirement of being adjustable to any size of conductor used in actual transmission line practice the resistance of standard cable or stranded conductors was investigated. Only the largest and smallest conductor of each number of strands per conductor was taken, except in the case of the conductor with seven strands where only the largest cable was considered. Table II gives the resistance for above mentioned copper conductors for both 1000 ft. and 10 miles of line. The resistance varying from 8.554 ohms at 25° C. for #2 conductor to 0.285 ohms at 25° C. for a conductor of 2,000,000 circular mils.

Table III was then made up from values given in Table VIII of circluar No. 30 of the Bureau of Standards. Then by referring to the Inductance Chart, Fig. 11b, given in Bulletin No. 53 of the University of Illinois, it was found that the most economical wire to use was No. 20. It was calculated that 2.54 lbs. were necessary, but 2.75 lbs. were ordered for the first unit.

Resistance: In order to obtain the resistance necessary to represent any line larger than #2 A.W.G. copper conductor it will be necessary to use a resistance in parallel with the inductance. Because of the fact that this is a "T" line it is considered best to make two seperate sections of each unit and tie the resistance in at the point from which the connection to the condensers and neutral wire is taken. That being the case, the maximum resistance in the coils on either side of the neutral point will be 8.554/2 or 4.277 ohms, and as the unit was designed to represent a ten mile section of #2 A.W.G. copper conductor it will not be necessary to use the resistance loops in parallel for that line, but to represent the larger conductors the equivalent resistance required in each half-unit will vary from 6.811/2 to 0.285/2 ohms or 3.405 to 0.1425 ohms.

Required resistance in parallel with each half-unit:

$$1/r = 1/3.405 - 1/4.277 \text{ (maximum).}$$

$$= 16.67 \text{ ohms.}$$

(With a maximum of 15 ohms the equivalent resistance will be 6.667 ohms.)

$$1/r = 1/0.1425 - 1/4.277 \text{ (minimum)}$$

$$= 0.1475 \text{ ohms.}$$

From the above calculations it is seen that two units of the slide-wire type, of at least 17 ohms, will be required.

Inductance: In determining the maximum and minimum inductance required for a ten mile section only the smallest and largest conductors were considered, the inductance being calculated for each standard spacing. The formula used was,

$$L = s(k_1 \times \log D/R - k_2) \times 10^{-5}$$

in which

L = inductance in henries.

s = length of line = 10 miles.

k_1 = 741.13. k_2 = 83.3

D = 1.26d or effective spacing in inches.

R = radius of conductor in inches.

The results are shown in tables IV and V.

Four short air-core solenoids arranged in a square are used to give the inductance. The resistance required limits the maximum length of wire available for each unit to 822.5 feet of No. 20 d.c.c. copper wire. The length of wire for each coil is 822.5/4 or 204 ft. Then to find the dimensions of each coil in order to give its proportion of the total inductance of each unit, Brook's formula was used. As the inductance of each unit is to be 0.02608 henries or less (no allowance being made for mutual inductance), the given inductance per coil is 0.02608/4 or 0.00652 henries. By referring to figure 15b, p. 55 of Bulletin No. 50 of the University of Illinois, it was found that the radius of the core would be about 0.70 inches. With this a a basis the dimensions of the coil were found:

a = mean radius = 1.05 inches.

b = coil width = 0.84 inches.

c = coil thickness = 0.72 inches.

R = r - c = 2r = 1.40 inches.

Substituting these values in the formula,

$$L = \frac{0.366 \times (205/1000)^2}{b - c - r} \times F' \times F''$$

Values of F' and F" are as follows:

$$F' = \frac{10b - 12c - 2R}{10b - 10c - 1.4R}$$

and $$F'' = 0.5 \log \left(100 - \frac{14R}{2b - 3c}\right) ;$$

Substituting the above values in the equation, L was found to be 0.00573 henries, which is too low a value. After several attempts it was decided to let c = 0.76 in. or 19 layers (as the diameter of the wire was given as 0.04 inches) and b = 0.80 inches or twenty turns, making the total number of turns = 19 x 20 or 380. Then by knowing the number of turns and the length of wire the mean radius 'a' can be found by substituting in the formula, feet = 2 aN/12, from which 'a' was found to equal 1.025 inches. The radius of the coil was then found by subtracting 0.76/2 from 1.025, which is 0.645 inches.

By substituting the above dimensions in Brook's formula the inductance 'L' was found to be 0.00589 henries. Formula No. 20, on page 28 of Bulletin No. 53 of the University of Illinois was then used giving 0.00605 for the inductance. When the mutual indictance of the unit is considered the inductance is sufficiently close to 0.00652 henries.

Four coils of 19 layers with 20 turns per layer were wound on a core, the diameter of which was 0.65 inches. In winding the last coil, taps were brought out at the sixth, eleventh and fifteenth layer from the center. All of the coils were impregnated with a high grade insulating varnish and wrapped with 3/4 inch linen tape.

No tests have been made on any of the coils.

Capacity: Tables VI and VII were calculated from the same data as was used in calculating Tables IV and V, except that the result shows the capacity of the largest and smallest cable conductors at the standard spacings considered. The following formula was used:

$$C = \frac{38.83}{\log (D/R - R/D)} \times 10^{-2}$$

in which

D = 1.26d

R = radius of the conductor.

C = capacity in microfarads.

As shown by the above-mentioned tables the maximum capacity is 0.20 m.f. and the minimum capacity is 0.11 m.f. Of the various means considered for obtaining this capacity and at the same time getting different steps the limits of 0.20 and 0.11 m.f., the telephone condenser was chosen as the most economical instrument. Six condensers of type No. 21 U tested at 1200 volts A.C., and of 0.05 m.f. capacity were ordered for the first unit.

The diagram of connections for the entire unit is shown in Figure I.

TABLE I.

Volts	44000	55000	66000	88000	110000	138000	150000	175000	200000
Spacing	60	72	84	96	120	144	210	240	300
Length	44	55	66	88	110	138	150	175	200

Table II.

A.W.G. No	2	1	4/0	--	--	--
STRANDS	7	19	19	37	37	61
AREA	66.40	83.70	212.0	250.0	500.0	550.0
R/1000 ft.	0.162	0.129	0.509	.0431	.0216	.0196
R/10 miles.	8.554	6.811	2.688	2.276	1.141	1.035

STRANDS	61	91	91	127	127
AREA	1000	1100	1500	1600	2000
R/1000 ft.	.0108	.0098	.0072	.0067	.0054
R/10 miles.	0.570	0.518	0.380	0.356	0.285

In the above table the area is given in thousands of circular mils.

R equals ohms.

TABLE III.

Resistance = 8.554.

Length = 8.554/R/1000 = 8.554 x 1000/R

Weight = Length x W/1000

B.& S. No.	R	W/1000	Length	Weight
14	2.58	12.40	3315.3	41.10
15	3.25	9.86	2631.9	23.30
16	4.09	7.82	2091.3	16.40
18	6.51	4.92	1313.9	6.50
20	10.40	3.09	822.5	2.54
21	13.10	2.45	653.0	1.60

TABLE IV

Inductance for #2 - 7 strand conductor.

R = .148 inches; k_1 = 741.13; k_2 = 83.3

s	d	$\frac{1.26d}{0.148}$	log D/R	x k_1-k_2	x 10^{-5} = L
44	60	510.81	2.70826	2173.77	.02174
55	72	612.97	2.78744	2232.45	.02232
66	84	715.14	2.85439	2282.07	.02282
88	96	817.30	2.91238	2325.05	.02325
110	120	1021.62	3.00933	2396.9	.02397
138	144	1225.9	3.08845	2455.6	.02456
150	210	1787.83	3.25233	2577.0	.025777
175	240	2043.24	3.31032	2619.97	.02620
200	300	2554.1	3.40723	2608.49	.026085

TABLE V

Inductance of 2,000,000 C.M. 127 strand cable.

$R = 1.632/2 = .8155 \quad k_1 = 741.13 \quad k_2 = 83.3$

s	d	$\frac{1.26D}{.8155}$	log D/R	x k_1-k_2	x 10^{-5}= L
44	60	92.7056	1.967097	1541.2	.0154
55	72	108.154	2.034043	1590.8	.01591
66	84	129.785	2.113225	1649.5	.01649
88	96	148.3257	2.17117	1692.3	.01692
110	120	185.4072	2.26811	1764.8	.01765
138	144	222.4886	2.34729	1824.3	.01824
150	210	324.463	2.511162	1944.4	.01944
175	240	370.814	2.569156	1987.4	.01987
200	300	463.518	2.666068	2059.2	.02059

TABLE VI.

Capacity for #2 Conductor R = 0.146 inc.

Smallest.

d	D	D/R - R/D	log D/R - R/D	Capacity	x 10^{-2}
60	75.60	517.8063	2.714167	0.14306	0.143
72	90.72	621.3682	2.7933489	0.139008	0.139
84	105.84	724.930	2.860296	0.135755	0.136
96	120.96	828. 492	2.9182883	0.133057	0.133
120	151.20	1035.615	3.015200	0.128781	0.129
144	181.44	1242.738	3.094380	0.125486	0.125
210	264.60	1812.33	3.2582373	0.119175	0.119
240	302.40	2070.23	3.3162283	0.117091	0.117
300	378.0	2589.04	3.4131388	0.113766	0.114

TABLE VII.

Capacity for 127 strand conductor. R = 0.8155

Largest.

d	D	D/R - R/D	log D/R-R/D	Capacity.
60	75.60	92.69308	1.967047	0.197403
72	90.72	111.2358	2.046245	0.189762
84	105.84	129.7777	2.1132011	0.183749
96	120.96	148.3194	2.1711968	0.178841
120	151.20	185.402	2.2681144	0.171199
144	181.44	222.484	2.3472988	0.165424
210	264.6	324.461	2.5111625	0.154629
240	302.4	370.813	2.5691549	0.151139
300	378.00	463.517	2.6660657	0.145645

Figure 1.

Scale - 4" = 1'