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CONSIDERATIONS OF AN ELECTRIC LINE - LEWIS

FUNCTIONAL AND ECONOMIC CONSIDERATIONS OF AN ELECTRIC LINE FEEDING LARGE CONCENTRATED LOADS

By

Seth O. Lewis

A Thesis

Submitted in Partial Fulfillment of the

Requirements for the Degree of

Master of Science in Electrical Engineering

The University of New Mexico

1960

This thesis, directed and approved by the candidate's committee, has been accepted by the Graduate Committee of the University of New Mexico in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

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May 9, 1960
Date

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PREFACE

University graduate work in the electrical power field is seldom attempted today because extensive research is needed to fulfill the nation's requirements for elaborate radar and communication networks. It is even difficult for a University to offer enough credit hours in electrical power for one to achieve a Master's Degree because the enrollment in such courses is too small to meet minimum requirements. The growth of the power companies in the United States, however, has equaled or surpassed that of most concerns in this country. This growth has accompanying problems which require a higher level of education than that provided by a Bachelor of Science Degree. The companies in some cases have paid a higher cost than was necessary for their systems, without a higher or better performance, because their engineers lacked the knowledge afforded by University graduate work. A better educational background may equip the engineer with the knowledge and methods of deriving much greater long-range economy and better system performance for his electrical system.

One of the problems encountered by the author while working as assistant planning engineer for an electrical utility company was the selection, without extensive computations and graphs, of an economic system of supplying load and also the most economical size of a transmission line conductor. A knowledge of methods to determine

PREFACE

University graduate work in the electrical power field [illegible] seldom attempted today because [illegible] fill the nation's requirements for [illegible] networks. It is even difficult [illegible] credit hours in electrical power [illegible] because the enrollment in [illegible] requirements. The growth of the [illegible] however, has equaled or [illegible] country. This growth has [illegible] ar level of education [illegible] Degree. The [illegible] was necessary for their [illegible] mance, because their [illegible] versity graduate work. A better [illegible] the engineer with the [illegible] long-range economy and better system performance [illegible] system.

One of the problems [illegible] as assistant planning engineer [illegible] the selection, without extensive computations [illegible] nomic system of supplying load [illegible] a transmission line conductor. A [illegible] and/or improve line performance was also required. This thesis has been prepared to give an engineer that information, which he would usually get only on a graduate level in a University, necessary to determine the economical method of supplying load and of determining transmission line performance. An original method has been developed which will tell the engineer very quickly, with little calculating and no graphs, the conductor size that will give him the most over-all economy for a transmission line.

The author is indebted to the engineers and administrators of the Public Service Company of New Mexico for their suggestions and for the use of the company's name in the illustrative problem in Chapter IV. The assistance and critical analysis of Rex A. Tynes of the Public Service Company has been particularly helpful. The aid of Daniel P. Sheldon in developing and checking the various formulas was appreciated. Gratitude is expressed also to Ahmed Erteza and E. L. Jordan, Staff Members of the Electrical Engineering Department at the University of New Mexico, for their patience, cooperation, and adept guidance during the development of this thesis.

and/or improve line performance was also required. This thesis has been prepared to give an engineer that information, which he would usually get only on a graduate level in a University, necessary to determine the economical method of supplying load and of determining transmission line performance. An original method has been developed which will tell the engineer very quickly, with little calculating and no graphs, the conductor size that will give him the most over-all economy for a transmission line.

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INTRODUCTION

The electrical power companies of the United States have experienced an average annual load growth of six and eight-tenths per cent during the last twenty-five years. In the rapidly growing southwestern United States the growth has varied from nine to twelve per cent and the growth of electrical load in the Albuquerque, New Mexico, area has increased annually at the average rate of eleven and two-tenths per cent for the past several years. This growth has required the power companies to continuously increase their generating capacities. Due to the remoteness of fuel and water sources, the generating plants have often been located at distances far from the loads to be served and long transmission lines have been required to transfer the power from the remote power plants to the load locations. The characteristics of the transmission lines have been determined to provide satisfactory service conditions and to achieve the most economical transmission of power.

This paper discusses the considerations required for selecting particular characteristics of the line and presents an original method of obtaining the most economical solution. A typical problem at the Public Service Company of New Mexico is solved to illustrate the usefulness of this method.

CHAPTER I

ABSTRACT

The electrical power companies of the United States have experienced an average annual load growth of six and eight-tenths per cent during the last twenty-five years. In the rapidly growing southwestern United States the growth has varied from nine to twelve per cent and the growth of electrical load in the Albuquerque, New Mexico, area has increased annually at an average rate of eleven and two-tenths per cent for the past several years. This growth has required the power companies to continuously increase their generating capacities. Due to the remoteness of the large water sources, the generating plants have often been located at distances far from the loads to be served and long transmission lines have been required to transfer the power from the remote generation to the load locations. The characteristics of the transmission lines have been determined to provide satisfactory service conditions and to allow the most economical transmission of power.

This paper discusses the considerations involved in selecting particular characteristics of the lines and presents an organized method of obtaining the most economical solution. A typical problem of the Public Service Company of New Mexico is used to illustrate the usefulness of this method.

CHAPTER II

GENERAL FUNCTIONAL AND ECONOMIC CONSIDERATIONS FOR NEW TRANSMISSION LINES

A. Voltage

The first alternating current line over which power was transmitted was constructed in Italy in 1886. The line operated at 2,000 volts, it was seventeen miles long, and it was built to transmit 150 horsepower.[1]

Transmission voltages have progressively increased and today transmission lines exist which operate at 380,000 volts.[2] Experimental lines have been built to study operating voltages up to 500,000 volts[3] and the General Electric Company is constructing an experimental line to test operating voltages up to 750,000 volts.[4]

In selecting the transmission voltage, consideration must be

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[1] C. A. Powel et al., Electrical Transmission and Distribution Reference Book (3d ed.; East Pittsburgh, Pennsylvania: Westinghouse Electric and Manufacturing Company, 1944), p. 4.

[2] George V. Boll, "Extra High Voltage Transmission on 3 Continents," Elec. World, v. CXLIX, (May 26, 1958), pp. 356-359.

[3] L. M. Robertson, "High Altitude 500 KV Corona Tests in Colorado," Elec. Engr., v. LXXVI, #4, (April, 1957), pp. 286-293.

[4] P. A. Abetti, "Project EHV," Elec. Engr., v. LXXVII, LXXVIII, (August, 1958), pp. 669-673.

given to the existing and probable future voltages in the vicinity of the line to be built. These considerations may be as important a factor as line losses or voltage regulation. The advantage of being able to interconnect adjoining power districts at a common voltage may outweigh a choice of voltage based on lowest immediate cost. If the contemplated transmission line is remote from any existing system, a complete study of all factors may be required to select the voltage. The initial and operating cost which corresponds to various voltages and various conductor sizes and types may be tabulated to select the most economical voltage.

A committee formed jointly by the National Electric Light Association and the National Electrical Manufacturers' Association published a report in 1930 which recommended "preferred voltages."[5] The electrical manufacturers have standardized their equipment on these preferred voltages since 1930, and equipment for other voltages is usually more costly.

B. Conductor Size and Type

The type and size of the conductor for a planned transmission line will depend to a large extent on the voltage that is to be used. If the voltage is to be selected on the basis of a connection to an

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[5] Powel, loc. cit.

given to the existing and probable future voltages in the vicinity of the line to be built. These considerations may be as important a factor as line losses or voltage regulation. The advantage of being able to interconnect adjacent power systems at a common voltage may outweigh a choice of voltage based on [illegible] cost. If the contemplated transmission line is to be a part of an existing system, a complete study of all factors may be required to select the voltage. The initial and operating cost which corresponds to various voltages and various [illegible] and types of [illegible] calculated to select the most practical voltage.

A committee [illegible] of the [illegible] Electric [illegible]mentation and the National Electrical Manufacturers' Association published a report in 1950 which recommended preferred voltages.[5] The electrical manufacturers [illegible] equipment for these preferred voltages since 1950, and equipment for other voltages is usually more costly.

B. Conductor Size and Type

The type and size of the conductor for a proposed transmission line will depend to a large extent on the voltage that is to be used. If the voltage is to be selected on the basis of a conductor to

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[5] [illegible], loc. cit.

existing line, it is important that the operating voltage be established before other planning is done or calculations are commenced. The minimum conductor resistance may then be calculated from the fixed charges on the line, and the allowable line loss. This calculation, and an example of it, is explained further in Chapter III of this Thesis.

The contour of the land will usually determine the length of spans in a transmission line. The length of spans may then be used to select the type of conductor, copper or ACSR, but the type will generally be determined on a "cost per unit resistance" basis.[6] The calculation referred to in the previous paragraph may be required for each type of conductor considered.

If the transmission line is not to be connected to existing lines, the most economical conductor size for each operating voltage which is considered can be decided by using the formulas developed in Chapter III. If more than one type of conductor is investigated, the least expensive conductor size for each type can be found by the same formulas.

C. Load Characteristics

Before any transmission line can be built or even planned, the characteristics of the load to be served must be determined in

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[6] "Cost per unit resistance" means the cost of losses due to resistance in a mile of conductor.

existing line, it is important that the receiving voltage be established before other planning is done for the [illegible] line. The minimum conductor [illegible] then be determined. The fixed charges on the line, and the [illegible] are [illegible] calculation, and an example of [illegible] application is given in Chapter XIII of this Thesis.

The cost of the line will largely depend on the length of spans in a transmission line. The [illegible] must be used to select the type of conductor, whether of ACSR, [illegible] will generally be determined by [illegible] availability [illegible]. The calculation required to fit the optimum [illegible] size of [illegible] for each type of conductor considered.

If the transmission line is not to be connected to existing lines, the most economical conductor size for each voltage, voltage which is considered can be obtained by using the formulas developed in Chapter III. It may be that the type of [illegible], the least expensive conductor [illegible] can be [illegible] by the same formulas.

C. Load Characteristics

Before any transmission line can be built or even planned, the characteristics of the load to be served must be determined. It

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[5] Cost per unit [illegible] resistance in a mile of conductor.

order that load capacity for the line can be established. If load characteristics cannot be determined in advance of construction, then they must be estimated. The most economical line can be found normally for only one set of load characteristics. When these characteristics change, a new set of computations must be made.

1. Load Size and Growth

The load size is defined as the peak demand which will occur for a given line. The life of a planned transmission line and the maximum load to be served by the line during its lifetime are estimated in order that load capacity for the line can be established. The future load is calculated by projection of past peaks to a future date corresponding to the lifetime of the line. For example, if a hypothetical load had annual peaks from 1940 to 1958 as shown in the following table, either a curve could be drawn or a "compound interest" formula might be written to estimate future loads as given for the years 1960 to 1964.

TABLE 1

PAST AND PREDICTED PEAK LOAD, HYPOTHETICAL CASE

Year	Peak Load, kw	Year	Peak Load, kw
1940	1000	1954	2580
1942	1150	1956	2960
1944	1310	1958	3380
1946	1500	1960	3880
1948	1720	1962	4440
1950	1970	1964	5080
1952	2250		

The formula would appear as follows:

$$i = \left[\left(\frac{A}{P}\right)^{1/n} - 1\right] (100\%)$$

where

i = per cent of annual load increase
P = load at a given time
n = number of years from the time of P to the year in which A occurred.
A = load after a number of years, n.

The compound interest formula has become widely used by the electric power companies of the United States to estimate future loads. In some instances, however, the growth of a company may be found to vary considerably from this formula. In these instances it is necessary to consider special influences, both past and present, which have affected the load growth and to use skill and judgment from direct experience in establishing a reasonably accurate "trend" of the future growth. The experiences of most electric power companies in the United States, however, have empirically proved the validity of the compound interest formula for estimating future loads. When this method is used, the per cent rate of growth may be found by selecting any two known peaks and substituting in the formula. If the years 1944 and 1950 were selected from the above table, the substitution would be made as follows:

$P = 1310$; $A = 1970$; and $n = 6$ years

$$i = \left[\left(\frac{1970}{1310}\right)^{1/6} - 1\right] (100\%) = 7 \text{ per cent increase per year}$$

The formula [illegible] is follows:

$$i = \left[\left(\frac{A}{P}\right)^{1/n} - 1\right](100\%)$$

where

i = per cent of annual load increase
P = load at a given time
n = number of years from the time [illegible] the year
    in which A occurred.
A = load after n number of years, n.

The compound interest formula has been widely used by the electric power companies of the United States to [illegible]. In some instances, however, the growth of a company may be found to vary considerably from this formula. In these instances it is necessary to consider special influences, such as war, [illegible], which have affected the load growth in the past and [illegible] past experience in which the [illegible] future growth. The [illegible] of load [illegible] companies in the United States, however, [illegible] of the compound interest formula [illegible]. When this method is used [illegible] found by selecting any two known loads and [illegible] in the formula. If the years 1941 and 1947 were selected from the above table, the substitution would be made as follows:

P = 1310; A = [illegible]; n = [illegible]

$$i = \left[\left(\frac{[illegible]}{1310}\right)^{1/n} - 1\right](100\%) = [illegible] \text{ per cent per year}$$

When the above method of estimating loads is used, a history three times as long as the estimated future should be used, if possible. If a lesser period is used, an inaccurate estimate may result from unusual business conditions. For example, estimates of peak electrical loads for the City of Albuquerque for the five year period 1950-1955 would have proven too high if the estimates were made from the load experience of the period 1945-1950. Albuquerque experienced an unusual surge in electrical demand during the last half of the 1940's and this surge would have been reflected in the 1950's estimates. If, however, the 1950-1955 loads were estimated from a formula or curve developed for the period 1935 to 1950, the estimated loads would have closely approximated the actual loads.

2. Load Factor

The load factor is defined, for the purposes of this Thesis, as the fraction of full load that the line carries. The load factor can be found for any period of time such as a day, month, or year; but the annual load factor is of more interest in a transmission line economic analysis. The annual load factor for a transmission line is found by dividing the load, in kilowatt-hours, transmitted in one year by the product of the line capacity, in kilowatts, and the number of hours in a year. For a new line the kilowatt-hours transmitted can only be approximated, but some data is usually available for making reasonably accurate estimates. The past load experience of a

Then the above method of [illegible] is used, a [illegible] three times as long as the period to be estimated is usually advisable. If a lesser period is used, the [illegible] may [illegible] from unusual business conditions. For example, estimates of [illegible] electrical loads for the City of Albuquerque for the five year period 1950-1955 would have proven too high if the estimates were based on the load experience of the period 1945-1950. Albuquerque experienced an unusual surge in electrical demand during the last half of the 1940's and this surge would have been reflected in the estimates. If, however, the 1950-1955 loads were estimated from a formula or curve developed for the period 1935 to 1945, the estimated loads would have closely approximated the actual loads.

2. Load Factor

The load factor is defined, for the purpose of this thesis, as the fraction of full load hours for a [illegible] period. A load factor can be found for any period of time such as a day, month, or year, but the annual load factor is of most [illegible] and application in economic analysis. The annual load factor for a distribution line is found by dividing the total kilowatt-hours transmitted during the year by the product of the line capacity in kilowatts and the number of hours in a year. For a new line the kilowatt-hours transmitted can only be approximated, but [illegible] making reasonably accurate estimates. The past load experience of company will give an indication of the load that may be transmitted over the line. The planned operating procedure of the company must then be the primary consideration. Economics may indicate that the major block of power demand can be served from the new line and other facilities be used only for peak load demands. The cost per kilowatt-hour at the load bus will prove whether this plan is more economical or whether the new line should be used primarily for peak demands.

3. Reliability Requirements

The reliability requirement of the load to be served is a primary concern of the transmission line designer. Some electrical loads cannot be dropped except under emergency conditions. Such loads may require stand-by generators, or they may require service from more than one transmission line. Two or more transmission lines from a remote site to such a load may not increase capacity but they do increase reliability.

A transmission line may be made very resistant to outages caused by adverse weather conditions such as wind, ice, lightning, etc. Two overhead ground wires and sufficient lightning arrestors will prevent most outages caused by lightning. Increased conductor spacing, guy wires at all points of stress, short span lengths, ice removal equipment, and over-size construction materials will avert outages caused by ice and wind. To include all of these devices into a single transmission line would cause the cost of the line to company will give an indication of the load [illegible] over the line. The planned [illegible] then be the primary consideration. [illegible] may indicate that the major block of power should be moved from the new line and other facilities be used only for local load demands. [illegible] per kilowatt-hour at the load end will prove whether this plan is more economical or whether the new line should be used primarily for peak demands.

3. Reliability Requirements

The reliability requirements of the load to be served is a primary concern of the transmission line designer. Some customers' loads cannot be dropped without undue economic hardship. Such loads may require stand-by generation, or they may require service from more than one transmission line. The provision of [illegible] lines from a remote site to serve a load may not [illegible] but may [illegible] increase reliability.

A transmission line may be made very resistant to outages caused by adverse weather conditions such as wind, ice, lightning, etc. Two overhead ground wires and sufficient insulating clearances will prevent most outages caused by lightning. Increased conductor spacing, guy wires at all points of stress, [illegible] removal equipment, and [illegible] will prevent outages caused by ice and wind. Nevertheless, [illegible] a single transmission line [illegible] approximate the cost of two separate lines without the devices. Two lines would provide greater assurance of continuous service than the one expensive line. A line outage is usually caused by a local condition such as a weak point in a conductor or lightning striking a line. Even if two separate lines are physically close together the lightning would strike only one of them at a particular time. An outage caused by a lightning strike would normally be corrected and the line would be restored to service before the second line could be struck by lightning. In a similar manner, if ice caused a conductor to break, it is unlikely that the two lines would have a conductor weak point at the same geographical location. Adverse weather at a conductor weak point on one line would cause service on only that one line to be interrupted. The two separate lines would also give protection from load interruptions caused by adverse conditions such as floods, snow slides, and crashes of mechanized equipment, i.e., airplanes, automobiles, etc. Loop feeds are presently being utilized by many companies when more than one line is required to a particular point. Transmission lines in the loop feed configuration, although starting and ending at the same points, may be separated by several miles. This type of system would further increase reliability by eliminating the possibility of one event, such as extreme ice loading or an airplane crash, causing two lines to be put out of service.

approximate the cost of the generator [illegible]. Two lines would provide greater dependability [illegible] than one expensive line. A [illegible] of a local condition such as a [illegible] striking a line. Even if two separate lines [illegible] lightning would strike [illegible] one of them [illegible]. An outage caused by a lightning stroke would normally be [illegible] the line would be restored to service before the second line could be struck by lightning. In a similar manner, [illegible] to break, it is unlikely that the two lines would [illegible] same point at the same geographical location. [illegible] conductor weak point on the line would cause [illegible] one line to be interrupted. The two separate lines would [illegible] protection from line interruptions caused by adverse conditions such as floods, snow slides, and crashes of mechanized equipment, i.e., airplanes, automobiles, etc. [illegible] by many companies [illegible] point. Transmission lines in the loop feed [illegible] starting and ending at the same point, may be separated by several miles. This type of system would further increase reliability by eliminating the probability of one break, such as [illegible] or an airplane crash, causing two lines to be put out of service.

CHAPTER III

ECONOMIC MAXIMUM RESISTANCE

Present practice in the electric power industry is to select a desirable conductor size for the anticipated load and to make a cost analysis of different generation and transmission methods on the basis of that one conductor. A method, which as far as is known is original with the author, is presented in this chapter to determine that conductor size which will give equal cost at the load point for different generation locations. An original method to determine the most economical conductor size is also presented.

Kelvin's law for the most economical conductor states, "The most economical area of conductor is that for which the annual cost of energy wasted is equal to the interest on that portion of the capital outlay which may be considered as proportional to the weight of conductor used."[1] The formulas in this chapter may be considered an extension of this law with the inclusion of other cost factors such as maintenance, taxes, etc. The formulas presented here may also be considered as reducing this law to the solution for only one value, a value which will establish a conductor size of maximum economy. Another formula given here makes the "equal cost" conductor size, described in the above paragraph, easily attainable.

The method presented in this chapter will have the following

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[1] A. E. Knowlton (ed.), Standard Handbook for Electrical Engineers (New York: McGraw-Hill, 1949), p. 1173.

advantages: (1) The economic feasibility of remote generation can be quickly determined. (2) That conductor size which will give equal load center power cost for generation at a remote site or at the load center is readily ascertained. This conductor size will generally represent the minimum size conductor for a transmission line from the remote site. (3) That conductor size which will provide the most economy may be quickly computed.

The cost of power generation at a remote site must be less than the generation cost at the load center to make the remote generation plan feasible. The difference in cost is used to determine the minimum and the most economical size conductor which may be used for the transmission line. All cost factors of the line must be included to make the computations realistic, however. These factors are: (1) maintenance cost of the line; (2) cost of line power losses; and (3) fixed charges on the cost of the line. These charges include interest, taxes, profit, etc.

With these factors an equation may be established for the total cost at the load center of power generated at a remote location.

$$T = S + M + L + F$$

where

T = total cost per kilowatt-hour at the load center for power generated at a remote location.[2]

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[2] Definitions of all symbols in the formulas of this chapter are given in Appendix I.

advantages: (1) The economic capacity of a remote generating [illegible] can be quickly determined. (2) The generator size which will cause equal load center power cost for generation at a remote site and at the load center is readily ascertained. This generator size will generally represent the minimum size generator for a transmission line from the remote site. (3) This procedure [illegible] will provide the most economy and be quickly computed.

The cost of power generated at a remote site must be less than the generation cost at the load center to make the transmission plan feasible. The difference in cost is [illegible] the minimum and the most economical size of carrier which may be used for the transmission line. [illegible] the line must be sufficient to take the power from the remote site, [illegible] the costs: (1) [illegible]; (2) maintenance cost of the line; (3) [illegible]; and (3) Fixed charges on the cost of the line. Fixed charges include interest, taxes, [illegible], etc.

With these factors an equation may be established for the total cost at the load center of power generated at a remote location.

$$Z = S + T + L + [illegible]$$

where

Z = total cost per kilowatt-hour at the load center of power generated at a remote location.

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[1] Definitions of all symbols used in the formula and all equations are given in Appendix I.

S = generation cost per kilowatt-hour at the remote site
M = total transmission line maintenance cost per kilowatt-hour
L = cost of transmission line power losses per kilowatt-hour
F = cost of fixed charges on the transmission line per kilowatt-hour

The last two parts, L and F, of the equation contain variables. The power losses, L, will vary with the resistance of the conductor and the fixed charges, F, will vary with the size of the conductor. If these two parts could be made to contain the same variable, the equation could be solved for that particular variable which would make the load center power cost the same for generation at either location. Also, with only one variable in the equation, the cost could be differentiated with respect to that variable and the most economical conductor size could be found.

The cost in dollars of line losses per kilowatt-hour is expressed as

$$\text{Cost of losses} = \frac{3 \ I^2RHS \ (10^{-3})}{Y}$$

where

I^2 = average of the current squared over a year
R = total resistance of line per phase
H = number of hours per year
S = generation cost per kilowatt-hour at remote site
Y = total kilowatt-hours transmitted per year

The only variables in the equation are R, the resistance, and I, the current. The resistance will be found in formulas developed in a later part of this chapter. The current is the square root of the mean squares of the current, and thus is dependent on the form of

S = generation cost per kilowatt-hour at power plant
K = total transmission line investment per [illegible] [illegible]
L = cost of transmission line power losses per kilowatt-hour
F = cost of fixed charges of the distribution center per kilowatt-hour

The last two terms, L and F, are functions of load center location. The power factor, S, will vary with the distance of the generation as the fixed charges, F, will vary with the size of the substation. If these two parts could be made to approach the same variable, the equation could be solved for each particular situation which would make the load center power cost a minimum for each particular location. Also, with all the variables in equation, one could be differentiated with respect to that variable and the most economical conductor size could be found.

The cost of delivery of line losses per kilowatt-hour may be expressed as

$$\text{Cost of losses} = \frac{I^2 RHS(10^{-3})}{Y}$$

where

I^2 = average of the currents squared over a year
R = total resistance of line per phase
H = number of hours per year
S = generation cost per kilowatt-hour at power plant
Y = total kilowatt-hours transmitted per year

The only variables in the equation are R, the resistance, and I, the current. The resistance will be found in formulas developed in a later part of this chapter. The current is the square root of the mean square of the current, and thus is dependent on the [illegible] the load curve. The load curve is not accurately described by the load factor, but over a limited area and period of years the ratio of the kilowatt-hours to the kilowatt peak varies with the load factor.[3] Such a relation is generally determined empirically. By using the load factor relation the current can be considered a constant for the computation of line losses.

The annual fixed charges on the cost of a transmission line are ordinarily listed as a percentage of the total original cost of that line. If a transmission line cost D dollars per mile to build, and the line is Z miles long, the annual fixed charges in dollars, X, on the line are

$$X = (K)\ (D)\ (Z),$$

where K is the fraction of the original cost which the annual fixed charges represent.

The cost per mile, D, in the above equation can be considered in two parts: (1) the cost of the line less conductor and (2) the cost of the conductor. The above equation then becomes

$$X = KZ\ (B+3E)$$

where B is the cost per mile of the line less conductor and E is the cost of the conductor per mile per phase.

The cost of the line, less conductor, will include rights-of-way, pole line structures, lightning protection, and labor costs. These costs have been found to be nearly constant for all sizes of

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[3] Knowlton, loc. cit.

the load curve. The last curve [illegible] load factor, but even [illegible] of the kilowatt-hours to the kilowatt [illegible] load factor.[3] Such a [illegible] using the load factor relation [illegible] stand for the [illegible].

The annual fixed charges [illegible] are ordinarily [illegible] percentage of the total [illegible] that line. If [illegible] per mile [illegible], and the line [illegible] per cent [illegible] I, on the line and

I = (C) (L) (S),

where S is the [illegible] charges represent.

The cost per mile, C, [illegible] in two parts: (1) the cost of the line [illegible] and (2) the cost of the conductor. [illegible]

C = B. (S+K)

where B is the cost per mile of [illegible] cost of the conductor per mile [illegible].

The cost of the line [illegible] way, pole line structures, lightning protection, [illegible]. These costs have been found to be fairly [illegible]

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[3] Russell, loc. cit.

conductors.[4] Some companies with favorable land contours and weather conditions have found the cost of the line-less-conductor to actually decrease with increased conductor size.[5] The decrease was realized from the fewer number of support structures required for the larger conductor. The larger the conductor the greater its mechanical strength. If the land contour will permit longer spans, and if the wind force and ice loading do not require additional mechanical strength, the cost of the line-less-conductor may be made less for larger conductors by increasing the average span length. Some areas which experience high winds and ice loading will require additional mechanical strength with increasing conductor size because the larger conductor area will raise the wind and ice forces on the structures. The cost of the increased mechanical strength for these cases are offset by the longer spans and the cost of the line-less-conductor becomes nearly a constant for all sizes of conductor.

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[4] J. M. Henderson and A. J. Wood, "Conductor Economics on High Voltage Transmission System," Power Apparatus and Systems, (New York: A.I.E.E., Aug., 1957). The authors of this article prepared curves for lines with steel tower supports but stated that the curves were ". . . also representative of those obtained with other construction types such as . . . wood pole, etc.". The curves presented in the article show an increasing total line cost for rising conductor cost but the increase is due to the larger conductor and not to the structure for the conductor.

[5] Ralph G. Yerk, "Transmission Design and Construction," a paper presented to the Tulsa Section of the American Institute of Electrical Engineers, Nov. 20, 1947.

conductors.[4] Some comparisons with [illegible] load [illegible] and voltage conditions have found the cost of the line-[illegible] decrease with increased conductor size.[5] The difference may be found from the fewer number of support structures required for the larger conductor. The larger [illegible] conductor has greater [illegible] strength. If the land [illegible] longer spans, and if the wind force and ice loading [illegible] additional mechanical strength, the cost of the line-[illegible] for larger conductors by increasing the [illegible] span length. Some areas which experience high winds and [illegible] mechanical strength [illegible] increase in the conductor area will [illegible]. The cost of the increased [illegible] offset by the longer spans and the cost of the line-loss-conductor becomes nearly a [illegible] of conductor.

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[4] H. H. [illegible] and [illegible], "[illegible] Voltage Transmission Systems," [illegible] (New York: A.I.E.E., [illegible]). [illegible] for lines [illegible] ". . . [illegible] types such as . . . [illegible]" [illegible] article show an interesting [illegible] but the [illegible] for the conductor.

[5] Ralph J. [illegible], "[illegible]," paper presented to the [illegible] Electrical Engineers, [illegible].

In those cases where larger conductor sizes require additional mechanical strength the additional cost may be represented as a percentage of the conductor price. That is, the conductor price may be multiplied by a constant which will reflect the change in price of transmission line structures as the conductor size changes. The cost of the line-less-conductor would still be treated as a constant in this case. An alternate to this procedure would be to multiply the cost of the transmission line structures by a factor which represents the increase in structure price as the conductor size increases. Either of these methods could be included in the formulas in the remainder of this chapter. The formulas have been developed, however, without including either of these factors due to the reasons given in the above paragraph.

The cost on the conductor will vary because the fixed charges will increase as the conductor size increases. The cost per mile per phase of the conductor, E, may be equated as

$$E = W \text{ (pounds per mile)}$$

where W = conductor cost per pound.

Since the cost per pound for a conductor is approximately the same for all sizes of wire, the only variable in the formula is the pounds per mile. The pounds per mile will vary directly with the size of the conductor. If this variable and the line loss variable in the equation on page 12 can be made the same, then the formula on page 11 can be solved for that conductor size which will make the load center

In these cases where larger conductors [illegible] addi-tional mechanical strength) the additional cost may be represented as a percentage of the conductor price. That is, the conductor price may be multiplied by a constant which is [illegible] the change in price of transmission [illegible] [illegible] [illegible]. The cost of the line-loss [illegible] would [illegible] [illegible] con-stant in this case. [illegible] [illegible] [illegible] [illegible] mul-tiply the cost of the [illegible] [illegible] [illegible] [illegible] which represents the increase in [illegible] [illegible] [illegible] de-creases. Either of these [illegible] [illegible] [illegible] [illegible] in the remainder of this chapter. The [illegible] [illegible] [illegible], however, without [illegible] [illegible] [illegible] [illegible] to the results given in the above paragraph.

The cost of the conductor will vary [illegible] [illegible] [illegible] will increase as the conductor [illegible] [illegible]. The [illegible] per mile per phase of the conductor, C, may be expressed as

$C = W$ (pounds per mile)

where c = conductor cost per pound.

Since the cost per pound of [illegible] [illegible] [illegible] the same for all sizes of wire, the only variable in the formula is the pounds per mile. The pounds per mile will vary directly with the size of the conductor. If this variable [illegible] [illegible] [illegible] in the equation on page 12 can be [illegible] [illegible], then the [illegible] 11 can be solved for that conductor size which will make the [illegible] [illegible] cost the same for the two generation locations. The size which will be the most economical can also be found.

Appendix II shows that the weight multiplied by the resistance is approximately a constant for all conductors; i.e., the resistance varies inversely with the weight. For 30/7ACSR conductor the (wt/mile/phase) x (resistance/mile/phase) = 850 or wt/phase/mile =

$$\frac{850}{\text{resistance/phase/mile}} .$$

The cost per mile per phase of the conductor is $E = (W)\,\frac{(850)}{r}$ where r = resistance in ohms per mile per phase of the conductor. The annual fixed charge on the line, from the equation on page 13 is

$$X = (K)\ (Z)\ (B) + 3(K)\ (Z)\ (W)\ \frac{850}{r} .$$

The formula may be generalized by using the letter G to represent the constant of pounds/mile/phase to resistance/mile/phase. The formula then becomes

$$X = (K)\ (Z)\ (B) + \frac{3KZWG}{r} .$$

Dividing this value by Y, the total kilowatt-hours per year, will give the cost of the fixed charges per kilowatt-hour, F.

The maintenance cost, M, in the formula on page 11 is usually expressed as annual cost per mile. To get this in cost per kilowatt-hours the annual cost per mile is multiplied by the length of the line and divided by the kilowatt-hours per year. That is

$M = \frac{mZ}{Y}$ where m is the annual maintenance cost per mile.

The formula on page 11 for the total cost per kilowatt-hour of power cost the same for the two [illegible] transmission. The size which will be the most economical [illegible].

Appendix II shows how the [illegible] is [illegible] the resistance is approximately [illegible] for all [illegible], the [illegible] varies inversely with the [illegible] (ut/mile/phase) [illegible] =

$$\frac{540}{\text{resistance/phase/mile}}$$

The cost per mile [illegible] where r = resistance in ohms per mile [illegible]. The annual fixed charge [illegible]

X = [illegible]

The formula may be generalized [illegible] send the [illegible]. The formula then becomes

Y = [illegible]

Dividing this value by E, the total kilowatt-hours per year, will give the cost of the fixed charges per kilowatt-hour, F.

The maintenance cost, M, in the formula on page 21 is usually expressed as annual cost per mile. To get this in [illegible] kilowatt-hours the annual cost per mile is multiplied by the length of the line and divided by the kilowatt-hours per year. Thus

M = [illegible] where m is the annual maintenance cost per mile.

The formula on page 21 for the total cost per kilowatt-hour delivery generated at a remote location may now be written as

$$T = S + M + L + F$$

$$T = S + \frac{mZ}{Y} + \frac{3I^2RHS\ 10^{-3}}{Y} + \frac{KZB}{Y} + \frac{3KZWG}{Yr}$$

$$T = S + \left[\frac{(m + KB)}{Y}\right] Z + \frac{3}{Y} \left[I^2RHS\ 10^{-3} + \frac{KZWG}{r}\right]$$

Only the last two parts of this equation contain variables. If the total resistance of the line, R, is made equal to the resistance per mile, r, times the length of the line, then the third part of the equation becomes $\frac{3I^2\ r\ ZHS10^{-3}}{Y}$ and the total equation becomes

$$T = S + \left[\frac{m + KB}{Y}\right] Z + 3\,\frac{Z}{Y} \left[I^2rHS\ 10^{-3} + \frac{KWG}{r}\right]$$

clearing the constants

$$T = S + \left[\frac{m + KB}{Y}\right] Z + \frac{3Z}{Y} \left[8.76I^2Sr + \frac{KWG}{r}\right]$$

This equation contains only one variable, r. If the cost of power generation at the load center is greater than the cost at a remote site, the above equation may be set equal to the cost at the load center and the equality solved for r. With the solved value of r the conductor size which will give equal load center costs for the two generation locations will be found.

If the formula above is differentiated with respect to resistance and set equal to zero, that value of r which will identify

the most economical size of conductor will be found. The formula is differentiated as follows:

$$T = S + \frac{(m + K\ B)}{Y} Z + \frac{3Z}{Y} \left[I^2 r\ HS\ 10^{-3} + K\ W \frac{G}{r} \right]$$

$$\frac{dT}{dr} = \frac{3Z}{Y} \left[I^2\ HS\ 10^{-3} - K\ (W) \frac{G}{r^2} \right]$$

Setting this equation equal to zero and solving for r

$$r = \frac{1}{I} \sqrt{\frac{(K)\ (W)\ (G)}{HS\ 10^{-3}}}$$

$$= \frac{0.338}{I} \sqrt{\frac{(K)\ (W)\ (G)}{S}}$$

The resistance found by this formula represents the most economical resistance in ohms for the conductor in a transmission line. The resistance can be converted to conductor size by reference to Appendix II. The formula may be used for different types of conductors by using the proper value for G as found in Appendix II.

CHAPTER IV

EXAMPLE OF FORMULAS FOR ECONOMIC CONDUCTOR SIZES

To illustrate the use of the formulas in the preceding chapter, a problem which applied to the Public Service Company of New Mexico will be solved. The solution is designed to illustrate the use of the formulas. Factors concerning future loads, material and labor costs, generation policy and generation costs which are not known to the author may change these final answers. To arrive at a final solution it would be necessary to include these factors and solve the formulas again. The following work will suffice to illustrate the usefulness of the formulas.

A. System of the Public Service Company of New Mexico

The Public Service Company of New Mexico now serves an interconnected electrical load which has an annual peak demand in excess of 125,000kw. It has transmission lines operating at 115,000 volts and it is interconnected with one private electric power company, three electric cooperatives, and the U. S. Bureau of Reclamation.

The company began operation as a subsidiary of the Cities Services Incorporated of New York, New York. Each city which now is a part of the Public Service Company of New Mexico formerly had its own generating plant and only part of them were interconnected. Generating plants were located at Las Vegas, Santa Fe, Bernalillo,

CHAPTER [illegible]

EXAMPLE OF SOLVING [illegible]

To illustrate the use of the formulas derived in the preceding chapter, a problem which applies to the Public Service Company of New Mexico will be solved. The data used are designed to illustrate the use of the formulas. Factors concerning future sales, material and labor costs, generation policy and general economy which are not known to the author may change the final answer. To obtain a final solution it would be necessary to consider these factors and solve the formulas again. The simplified case will serve to illustrate the usefulness of the formulas.

A. System of the Public Service Company of New Mexico

The Public Service Company of New Mexico now serves an interconnected electrical load which has an annual peak demand in the area of 125,000kw. It has transmission lines operating at 115,000 volts and it is interconnected with one private electric power company, three electric cooperatives, and the U. S. Bureau of Reclamation.

The company began operations as a subsidiary of [illegible] Services Incorporated of New York, New York. Each city which now is a part of the Public Service Company of New Mexico had its own generating plant and very few of them were interconnected. Generating plants were located at [illegible], Albuquerque, Belen, and Deming. The loads were served in many instances directly from the generator bus without being transformed to a higher voltage. As the system grew, Belen, Albuquerque, and Santa Fe were interconnected with a 44,000 volt line.

Las Vegas was connected to the system in 1953 by a 115,000 volt line, but the line has been operated at 44,000 volts; the 44,000 volt operation will continue until the Las Vegas load increases. A USBR 115,000 volt line was connected to the Public Service Company of New Mexico at Albuquerque and at Deming in 1953. El Paso Electric Company is connected to the same 115,000 volt line.

Today the Public Service Company of New Mexico has four generating plants in operation. Three of the operating plants are located at Albuquerque: Prager, Person and Reeves Stations. The other operating plant is in Santa Fe. The company now transmits its large quantities of power over 115,000 volt lines. The 44,000 volt lines, which were originally the transmission lines, have been made a part of a subtransmission system. The 44,000 volt lines feed substations which step voltage down to the distribution voltage, 4,160 volts or 12,700 volts. The subtransmission system is used in both Albuquerque and Santa Fe. The 44,000 volt lines are still used as transmission lines for areas outside but proximate to the larger cities. The loads in these areas are not large enough to justify the 115,000 volt transmission line. Belen is connected to the Albuquerque system by two 44,000 volt lines; these lines form a loop feed to Belen.

Albuquerque, Belen, and Socorro. [illegible] were [illegible] in-stances directly from the [illegible] plants [illegible] to a higher voltage. [illegible], [illegible], and Santa Fe were interconnected with a [illegible] volt line.

Las Vegas was connected to [illegible] in [illegible] with a [illegible],000 volt line, but this line has been converted to [illegible],000 volts, the [illegible] volt operation with [illegible]. A [illegible] 115,000 volt line was connected to the Public Service Company of New Mexico at Albuquerque and [illegible] in [illegible]. [illegible] Electric Company is connected to the same 115,000 volt line.

Today the Public Service Company of New Mexico has [illegible] generating plants in operation. [illegible] of the [illegible] plants are located at Albuquerque: [illegible], [illegible] and [illegible] Stations. The other generating plant is in Santa Fe. The company [illegible] the large quantities of power over 115,000 volt lines. The [illegible],000 volt lines, which were originally the [illegible] lines, have now become a part of a subtransmission system. The [illegible],000 volt lines [illegible] to step the voltage down to the distribution voltage, [illegible],000 volts or 13,200 volts. The subtransmission system is [illegible] in both [illegible]. The 44,000 volt lines are [illegible] the [illegible] outside but [illegible] to the [illegible]. The [illegible] are not large enough to justify the 115,000 volt [illegible]. Belen is connected to the Albuquerque [illegible] by [illegible] volt lines. These lines form a [illegible].

B. Planned Line

A generating plant which could utilize the cheap fuels in the northwest corner of New Mexico has been planned. To reach its heaviest load center the Public Service Company of New Mexico would have to build a transmission line from the generating plant to Albuquerque.

All transmission lines within the state of New Mexico are shown in Figure 1. The figure shows that the highest operating voltage in the state is 115,000 volts. The new line from the generating plant in northwestern New Mexico is drawn in to show its future place in the Public Service Company of New Mexico system. The line as drawn is approximately 120 miles long.

C. Present and Predicted Loads

A transmission line built from the Northwest area in New Mexico to the City of Albuquerque could serve other areas along the route of the line. The Public Service Company of New Mexico has not contracted to sell any power from such a line, however, so any loads that may be served can only be estimated. The planning for the transmission line should account for any loads of this nature which may occur. For the purpose of the problem two points called Point A and Point B have been selected and assigned load values which are typical for medium size New Mexico cities.

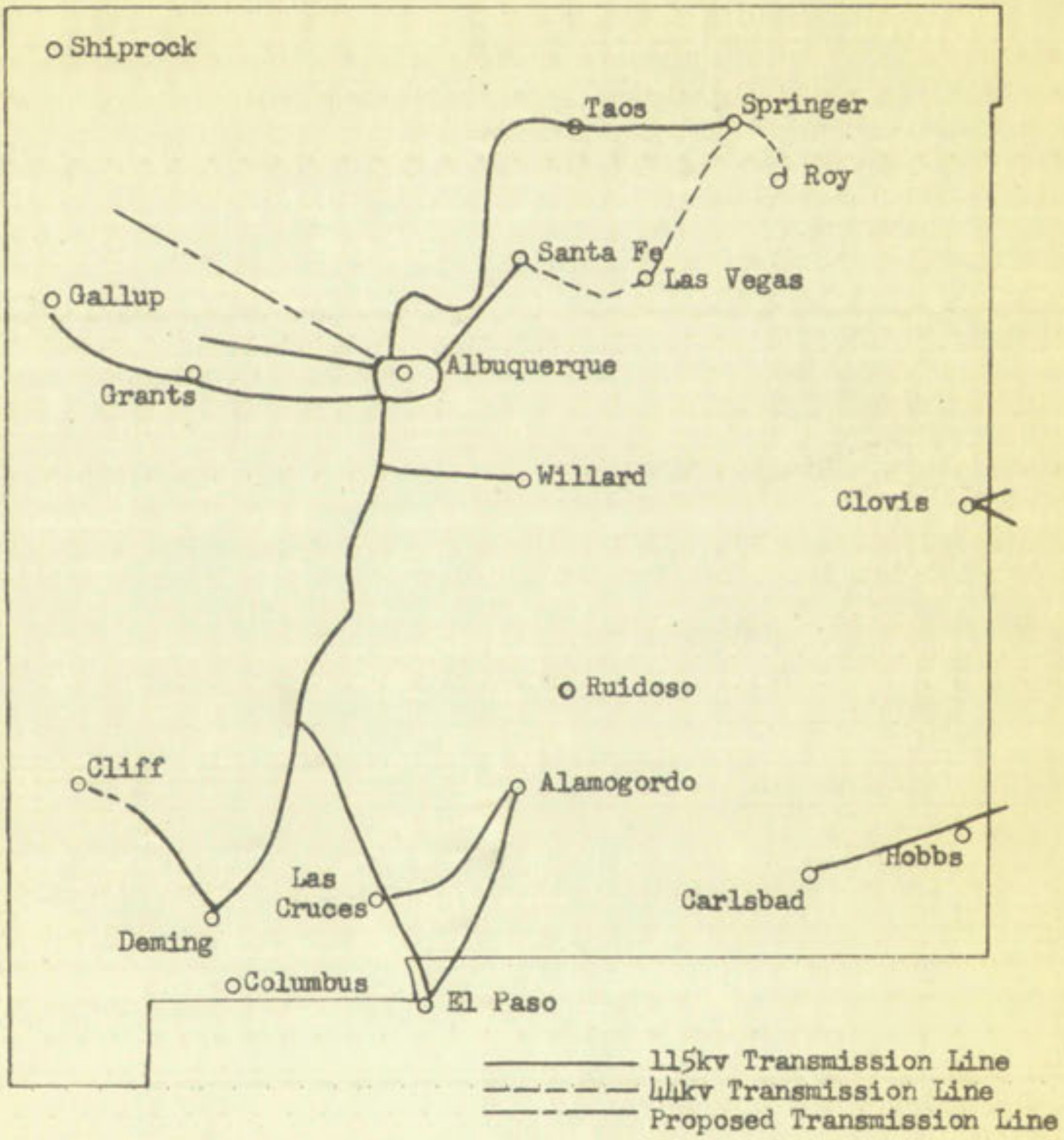


Figure 1. Transmission lines in the state of New Mexico

1. Loads at Point A

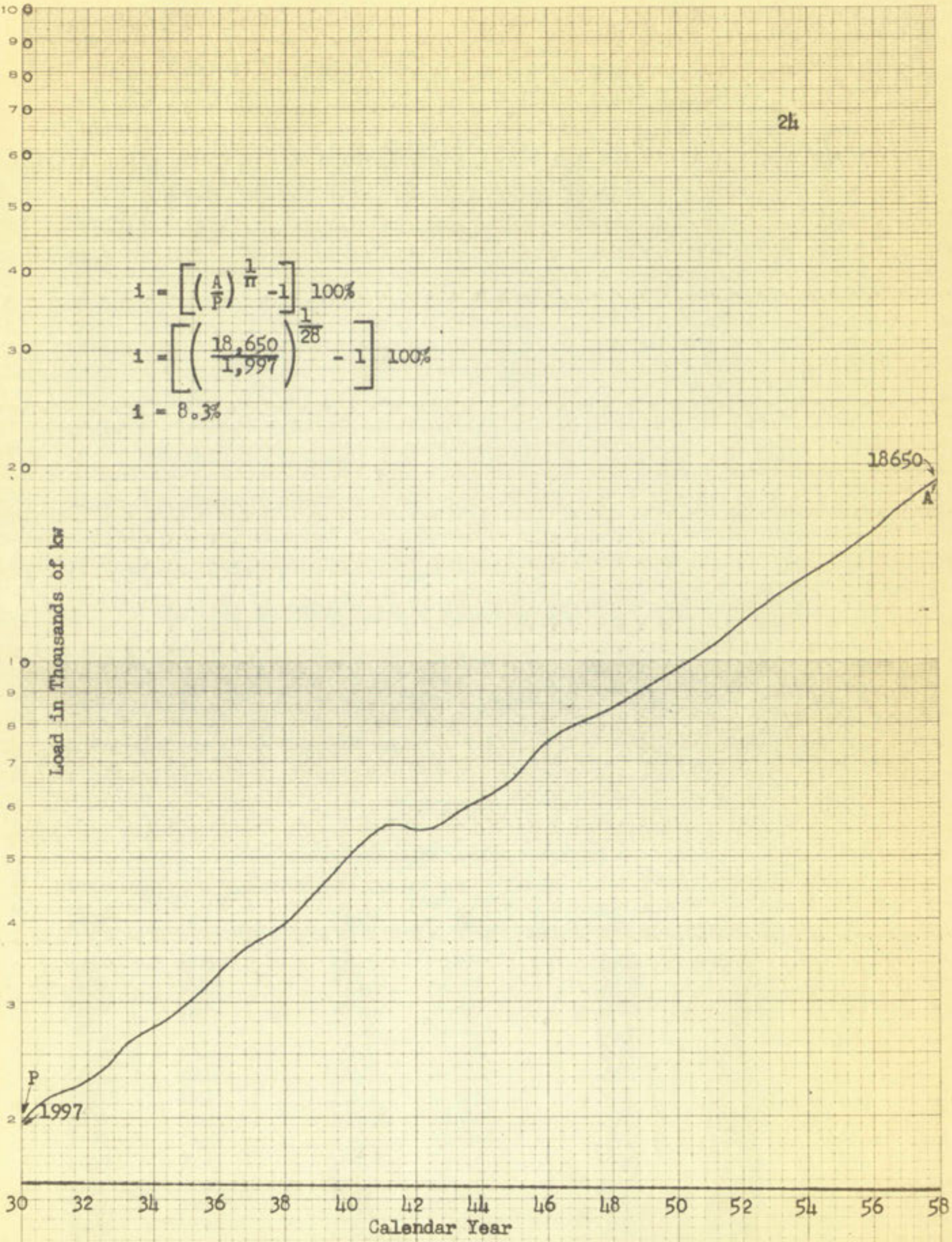
The city which Point A represents would have a population of approximately 12,000 people, and it would have had annual peak loads since 1930 as listed in Table 2.

TABLE 2

ANNUAL PEAK LOADS OF CITY A FROM 1930 TO 1958

Year	Peak Load, kw	Year	Peak Load, kw
1930	1997	1945	6680
1931	2160	1946	7440
1932	2270	1947	7920
1933	2530	1948	8500
1934	2760	1949	9040
1935	2980	1950	9700
1936	3310	1951	10450
1937	3630	1952	11600
1938	3940	1953	12440
1939	4410	1954	13500
1940	5070	1955	14600
1941	5560	1956	16000
1942	5430	1957	17220
1943	5780	1958	18650
1944	6070		

The plot on semi-log paper of the load values in Table 2 is shown in Figure 2. This curve shows that the loads have increased annually at an average rate of 8.3 per cent. The increased percentage is obtained by the method given in Chapter II. Using the 8.3 per cent annual increase, the predicted loads for the next eight years are shown in Table 3.



$$i = \left[\left(\frac{A}{P}\right)^{\frac{1}{n}} - 1\right] 100\%$$

$$i = \left[\left(\frac{18,650}{1,997}\right)^{\frac{1}{28}} - 1\right] 100\%$$

$$i = 8.3\%$$

Figure 2. Load Growth Curve of City A

TABLE 3

PREDICTED PEAK LOADS FOR CITY A FROM 1959 TO 1968

Year	Predicted Load, kw	Year	Predicted Load, kw
1959	20200	1964	31300
1960	21920	1965	33900
1961	23740	1966	36700
1962	25700	1967	39750
1963	28900	1968	43100

Point A is located approximately twenty-one miles from the remote generating plant.

2. Loads at Point B

The city at Point B would have characteristics similar to city A, but it would have a 1959 population of approximately 18,000 people. Its past annual electrical peaks and its estimated future peaks are tabulated in Table 4.

TABLE 4

PAST AND PREDICTED LOADS FOR CITY B

Year	Peak Load, kw	Year	Peak Load, kw	Year	Peak Load, kw
1930	4800	1943	9820	1956	26300
1931	5070	1944	10300	1957	27340
1932	5230	1945	11000	1958	29140
1933	5180	1946	11940	1959	31050
1934	5360	1947	13800	1960	33100
1935	5950	1948	15700	1961	35300
1936	6400	1949	17640	1962	37650
1937	6590	1950	18680	1963	40100
1938	7210	1951	19830	1964	42900
1939	7880	1952	21010	1965	45600
1940	8400	1953	21890	1966	48600
1941	9000	1954	23150	1967	51900
1942	9030	1955	24700	1968	55300

The average annual load growth computed from the values of past load experience in Table 4 is 6.63 per cent. This growth average was used to compute the estimated loads.

Point B is located approximately forty-five miles from Albuquerque.

3. Loads at Albuquerque

Since all cities served by the Public Service Company of New Mexico, at the present time, are connected by transmission lines to the Albuquerque electrical system, and since 90 per cent of the existing generating capacity is located at Albuquerque, the entire electrical load of the Public Service Company of New Mexico may be considered to be located at Albuquerque. In the past, the Albuquerque system has accounted for approximately 80 per cent of the total system peak. The system peaks of the Public Service Company of New Mexico since 1934 are given in Table 5.

TABLE 5

PEAK LOADS OF THE PUBLIC SERVICE COMPANY
OF NEW MEXICO FROM 1934 TO 1958

Year	Peak Load, kw	Year	Peak Load, kw	Year	Peak Load, kw
1934	9050	1942	16100	1950	54010
1935	10780	1943	18030	1951	60880
1936	12050	1944	19240	1952	70680
1937	12680	1945	23900	1953	75320
1938	13650	1946	27240	1954	85130
1939	15570	1947	31350	1955	93130
1940	16590	1948	35920	1956	105860
1941	17670	1949	43140	1957	115000
				1958	130000

These system peaks are plotted and the per cent of yearly increase, 11.7 per cent, is computed in Figure 3. The estimated future demands for the system are shown in Table 6.

TABLE 6

ESTIMATED PEAK LOADS FOR
THE PUBLIC SERVICE COMPANY OF NEW MEXICO

Year	Predicted Peak Load, kw	Year	Predicted Peak Load, kw
1959	145200	1965	281000
1960	162000	1966	314500
1961	181000	1967	352000
1962	212000	1968	393500
1963	226000	1969	441000
1964	252000		

As indicated by the above tables, the load growth computations were made prior to the peak load of 1959. The actual peak load which was recorded in 1959 was considerably above that shown in Table 6. The unusual increase was due primarily to connections to large industrial users which had supplied their own power or had obtained it from other utilities previous to 1959. This type of connection, which will be known to the utility load growth estimator, must be included in the growth analysis. The net effect of such loads is to move the load growth curve up by an amount equal to that which these unusual loads will add to the system peak. Neglecting this high peak for 1959 will not effect the illustrations here so the unusual peak condition has not been included in this study.

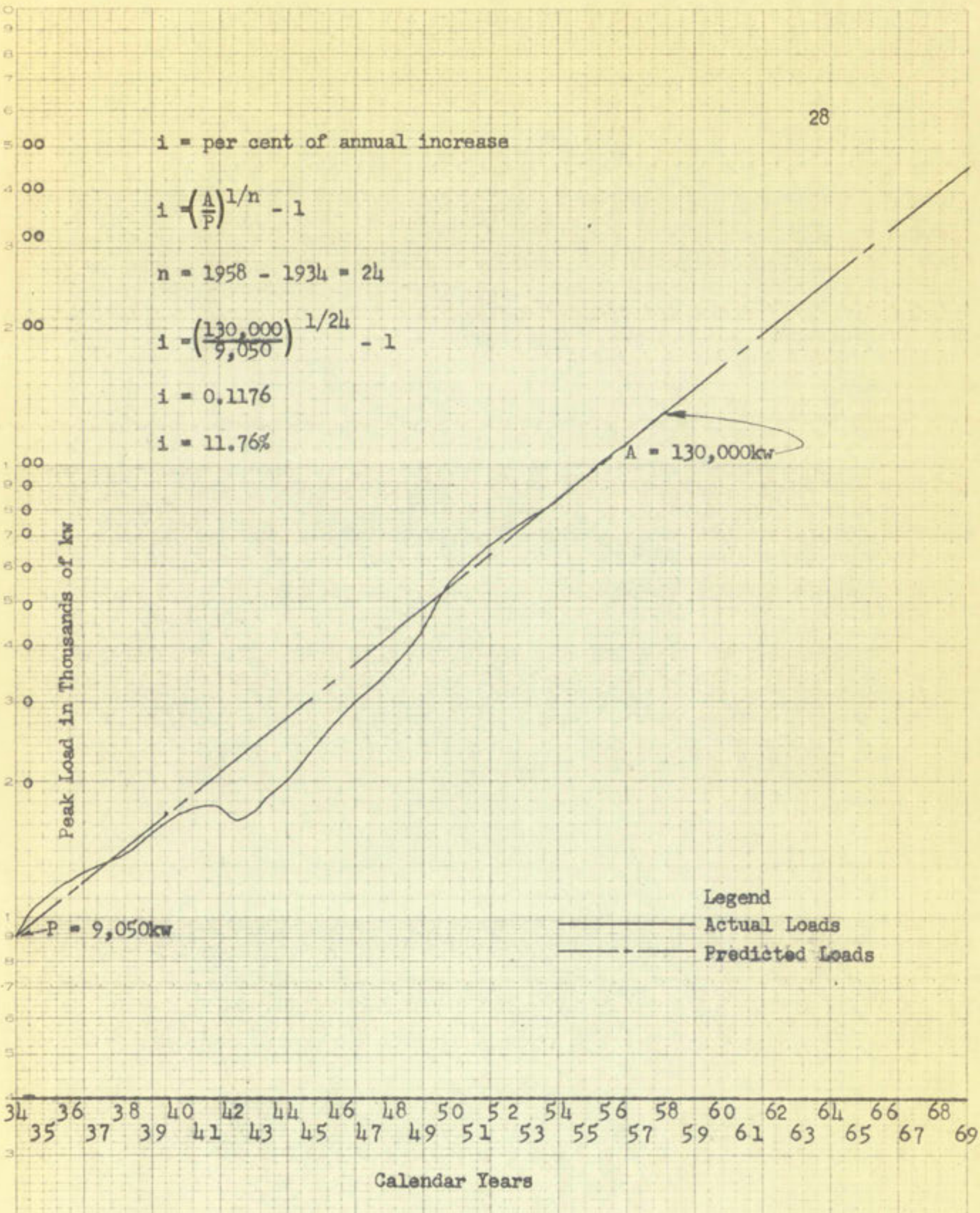
These system peaks are plotted and the rate of [illegible] increase, 11.7 per cent, is [illegible] in Figure 8. The [illegible] future demands for this system are given in Table 9.

TABLE 9

ESTIMATED PEAK LOADS FOR
THE [illegible] SERVICE COMPANY OF [illegible]

Year	Predicted peak load, kw	Year	Predicted [illegible], kw
1959	145?00	1958	[illegible]
1960	1?7000	1960	[illegible]
1961	[illegible]	[illegible]	[illegible]
1962	[illegible]	[illegible]	[illegible]
1963	[illegible]	[illegible]	[illegible]
1964	[illegible]		

As indicated by the above table, the load growth expectations were made prior to the peak [illegible] of 1959. The actual peak load which was recorded in 1959 was considerably more than shown in Table 8. The unusual increase was due primarily to the addition of large industrial users which had supplied their own power or had obtained it from other utilities previous to 1959. This type of connection, which will be known by the utility long enough in advance, must be included in the growth analysis. The most effective of [illegible] loads is to have the local [illegible] by an amount equal to that which these unusual loads [illegible] above the [illegible] of this high year [illegible] the unusual peak [illegible].



i = per cent of annual increase

$$i = \left(\frac{A}{P}\right)^{1/n} - 1$$

$$n = 1958 - 1934 = 24$$

$$i = \left(\frac{130{,}000}{9{,}050}\right)^{1/24} - 1$$

$$i = 0.1176$$

$$i = 11.76\%$$

Figure 3. Plot of Peak Loads for Albuquerque and Computation of Per Cent of Annual Load Increase

D. Comparative Power Cost

An economic analysis of a transmission line versus additional generating capacity at Albuquerque needs to include only the present Public Service Company of New Mexico system. The cities, A and B, described above would be served only if the transmission line were built, but their loads must be considered when the characteristics of the line, such as voltage regulation, are determined. The loads of cities A and B should not be included, however, in a study being made to decide if the transmission line should be built or if new generating capacity should be added at Albuquerque. To make the generator-transmission line decision, the Albuquerque bus cost of a kilowatt-hour by the two generation methods will be equated. The Albuquerque bus cost of the remotely generated power must contain all cost factors of the transmission line as listed in Chapter III, as well as the generation cost.

E. Additional Generating Capacity at Albuquerque

The Reeves Power Plant on the north side of Albuquerque has a 40,000kw generator as its first operating unit and a second 40,000kw generator will be operating in 1960. The present plans call for a 60,000kw generator to be added when the system load requires it. The purchase of the 60,000kw generator may be delayed, however, if the proposed transmission line is built. The Public Service Company of New Mexico has operating experience and statistics on the cost of

generation on two 30,000kw generators at its Person Station and on the 40,000kw generator at Reeves Station. The generation cost for the second 40,000kw generator at Reeves Station can be estimated closely by the experience gained from the existing generators. The cost of generation for this generator has been estimated to be $0.0049 per kilowatt-hour. This includes all fixed and operating costs for power at the power plant.

F. Power at the Northwest New Mexico Generating Plant

Two sizes of plant have been studied for the northwest New Mexico plant; one would have a generation cost of $0.0041 per kilowatt-hour and a larger plant would have a generation cost of $0.0040 per kilowatt-hour. These costs represent the power plant costs as did the Reeves Station costs. The cost of a kilowatt-hour at the larger plant will be used for the problem studied in this chapter.

G. Reliability

To provide more reliable service to its customers, the operating procedure of the Public Service Company of New Mexico has been to make available excess generating capacity equal to that of its largest generating unit. This policy permits the company to eliminate most outages due to generation difficulty. Enough "spare" generators are kept spinning to pick up all load in the event the largest generator is disabled for whatever reason. This policy also provides the company with capacity enough to perform necessary maintenance work on generation on two 15,000 kw generators at [illegible] and the 10,000 kw generator at [illegible]. The generation cost at the second 15,000 kw generator [illegible] closely by the experience gained [illegible]. The cost of generation for this generator has been estimated to be $0.0049 per kilowatt-hour. [illegible] costs for power at the power plants.

F. Power at the [illegible] Plant

Two sizes of plant have been [illegible] Mexico plant, one would have a generation cost of [illegible] per kilowatt-hour and a larger plant would have a generation cost of [illegible] per kilowatt-hour. These costs [illegible] the power plant [illegible] did the [illegible]. The cost of [illegible] at the larger plant will be used for the [illegible].

G. Reliability

To provide more reliable service to its customers, the operating procedure of the [illegible] Company [illegible] has been to make available [illegible] capacity equal [illegible] of the largest generating unit. This policy [illegible]. Although most outages due to generation [illegible] are [illegible] to pick up [illegible] ator in [illegible] company with capacity enough [illegible] their generators during the light load season of the year.

The transmission line being studied will be treated as a generating unit for application of the excess-generator policy. The load delivered by the line to the Albuquerque system will be limited to the amount of excess generating capacity available. This limit does not include the loads delivered to the cities A and B along the route of the line, however. The excess generating capacity is found in Appendix III, and it is shown that the least excess capacity is approximately 75,000kw.

The 75,000kw limit to the Albuquerque system by the transmission line will effectively limit the life of the line to 1963. This does not mean that the line will last only to 1963, but rather that additional generating capacity, or transmission lines from the northwestern New Mexico area, will be required before the peak load of 1964 occurs.

H. Economic Maximum Resistance Calculations

A 115,000 volt transmission line has been selected for the illustrative problem which follows on the basis of economical connection to existing lines and as the voltage which will best illustrate the use of the formulas developed in Chapter III. Determination of operational difficulties can also be best illustrated by the selection of the 115,000 volt transmission line.

The cost of maintenance for a 115,000 volt transmission line their generators during the light load season of the year.

The transmission line [illegible] in a generating unit for supplying [illegible] in the [illegible]. The load delivered by the line to the [illegible] system will be limited to the amount of excess generating capacity available. This limit does not include the loads delivered to the cities [illegible] along the route of the [illegible]. The [illegible] generating capacity is found in Appendix [illegible], and it is found that the [illegible] excess capacity is approximately 73,000kw.

The 73,000 kw limit on the [illegible] of the transmission line will effectively limit the life of the line to 1964. This does not mean that the line will [illegible] in 1964, but rather that additional generating capacity, or [illegible] for the northeastern [illegible] area, will be required before the peak load of 1964 occurs.

H. Economic [illegible]

A 115,000 volt transmission line has been selected for the illustrative problem [illegible] on the basis of [illegible] connection to existing lines and on the voltages which will [illegible] trate the use of the formulas developed in Chapter [illegible]. Determination of operational [illegible] has also been made in [illegible] of the selection of the 115,000 volt transmission line.

The cost of [illegible] 115,000 volt [illegible] a line has been estimated as $150/mile/year. The cost of constructing a 115,000 volt transmission line, less conductor, has been estimated as $9,000/mile, and the annual fixed charges on the line have been computed to be 15.1 per cent per year. The estimates have been made from construction and maintenance cost experiences of power companies, and the fixed charges percentage is derived in Appendix IV.

To arrive at the number of kilowatt-hours per year which will be transmitted over the line from the northwest New Mexico area, it has been assumed that the line will be given a good load factor. The Albuquerque generators would be used to carry the remaining portion of the base load, and they would supply the peak demands. This practice may cause the Albuquerque cost of generation to increase slightly above the cost which would be experienced when the Albuquerque generators carried the entire load. The additional cost would be caused by the lower efficiency of generators when operated below full rating and of the generation labor cost; the labor cost would be nearly the same for either condition of loading on the generators. The total amount of the increase for a year should be computed and the value added to the cost of generation at the northwestern New Mexico plant. This addition would cause the effective generation cost of the remote generating plant to be increased slightly. Since the Albuquerque generators would continue to carry approximately two-thirds or better of the base load, the increase in Albuquerque generation cost as a result of base loading the transmission line is has been estimated at $250 million. The cost of [illegible] 115,000 volt [illegible] lines, [illegible], has been estimated as $5,000/mile, and the [illegible] for the line was then computed to be [illegible] per kilowatt-year. [illegible] have been made from [illegible] capacities, and the fixed charges [illegible] is covered in Appendix B.

To arrive at the value of kilowatt-hours [illegible] will be transmitted over the line, it was [illegible], has been assumed that the line will be [illegible] factor. The Albuquerque [illegible] tion of the high line, [illegible]. This practice may [illegible] slightly above the cost which would be [illegible] gas [illegible] will be caused by the lower efficiency of [illegible] full rating and of the [illegible] would be nearly the same for [illegible] of the generators. The total amount of the [illegible] and the value [illegible] New Mexico plants. [illegible] cost of the [illegible]. [illegible] the Albuquerque [illegible] two-thirds [illegible] tion cost as a result of [illegible].

considered slight. For this reason the increased generation cost at Albuquerque which results from assigning a high load factor to the transmission line has been neglected. The load factor assigned to the line for the following computations is 90 per cent. The annual kilowatt-hours may now be calculated:

$$\begin{aligned} Y &= (\text{load factor})\ (\text{hours/year})\ (\text{line peak loading}) \\ &= (0.90)\ (8760)\ (75{,}000) = 5.912\ 10^{8}\,\text{kwhr/year} \end{aligned}$$

Assuming a power factor of 90 per cent lagging the average current may be found:

$$I = \frac{\text{kwhr/year}}{(\text{power factor})\ (\text{voltage})\ (\text{hours/year})\ (\sqrt{3})}$$

$$= \frac{5.912 \times 10^{8}}{(0.9)\ (115{,}000)\ (8160)\ (\sqrt{3})} = 379 \text{ amperes}$$

As discussed in Chapter III, for a limited area and period of years, the average current, as computed above, may be treated as the square root current of the mean square current and consequently used to compute power losses. A high load factor, as the 90 per cent used in the illustrative problem, makes the current computed in the above manner even more nearly the true value of the square root of the mean square current. The current computed above, therefore, will be used in this manner for the computations which follow.

The formula for total load center cost of power generated at a remote site, which was developed in the previous chapter, may be set equal to the Albuquerque generation cost and solved for r, the resistance per mile per phase. The conductor size will be found considered alike. For this reason the incremental transmission cost at Albuquerque will not be affected materially if the load factor on the transmission line may be neglected. The load factor assumed to the line for the following calculations is 90 per cent. The annual kilowatt-hours may now be calculated:

$$Y = (\text{load factor})(\text{kilowatts})(\text{hours per year})$$
$$= (0.90)(10,000)(8,760) = 78.8 \text{ million kwh}$$

Assuming a power factor of 90 per cent for the line, the average current may be found:

$$I = \frac{\text{kilowatts}}{(\text{power factor})(\text{voltage})(\sqrt{3})}$$

$$= \frac{10,000}{(0.9)(115,000)(1.73)} = 57 \text{ amperes}$$

As discussed in Chapter XII, over a period of days and period of years, the average current, as computed above, may be treated as the square root of the mean square current and may be safely used to compute power losses. With high load factor, as the 90 per cent used in the illustrative problem, etc., the current computed in the above manner comes more nearly the true value of the square root of the mean square current. The average current, therefore, will be used in this manner for the computations which follow.

The formula for total load between point of power generation at a remote site, which was developed in the preceding chapter, may be set equal to the kilowatt-hour cost and solved for r, the resistance per mile of conductor. [illegible] which will make the Albuquerque cost of the two generation methods the same. The formula is solved as follows:

$$T = S + \frac{(m + KB)Z}{Y} + 3\frac{Z}{Y}\left[I^2\ rHS\ 10^{-3} + \frac{KWG}{r}\right]$$

$$T - S - \frac{(m + KB)Z}{Y} = 3\frac{Z}{Y}\left[I^2\ rHS\ 10^{-3} + \frac{KWG}{r}\right]$$

T = \$0.0049/kwhr
S = \$0.0040
M = \$150/mile
K = 15.1%
B = \$9,000/mile
Z = 120 miles
Y = 5.912×10^8 kwhr/year
I = 379 amperes
H = 8760 hours/year
W = \$0.35/lb[1]
G = 850 for 30/7ACSR[2]

The left side of the equation is

$$T - S - \frac{m + KB}{Y} Z = 0.0049 - 0.0040 - \frac{150 + (0.151)\ (9000)}{5.912 \times 10^8}(120)$$

$$= 5.937 \times 10^{-4}$$

The right side of the equation is

$$\frac{3Z}{Y}\left[I^2\ rHS\ 10^{-3} + \frac{KWG}{r}\right] = \frac{3(120)}{5.912 \times 10^8}\left[(379)^2\ (8760)\ (.004)\ 10^{-3} r\right.$$

$$\left. + \frac{(0.151)\ (0.35)\ (850)}{r}\right] = 3.065 \times 10^{-3} r + \frac{2.736 \times 10^{-5}}{r}$$

Equating the values of the two sides gives

$$5.937 \times 10^{-4} = 3.065 \times 10^{-3} r + \frac{2.736 \times 10^{-5}}{r}$$

$$30.65 r^2 - 5.937 r + 0.2736 = 0$$

---

[1] Approximate current price for ACSR conductor.

[2] Found in Appendix II.

which will make the lifetime cost of the two [illegible] the same. The formula is solved as follows:

T = c + [illegible]

[illegible]

T = 30.04¢/ton
B = 30.04¢
M = $150/mile
K = 15.3%
H = $8,000/mile
[illegible] = 120 miles
Y = 5.012 × 10[illegible]
E = [illegible]
L = 8760 hours/year
W = $1.75/[illegible]
G = $50 [illegible]

The left side of the equation is

[illegible]

= 5.937 × 10[illegible]

The right side of the equation is

[illegible]

[illegible]

[illegible]

5.937 × 10[illegible] = [illegible]

[illegible]

---

[1] [illegible]

[2] Found in Appendix [illegible]

$$r = \frac{5.937 \pm \sqrt{(5.937)^2 - 4\ (30.65)\ \ (0.2736)}}{2\ (30.65)}$$

$= 0.09685 \pm .02126$

$= 0.0756$ or 0.118 ohms/mile/phase

These resistances correspond to 900 million circular mills and to 1431 million circular mills ACSR conductors. This means that a 900 or 1431 million circular mills ACSR conductor on a transmission line 120 miles long will give equal Albuquerque cost for power generated at \$0.0049/kwhr at Albuquerque or at \$0.0040/kwhr at the other end of the transmission line.

It may be noted that actual resistances are 0.1185 and 0.0760 ohms for the 900 and 1431 million circular mills ACSR conductors respectively. These sizes, however, are the "standard sizes" with resistances most nearly the solved values.

The conductor size which will be the most economical may be found by the formula

$$r = \frac{0.338}{I}\sqrt{\frac{KWG}{S}}$$

which was developed in the preceding chapter.

Using the values

$K = 15.1\%$
$W = \$0.35/\text{lb}$
$G = 850$ for 30/7 ACSR
$S = \$0.0040/\text{kwhr}$
$I = 379$ amperes

The resistance of the most economic conductor size is:

$$r = \frac{0.338}{379}\sqrt{\frac{0.151\ (35)\ (850)}{0.0040}} = \frac{(.338)}{379}(105.8)$$

$$= 0.0943 \text{ ohms/mile/phase}$$

This resistance value corresponds to a conductor size of 1113 million circular mills, ACSR. This means that if other line characteristics are satisfactory, the most economy will be achieved by generating power in the northwest area of New Mexico and transmitting it to Albuquerque over a transmission line built with a 1113 million circular mills, ACSR conductor.

A curve of the Albuquerque cost of remotely generated power versus the resistance of the transmission line conductor is given in Figure 4. The figure graphically identifies the above value as the most economical conductor size.

The effect of the above solutions may be seen from the tabulation of costs for various parts of the line. Using the same values of load current, generation costs, etc., as was used in the previous calculations the cost of various parts of the line are tabulated in Table 7 for two of the conductor sizes found above. All values are for ACSR conductor.

TABLE 7

ANNUAL COST OF TRANSMISSION LINE FROM
NORTHWESTERN NEW MEXICO TO ALBUQUERQUE--TWO CONDUCTOR SIZES

Size	9000 MCM	1113 MCM
I^2R cost/year	\$ 214,727	\$ 175,577
Fixed charges/year	279,500	306,859
Maintenance cost/year	180,000	180,000
TOTAL	\$ 674,227	\$ 662,430

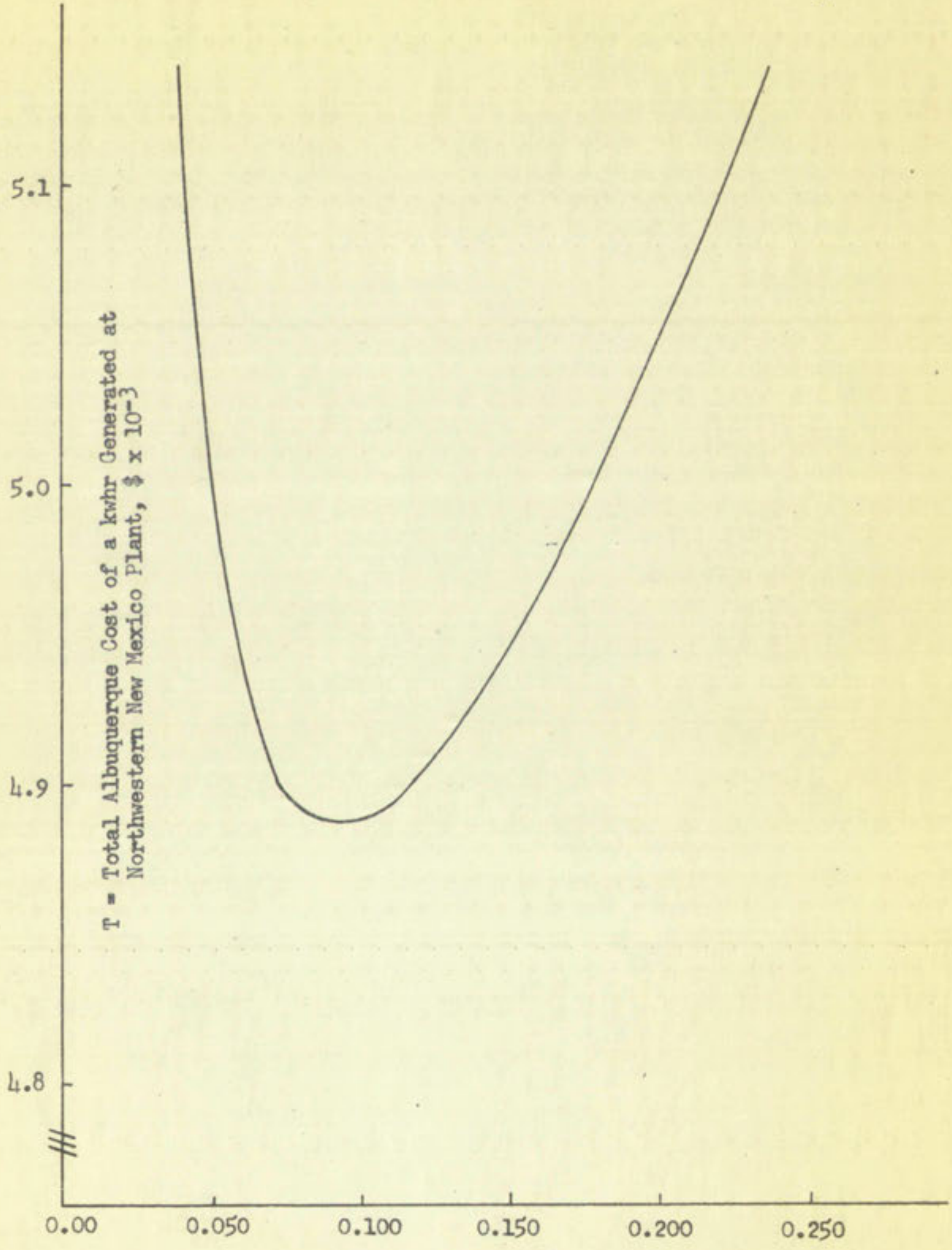


Figure 4. Curve of Albuquerque Cost of Remotely Generated Power versus Conductor Resistance

I. Voltage Regulation Check

The potential savings of a generation and transmission line may not be realized if the per cent of voltage drop is large. The per cent of voltage drop is defined as:

$$\text{Voltage Drop Percentage} = \frac{\text{Sending end voltage} - \text{Receiving end voltage}}{\text{Sending end voltage}} \times 100\%$$

The receiving end voltage for the transmission line described in the previous chapter was selected as 115,000 volts. The sending end voltage may be found by calculating the voltage drop in the line and adding it to the receiving end voltage.

The voltage drop may be found by resolving the line constants into an equivalent Pi representation. Any high voltage line must account for the capacitance charging of the line and the Pi representation is one of the simpler methods of doing this. The Pi representation is shown in the diagram below. In the diagram Y_s and Y_r equal one-half of the capacitance "load" of the line, X equals the line inductive reactance, R equals the line resistance, and E_s equals the sending end voltage.

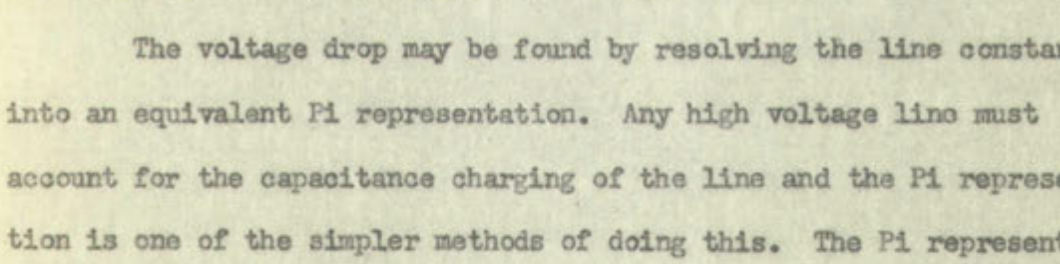


Figure 5. Equivalent Pi Representation

The sending end voltage may be found by the formula

$$E_s = E_r + (I_s \cos \theta \pm j\, I_s \sin \theta)\,(X + R)$$

The formula is made applicable to long lines by adding the current of Y_r and Y_s to the load current.[3] I_s is equal to the line current, I_L, when the charging current is negligible.

The transmission line would have a "one line" diagram as illustrated in Figure 6.

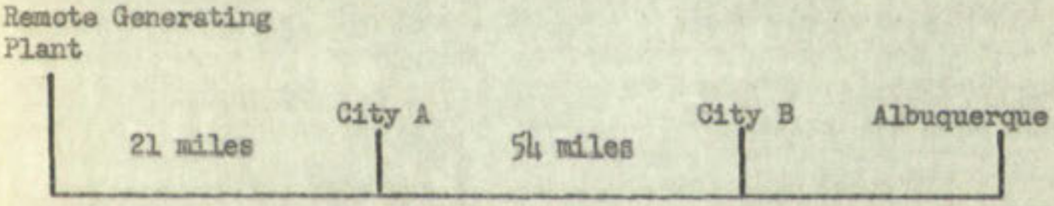


Figure 6. One line diagram of proposed transmission line

This diagram may be simplified from three sections to two sections by dividing the load of city B between city A and Albuquerque. The one line diagram for the simplified system is shown in Figure 7.

---

[3] Correction factors are required for long lines due to the distributed line characteristics being lumped in the equivalent "Pi" circuit. These corrections are $Z' = Z \frac{\sinh \theta}{\theta}$ where $Z = R + X$ and $\frac{Y'}{2} = \frac{Y}{2} = \frac{\tanh \theta/2}{\theta/2}$. See L. F. Woodruff, Principles of Electric Power Transmission, (N. Y., N. Y.: John Wiley & Sons, 1949), p. 114.

The sending end voltage may be found by the formula

$$E_s = E_r + (I_r \cos\theta + [illegible] I_c \sin\theta)(R + X)$$

The formula is made applicable to long lines by [illegible] the [illegible] of I_r and I_c to the load current.[6] I_c is [illegible] the current, I_c, when the charging current is negligible.

The [illegible] line [illegible] for [illegible] is illustrated in Figure 6.

Figure 6. One line diagram of [illegible]

This diagram may be simplified [illegible] into [illegible] sections by dividing the [illegible] and [illegible]que. The [illegible] line diagram and the simplified [illegible] is shown in Figure 7.

---

[6] [illegible] distributed line characteristics [illegible] circuit. These computations are [illegible] $\frac{Y'}{2} = \frac{Y}{2}\frac{[illegible]\,\theta/2}{\theta/2}$ [illegible] Transmission, [illegible]

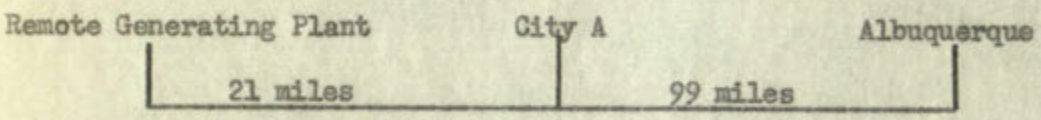


Figure 7. Simplified one line diagram of proposed transmission line

To make the two diagrams' electrical equivalents, the load of city B must be divided between city A and Albuquerque in inverse proportions of the distance between city B and the other cities. For example, that portion of B's load which is added to city A's load is found as

$$\text{Load}_{\text{B to A}} = \frac{(\text{B's total load})\ (45)}{99}$$

The load conditions of 1963 will be used for this problem because it was found in Appendix III that a second line from northwest New Mexico or additional generating capacity at Albuquerque would be required for the year 1964. The 1963 load of city B, 40,000kw, is divided as follows:

To city A

$$L_{\text{B to A}} = \frac{(40{,}100)\ (45)}{99} = 18{,}230\text{kw}$$

To Albuquerque

$$L_{\text{B to Alb}} = \frac{(40{,}100)\ (54)}{99} = 21{,}870\text{kw}$$

The load of city A for the equivalent two-section diagram = 28,900 + 18,230 = 43,130kw. With 75,000kw delivered to the city of Albuquerque as explained in Section G of this chapter, the total

Albuquerque load for the two-section diagram is 75,000 + 21,870 = 96,870kw. The one line diagram may now be redrawn as follows:

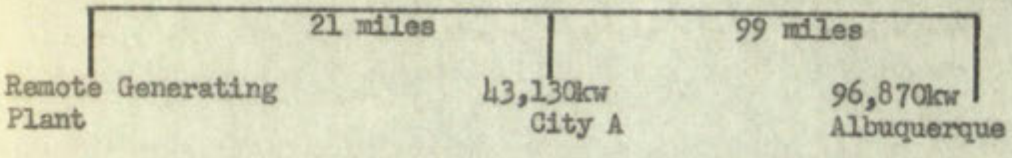


Figure 8. Equivalent one diagram of proposed transmission line

The constants for the Pi section will be found on a per mile basis to make them usable for both sections of the line.

The capacitance in farads per mile is found by the formula[4]

$$C = \frac{1940 \times 10^{-11}}{\log 10 \frac{D-r}{r}}$$

Where

D = geometric mean distance between conductors = 14.5 feet[5]

r = radius of conductor = 0.581 inches for 900 mcm ACSR conductor

$$C = \frac{1940 \times 10^{-11}}{\log_{10} \frac{(12)\,(14.5) - 0.581}{0.581}} = 1.406 \times 10^{-8} \text{ farads/mile}$$

The capacitive susceptance, b, is given by[6]

$$b = 2\pi fC$$

---

[4] R. M. Kerchner and G. F. Corcoran, Alternating Current Circuits, (2d ed., N.Y., N.Y.: John Wiley, 1943), p. 387.

[5] Value of 14.5 is a typical value. See R. W. Robbins and F. S. Rothe, G.E. Network Analyzers, (Schenectady, N.Y.: Apparatus Department, General Electric Company, 1950), p. 23.

[6] R. M. Kerchner and G. F. Corcoran, op. cit., p. 390.

where

$$f = \text{frequency} = 60 \text{ cycles/sec for power systems}$$

$$b = 2\,(60)\,\pi\,(1.406 \times 10^{-8}) = 5.3 \times 10^{-6} \text{ mho/mile/phase}$$

$$Y = jb = j\,5.3 \times 10^{-6} \text{ mho/mile/phase}$$

The inductive reactance/mile/phase, X, may be computed from the formula[7]

$$X = j \left[0.2794 \log_{10} \frac{2D}{2r} \right] \left[X \text{ internal} \right]$$

The inductive reactance/mile for the line under study was found to be 0.717 ohm/mile/phase.

The 60cps resistance per mile per phase at 50°C may be found from resistance tables to be 0.1185 ohms per mile per phase.

If the receiving end voltage at Albuquerque is 66,400 volts, i.e., $\frac{115{,}000}{\sqrt{3}}$, the voltage at Point A is the sum of the 66,400 plus the line drop between Albuquerque and city A. The drop is equal to the product of the receiving end current times the impedance of the line, Z_r. The receiving end current in this case is equal to the load current at the assumed 90 per cent power factor plus the current through the capacitive shunt in the "Pi" circuit, $\frac{Y}{2}$.

$$Z_r = (r + jx)\,(\text{distance}) = (0.1185 + j\,0.717)\,(99)$$

$$= 11.73 + j\,70.98 = 71.8 \underline{/80.6^\circ}$$

$$I_r = I_{load} + I_{Y_2} = \frac{kw}{KV\,(\sqrt{3})(\text{Power Factor})} \underline{/-25.8^\circ} + \frac{Y\,E}{2\sqrt{3}}\,(\text{miles})$$

$$= \frac{96{,}870}{115\,(\sqrt{3})\,(0.90)} \underline{/-25.8^\circ} + \frac{j\,5.3 \times 10^{-6}}{2}\,\frac{115{,}000}{\sqrt{3}}\,(120)$$

---

[7] Robbins and Rothe, *op. cit.*, p. 25.

$$I_r = 540 \angle \underline{-25.8^\circ} + 21.1 \angle \underline{90^\circ} = 531 \angle \underline{-23.8^\circ} \text{ amperes}$$

$$I_r Z_r = (531 \angle \underline{-23.8^\circ})\ (71.8 \angle \underline{80.6^\circ}) = 38{,}100 \angle \underline{56.8^\circ}$$

$$= 20{,}800 + j\ 31{,}900 \text{ volts}$$

If the loads of cities A and B are neglected, the voltage at the northwestern New Mexico plant, which is necessary to deliver 115,000 volts at Albuquerque, is found to be

$$E_{nw} = E_{Alb} + E_{drop} = E_{Alb} + I_r\, Z_r$$

I_r in this case is the Albuquerque load current $379 \angle \underline{-258^\circ}$ amperes plus the capacitive charging current of the line, $21.1 \angle \underline{90^\circ}$ amperes.

$$I_r = 341 - j\ 165 + j\ 21.1 = 341 - j\ 143.9 = 370 \angle \underline{-22.9^\circ}$$

$$Z_r = (0.1185 + j\ 0.717)\ 120 = (0.726 \angle \underline{80.6^\circ})\ 120$$

$$= 87.12 \angle \underline{80.6^\circ} \text{ ohms}$$

$$I_r Z_r = (370 \angle \underline{-22.9^\circ})\ (87.12 \angle \underline{80.6^\circ}) = 32{,}230 \angle \underline{57.7^\circ} \text{ volts}$$

$$= 17{,}200 + j\ 27{,}270 \text{ volts}$$

$$E_{nw} = (66{,}400 + j\ 0.0) + (17{,}200 + j\ 27{,}270) = 83{,}600 +$$

$$j\ 27{,}270 = 87{,}900 \angle \underline{18.1^\circ} \text{ volts}$$

These voltage values show that the voltage drop of the line would be too large for satisfactory operation. The voltage drop may be lowered, however, by installing capacitors at the receiving end of the line. The fixed charges of the capacitors must be included in the computations for the economic conductor size. The least number of capacitors, and, therefore, the most economical approach, would be achieved by connecting the capacitors in series with the

I_r = 300 /-25.8° + 72.4 /90° = [illegible] amperes

I_rZ = ([illegible]) (72.6 /[illegible]) = [illegible]

= 20,800 + j [illegible] volts

If the load of [illegible] is removed, [illegible] at the [illegible], which is [illegible] 115,000 volts [illegible]

E_s = [illegible]

I_r in this case is the [illegible] current [illegible] amperes plus the capacitive charging current of the line, [illegible] amperes.

I_r = [illegible]

Z_r = ([illegible]) 150 = [illegible]

= 37.15 /[illegible] ohms

I_rZ_r = ([illegible]) = [illegible] volts

= 12,200 + j [illegible] volts

E_s = (66,400 + [illegible]) + [illegible]

= [illegible] volts

These voltage [illegible] the [illegible] of the line would be too large for satisfactory operation. [illegible] be lowered, however, by [illegible] the receiving end of the line. The [illegible] in the computation [illegible]. The [illegible] of capacitors [illegible] would be achieved [illegible] line. The objection to this practice is the high voltages developed across the capacitors during line surges. This disadvantage may be overcome, however, by connecting arcing horns around the capacitors. A high voltage across the capacitors would thus be dissipated by an arc across the horns and the capacitors would not be damaged. The amount of capacitance required would be that quantity which would make the line capacitive impedance equal to the line inductive impedance. The capacitive impedance, therefore, must be (0.717) (120) = 86.04 ohms. The capacitors required to obtain the impedance is

$$C = \frac{1}{2\pi fX} = \frac{1}{2\pi(60)\ (86.04)} = 3.095 \times 10^{-5} \text{ farads}$$

At peak load conditions the KVAR required would be

$$I^2X_c = (379)^2\ (86.04) = 1.236 \times 10^7 \text{ VAR's} = 1236 \text{ KVAR'S}$$

Estimating the installed cost of the capacitors at \$200.00 per KVAR, the total cost would be \$247,200. The fixed charges on this cost would be (2.472×10^5) (0.151) = \$37,327, and the cost per kilowatt-hour would be

$$\frac{3.7327 \times 10^4}{5.912 \times 10^8} = 6.31 \times 10^{-5} = \$0.0000631/\text{kwhr}$$

This value must be subtracted from the left side of the following equation which was used in Section H of this chapter

$$T\text{-}S\ \frac{(m + KB)}{Y}\ Z = 3\frac{Z}{Y}\ \left[(I^2rHS\ 10^{-3}) + \frac{KWG}{r}\right]$$

$$5.937 \times 10^{-4} - 6.31 \times 10^{-5} = 3.065 \times 10^{-3}r + \frac{2.736 \times 10^{-5}}{r}$$

$$r = \frac{0.5306 \pm \sqrt{0.2812-0.3354}}{2(0.5306)}$$

It is seen that the value under the radical sign is negative. This means that the additional cost of capacitors to give satisfactory voltage regulation would make the transmission line and remote generation scheme uneconomical as compared to power generated at the load center.

An alternate plan to the capacitors would be to supply the capacitive KVAR's from the generators at Albuquerque. Excess generating capacity equal to the largest generating unit is kept spinning at the Albuquerque generating plants as described in Section G of this chapter. This excess capacity could be used to supply the capacitance KVAR's to improve the voltage regulation. Such a transmission scheme may present stability difficulties, however. These difficulties may be visualized by reducing the proposed generator and transmission system to a single load and to single generators at both Albuquerque and the remote generating plant. To study these difficulties, the condition of maximum load will be taken for the year 1963 with the proposed transmission line supplying 75,000kw. The loads of cities A and B will be omitted in this stability study. The Albuquerque generators will supply capacitive KVAR's to the transmission line in sufficient quantity to limit the voltage drop to 5 per cent. At these conditions the transmission line will be removed from

$$5.397 \times 10^{-6} - [illegible] = [illegible]$$

$$r = \frac{[illegible]}{[illegible]}$$

It is seen that the value of [illegible] is [illegible] percent. This means that the coaxial cable [illegible] required to give satisfactory voltage regulation would make the [illegible] generation scheme uneconomical as compared with generation at the load center.

An alternate plan is [illegible] to supply the capacitive KVAR's from the generators at [illegible]. [illegible] generating capacity equal to the [illegible] at the Albuquerque generating plants as discussed in [illegible] of this chapter. This scheme is [illegible] would be used to supply the capacitance KVAR's to [illegible]. [illegible] a transmission [illegible] may present stability [illegible]. These difficulties may be visualized by [illegible] transmission system [illegible] a single load and [illegible] Albuquerque and the remote generating plant. In spite of these difficulties, the condition of [illegible] in the year 1965 with the proposed transmission line supplying [illegible] loads of [illegible]. The Albuquerque [illegible] transmission line [illegible] the voltage [illegible] per cent. At these conditions the transmission line will be [illegible] the Albuquerque System to simulate an outage from a line fault and the stability of the remaining Albuquerque System will be investigated.

The Albuquerque System with the proposed transmission line connected is represented by the following diagram:

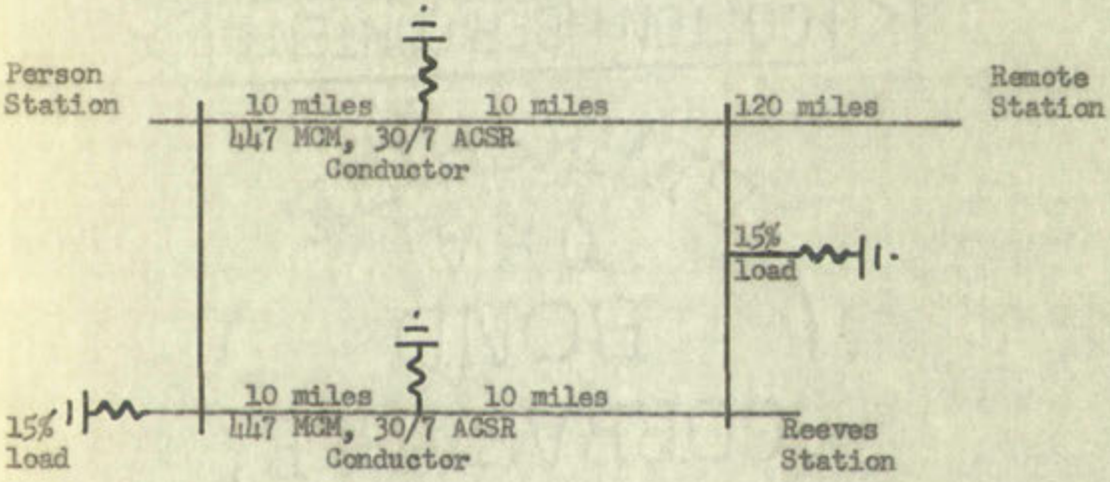


Figure 9. One line diagram, Albuquerque 115kv Electric System and proposed line from northwestern New Mexico

This system may be reduced to the following:

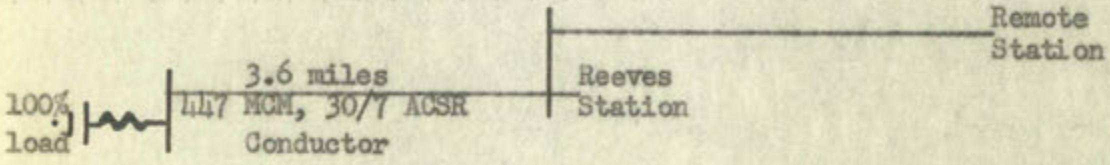


Figure 10. Equivalent one line diagram, Albuquerque 115kv Electric System

The peak load for the year 1963 is 226,000kw. With 75,000kw

being supplied from the remote transmission line, the Albuquerque generation load is 151,000kw.

Since the line is short, the charging and conductance current is neglected. The receiving end current is then equal to the sending end current and is found as follows

$$I_L = \frac{\text{KVA}}{\sqrt{3}\ (\text{KV})\ (\text{power factor})} = \frac{226{,}000}{\sqrt{3}\ (115)\ (.9)} = 1262 \text{ amp}$$

The line impedance from the Albuquerque generators to the load is:

Resistance for 447 MCM, 30/7 ACSR conductor = 0.216 ohms/mile.

Inductive reactance for the above conductor at 19.6 feet equivalent spacing = 0.780 ohms/mile.

$Z = 3.6\ (0.216 + j\ 0.780) = 0.756 + j\ 2.73.$

The impedance of the step-down transformer at the load is equivalent to the impedances of all the load transformers connected in parallel. On a 115,000 volt base this impedance is assumed to be 4.61 ohms, i.e., $X_t = 4.61$ ohms. The resistance is neglected in transformers greater than 500 KVA capacity because the inductive reactance is very large compared to the resistance.[8]

For these conditions the impedance between the load and the 115,000 volt bus at the Albuquerque generating station is

$$Z_{B-L} = 0.756 + j\ 2.73 + 4.61 = 0.756 + j\ 7.34 = 7.38\ \underline{/84.1^\circ}$$

---

[8] J. E. Hobson and R. L. Witzke, "Power Transformers and Reactors," Electrical Transmission and Disbribution Reference Book, (3d ed.; East Penn. Westinghouse Co., 1944), p. 401.

The Albuquerque generating station 115,000 volt bus is taken as the reference voltage, i.e., $V_s = \frac{115,000}{\sqrt{3}} = 66,400$ volts. The load voltage then becomes

$V_L = (66,400 + j\,0.0) - (Z_{B-L})\ \ (I\ \underline{/\theta})$ where θ = load power factor angle

$$\begin{aligned} V_L &= 66,400 - (7.38\ \underline{/84.1^\circ})\ (1262\ \ \underline{/-25.90^\circ}) \\ &= 66,400 - 9314\ \ \underline{/58.2^\circ} = 62,100\ \ \underline{/-7.33^\circ} \end{aligned}$$

The load current supplied by the transmission line from the northwestern area of New Mexico is

$$I_{T-L} = \frac{75,000}{115\sqrt{3}\ \ (0.9)} = 418\ \ \underline{/-25.90^\circ}$$

The northwestern New Mexico transmission line impedance from page 43 is 87.12 $\underline{/80.6^\circ}$ ohms. To limit the voltage drop to 5 per cent the "effective" line power factor can be found from the equality

$$\begin{aligned} E_{nw} &= \sqrt{V_S + IZ\cos(\theta_1 + \theta_2)\ \ ^2 + \ \ I\,Z\sin(\theta_1 + \theta_2)\ \ ^2} \\ &= \sqrt{V_S^2 + 2V_S\,I\,Z\cos(\theta_1 + \theta_2) + I^2\,Z^2} \end{aligned}$$

where

E_{nw} = voltage on transmission line at the remote generating station

V_S = Albuquerque generating station bus voltage = $\frac{115KV}{\sqrt{3}}$

I = magnitude of line current

Z = magnitude of the line impedance = 120 (0.1185 + j 0.717) = 87.12

θ_1 = power factor angle

θ_2 = impedance angle = 80.6°

The equation now becomes

$$E_{nw} = \sqrt{4.41 \times 10^9 + 1.157 \times 10^7 \, I \cos (\theta_1 + 80.6^\circ) + 7.6 \times 10^3 \, I^2}$$

If the value of $(I \cos \theta_1)$ is held constant, to supply the 75,000kw, and θ_1 is varied, a curve of E_{nw} versus θ_1 can be drawn. The minimum power factor angle, θ_1, which corresponds to the voltage representing maximum line drop, can be selected from the curve. For the study under discussion the angle was found to be 18.5°. This means that the transmission line current must be

$$\frac{418 \cos 25.9^\circ}{\cos 18.5^\circ} = 398 \;\underline{/18.5^\circ} \text{ amperes}$$

The Albuquerque generators must supply all the capacitive part of the current. Therefore, the Albuquerque generator supply to the transmission line

$$418 \sin 25.9^\circ + 398 \sin 18.5^\circ = 376 \;\underline{/90^\circ} + 126 \;\underline{/90^\circ} \text{ amperes}$$

The load current supplied by the Albuquerque generators on a 115,000 volt base is

$$\frac{226{,}000\text{KVA} - 75{,}000\text{KVA}}{115 \; (\sqrt{3}) \; (0.9)} = 843 \;\underline{/-25.9^\circ} = 758 - j\,368 \text{ amperes}$$

The total current supplied by the Albuquerque generators is

$$758 - j\,368 + j\,502 = 758 + j\,134 = 770 \;\underline{/10^\circ} \text{ amperes}$$

The impedance of the generator is equivalent to the impedance of all Albuquerque generators connected in parallel. For the present illustration this equivalent impedance is assumed to be 7.5 ohms on a

The equation now became

$E_m = \sqrt{[illegible]}$

If the value of [illegible] is [illegible] and 75,000kw, and [illegible] varied, [illegible]. The minimum power factor angle, θ, [illegible] representing the maximum line drop, can [illegible]. For the study under discussion the angle was found to be [illegible]°. This means that the transmission line current must be

$\frac{128 \cos [illegible]}{\cos [illegible]}$ = [illegible] amperes

The Albuquerque generators must supply all the reactive part of the current. Therefore, the Albuquerque generators supply to the transmission line

118 sin [illegible] - [illegible] = [illegible] amperes

The load current supplied by the Albuquerque generators on a 115,000 volt base is

$\frac{226,000\text{KVA} - 75,000\text{KW}}{115\ (\sqrt{3})\ (0.9)}$ = 841 [illegible] = [illegible] amperes

The total current supplied by the Albuquerque generators is

758 - j 360 + j 302 = 758 - j [illegible] = [illegible] amperes

The impedance of the generator is equivalent to the impedance of all Albuquerque generators connected in parallel. For the present illustration this equivalent impedance is assumed to be [illegible].

115,000 volt base, i.e., $X_d = 7.5$ ohms. If the step-up transformer at the generator is assumed to have the same impedance as the step-down transformer at the load then the total impedance from the internal voltage of the generators and the Albuquerque 115,000 volt bus is

$$j\,7.5 + 4.7 = j\,12.2 \text{ ohms}$$

The generator internal voltage is then

$$E_g = (66{,}400 + j\,0.0) + (770\ \underline{/10^\circ})\,(12.2\ \underline{/90^\circ}) = 65{,}500\ \underline{/8.1^\circ}$$

The electrical angle between the generator voltage and the load voltage is

$$\phi = 8.10^\circ + 7.33^\circ = 15.43^\circ$$

The maximum synchronizing power[9] is found by the formula

$$P_m = \frac{151{,}000\text{KVA}}{\sin 15.43^\circ} = 567{,}000\text{KVA}$$

The "swing" curve is found by the same formula. The curve for the problem is shown in Figure 11.

The system is initially operating at the 15.43° on the abscissa of the stability curve. If the transmission line to northwestern New Mexico is suddenly disconnected from the system, the Albuquerque generators immediately have 75,000kw to pick up. This increase is shown by the line at twenty-four degrees. The criteria for stability is that the area blocked in above the curve between 15.43° and 24° must not be greater than the area under the curve between 24° and $(180^\circ - 24^\circ) = 156^\circ$. A visual inspection of the curve

---

[9] Maximum synchronizing power is defined as the power available to restore stability after a transient condition. The maximum synchronizing power is equal to the maximum transfer of power from the generators to the load.

115,000 volt bus, i.e., X_s = 7.5 ohms. If the [illegible] at the generator is assumed to [illegible] the [illegible] down the [illegible] of the load [illegible] terminal voltage of the generator [illegible] 115,000 [illegible] bus is

$\sqrt{7.5 + 1.7} = \sqrt{12.2}$ [illegible]

The generator internal voltage is then

$E_g = (6,\!400 + [illegible]) [illegible]$

The electrical angle between the generator internal and the load voltage is

$\delta = [illegible] = 15.43°$

The maximum synchronizing power [illegible] is

$P_m = [illegible] = 137,000,000$ [illegible]

The "[illegible]" curve [illegible] The curve for the problem is shown in Figure [illegible]

The system is [illegible] δ = 15.43° [illegible] the abscissa of the stability curve.[9] [illegible] transmission line [illegible] western New Mexico is suddenly disconnected from the system, the Albuquerque generators [illegible] This increase is shown by the line [illegible] for stability is that the area [illegible] between [illegible] 15.43° and 24° [illegible] greater than the area under the curve between 24° and (180° − 24°) = 156°, [illegible] of the curve

---

[9] [illegible] synchronizing power is defined as [illegible] able to restore stability after a [illegible] synchronizing power [illegible] the generators [illegible] load.

shows this system would retain stability if it were required only to pick up the additional 75,000kw. When the line to the remote station is suddenly disconnected from the Albuquerque System, the Albuquerque generators are also required to change power factor quickly due to the leading power factor current the generators have been supplying to the northwestern New Mexico line. The generator voltage will become

$$E_g = 66{,}400\ \underline{/0^\circ} + (12.2\ \underline{/90^\circ})\ (1262\ \underline{/-25.9^\circ}) = 74{,}400\ \underline{/10.75^\circ}$$

The electrical angle between the generator voltage and load, therefore, increases $10.75^\circ - 8.10^\circ = 2.65^\circ$. This angle is added to the load angle and a vertical line is drawn to the load curve. This angle, $24.0^\circ + 2.65^\circ = 26.65^\circ$, intersects the load curve at approximately 254,000kw. The transient power drawn from the system is represented by the area "abca" in Figure 11. The system will regain stability if the area "abca" is less than the area "$dP_m db$." The point d is on the curve at $180^\circ - 26.65^\circ = 153.35^\circ$. A visual inspection of Figure 11 shows that this system will regain stability. If the visual inspection did not give an obvious answer, the areas could be found by integrating the curve between the indicated limits and comparing the two areas.

The above analysis shows, for the circuit values and assumption made, that the excess generating capacity at Albuquerque could be used to supply capacitive KVAR's to the transmission line from the remote generating station. These capacitive KVAR's could be

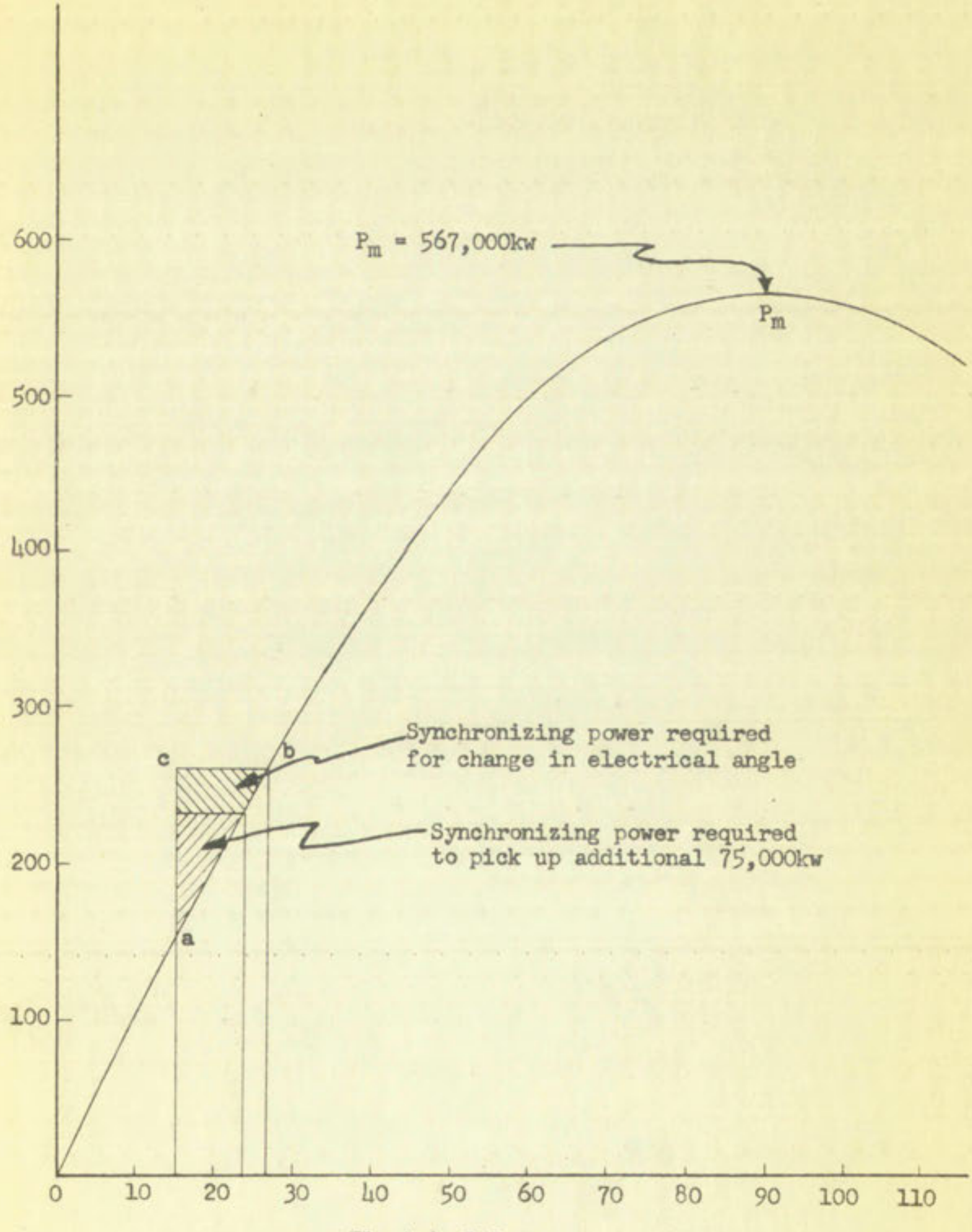


Figure 11. Swing Curve for Albuquerque System

supplied in quantity to limit the transmission line voltage drop to 5 per cent and an outage of the northwestern New Mexico transmission line would not cause instability in the Albuquerque System. Therefore, the analysis of Section H of this chapter indicates the conductor sizes for the equal Albuquerque cost for generation at either Albuquerque or northwestern New Mexico and also the conductor size that will give the greatest economic advantage. Supplying the large quantity of capacitive KVAR's to the transmission line does not require additional generating capacity on the line at Albuquerque because the Albuquerque generators change power factors to supply most of the KVAR's without exceeding the KVA ratings of the generators. The spinning excess capacity is utilized to supply the KVA not provided by changing the power factor.

J. Other Voltage Considerations

As stated in the first paragraph of Section H of this chapter, a voltage of 115,000 volts was selected because it best illustrated the use of the formulas developed in Chapter III, and it best illustrated the determination of transmission line difficulties. A higher voltage would not present the voltage regulation difficulties as vividly as did the 115,000 volts. If a higher voltage were to be selected for the study, a "rule of thumb" which has been widely used by utilities in the past would indicate that a voltage three times the magnitude of existing lines be studied. For the Public Service supplied in quantity to fill the requirements. If the voltage drop was [illegible] 5 per cent and not [illegible] the Farmington-Albuquerque [illegible] line would not cause instability on the Albuquerque system. Therefore, the analysis of Section 3 of this chapter that determined the capacitor sizes for the equal Albuquerque and Farmington voltages of either Albuquerque or Northwestern New Mexico and also the reactor sizes that will give the greatest economic advantage. Supplying the large quantity of capacitive KVAR's to the Farmington area does not require additional generating capacity on the line at Albuquerque because the Albuquerque generators [illegible] part of the KVAR's [illegible] the KVA [illegible] The [illegible] is required to supply the KVA not provided by changing the power factor.

4. Other Voltage Consideration

As stated in the first paragraph of Section 3 of this chapter, a voltage of 115 KV value was selected because it [illegible] the use of the Farmington [illegible] in Chapter [illegible] and [illegible] illustrated the determination of [illegible] KVAR values. A higher voltage would [illegible] vividly as did the 115,000 volts. [illegible] selected for the study [illegible] by utilities in the [illegible] a voltage [illegible] the magnitude of [illegible]

Company of New Mexico this voltage would be 3(115,000) = 345,000 volts. The loads of the Public Service Company of New Mexico would not justify the investment required for a transmission line of this voltage. Also, recent studies have indicated that 230,000 volt transmission lines are often more economical if due consideration is given in the cost analysis to dual lines or excess generating capacity which provide reliability.[10]

The 230,000 volt transmission line has been studied by the formulas developed in Chapter III. In these studies the following assumptions were made:

Peak line loading = 160,000kw
Line load factor = 75 per cent
System load factor = 65 per cent
Length of line = 120 miles
Cost of maintenance = $200.00 per mile per year
Annual fixed charges = 15.1 per cent
Increase in cost of Albuquerque generation due to good load factor on transmission line = $0.0025 per kwhr
Cost of Albuquerque generation without proposed transmission line = $0.0049
Cost of generation at northwestern New Mexico plant = $0.0040
Power factor of load = 90 per cent
Square root of the mean square current = average line load current
Cost of the 230,000 volt line without conductor = $18,000 per mile
Peak system load = 221,000kw

With these conditions the most economical conductor was found to be the largest size attainable, but the scheme was found uneconomical.

---

[10] Electrical World, "Utilities Offer 230KV Plan for Five-State Rocky Mountain Area," November 30, 1959, pp. 86-89.

That is, for the above conditions it would be more economical to install additional generating capacity at Albuquerque than to build a 230,000 volt transmission line from a generating plant located 120 miles from Albuquerque. A change of some of the above assumptions, however, could change this result and make the 230,000 volt line a greater savings than a 115,000 volt line. No further pursuit of this subject will be made, however, since the general methods of procedure and the use of formulas developed in this thesis have been fully illustrated.

K. Conclusions

The Public Service Company of New Mexico can economically build a 115,000 volt transmission line 120 miles long from Albuquerque to northwestern New Mexico to serve the Albuquerque system load. This conclusion is based on prices and assumptions given in Chapter IV of this paper. The transmission line must be supplied capacitive KVAR's from Albuquerque to give the line satisfactory voltage-drop characteristics and these KVAR's must be supplied at no additional investment cost. If additional investments were required for installing capacitors, the plan would be uneconomical due to the annual fixed charges on the capacitors. The capacitive KVAR's can be supplied by Albuquerque generators which are already supplying load not provided by the transmission line and which are kept running for emergency stand-by capacity. Supplying the KVAR's from the Albuquerque generators would require no additional investment to maintain

desired transmission line voltage characteristics. The leading power factor required of the generators supplying the capacitive KVAR's would cause no stability difficulties in case the transmission line to the remote generating plant were disconnected from the Albuquerque system. The electrical angle between the generator and load would change only a slight amount and the 75,000kw being supplied by the transmission line could be picked up by the Albuquerque generators without stability difficulties. These conclusions are based on the assumptions and calculations of the previous section of this paper. All calculations were made for 900 million circular mills conductors in the proposed transmission line because that is the size of conductor which makes the cost of the northwestern New Mexico generated power equal the cost of power from Albuquerque generators.

The transmission voltage for the line studies was selected as 115,000 volts on the basis of economy of connection to existing transmission systems and for illustrative purposes as explained in previous sections of this Thesis. A higher voltage would give better voltage regulation but the installation cost, and thus the fixed charges cost per kilowatt-hour, would increase. Computations which have been made for voltages above 115,000 volts have shown these voltages to be uneconomical. The results would be affected considerably, however, by differences in the various load and cost values which were used.

desired transmission line voltage [illegible]. The [illegible] factor required of the generators, [illegible] would cause no [illegible] to the remote generating plant [illegible] system. The electrical [illegible] between the generators and [illegible] would change only [illegible] by the transmission line [illegible] generators without [illegible]. [illegible] based on the assumptions and [illegible] of this paper. [illegible] this conditions in the [illegible] the size of conductor which [illegible] Mexico generated [illegible] generators.

The transmission voltage for the line studies was selected as 115,000 volts on the basis of economy and conformity to existing transmission systems and for illustrative purposes [illegible] previous sections of this thesis. A higher voltage would give better voltage regulation [illegible], and [illegible] fixed charges [illegible]. [illegible] which have been [illegible] for voltages above 115,000 volts [illegible] voltages to be uneconomical. The results would [illegible] considerably, however, by differences in the [illegible] which were used.

APPENDIX I

KEY TO FORMULA SYMBOLS OF CHAPTER III

A	Peak load at a known time, kw
B	Cost per mile in dollars of line less conductor
C	Generation cost in dollars per kwhr at load center
D	Total cost per mile of line in dollars
E	Cost of conductor per mile in dollars
F	Cost in dollars of fixed charges per kwhr
G	Constant for pounds per mile conversion to resistance per mile
H	Hours per year
I	Average current flow in amperes
K	Per cent of original cost for annual fixed charges
L	Cost of line power losses per kwhr
M	Annual transmission line maintenance cost
m	Annual transmission line maintenance cost per mile per kwhr
P	Peak load in future in kw
R	Total resistance of transmission line in ohms per phase
r	Resistance of line per mile per phase
S	Generation cost per kwhr at remote generating site
T	Total cost per year per kwhr at Albuquerque of remotely generated power
W	Cost per pound of conductor
X	Total amount of fixed charges in dollars
Y	Total kwhr per year
Z	Length of line in miles

APPENDIX II

CONSTANTS OF WEIGHT TIMES RESISTANCE FOR VARIOUS CONDUCTORS

ACSR 26/7 Stranding

Size MCM	Weight #/mile	Resistance ohms/mile	Constant Wt x ohms
266.8	1939	0.3850	747
300.0	2179	0.3420	745
336.4	2446	0.3060	748
397.5	2888	0.2590	748
477.0	3468	0.2160	749
556.5	4045	0.1859	751
605.0	4395	0.1720	755
	Average Constant, (wt) (ohms)		747.6

ACSR 30/7 Stranding

300.0	2473	0.3420	846
336.4	2783	0.3060	850
397.5	3288	0.2590	851
477.0	3946	0.2160	851
500.0	4122	0.2060	849
556.5	4604	0.1859	855
	Average Constant, (wt) (ohms)		850

Hard-drawn Copper, Stranded

1/0	1720	0.5502	946
2/0	2169	0.4365	947
3/0	2736	0.3462	947
4/0	3450	0.2745	947
250	4076	0.2323	947
300	4891	0.1936	947
350	5706	0.1660	947
400	6521	0.1452	947
450	7336	0.1291	947
500	8151	0.1162	947
550	8966	0.1056	947
600	9781	0.0968	947
	Average Constant, (wt) (ohms)		947

APPENDIX III

GENERATING CAPACITY

Existing Generating Capacity

1. Prager Station	33,000kw
2. Person Station	125,000kw
3. Reeves Station[1]	50,000kw
4. Santa Fe Station	23,000kw
5. From USBR Tie	15,000kw
6. From Plains Co-op	15,000kw
TOTAL	253,000kw

Computation of Excess Generating Capacity

Year	1959	1960	1961	1962
Generating Capacity, mw	253	303[2]	303	303
Peak Load[3]	145	162	181	202
Excess Capacity[4]	108	147	122	101

Year	1963	1964	1965	1966
Generating Capacity, mw	303	365[2]	365	428[2]
Peak Load	226	252	281	315
Excess Capacity	77	113	84	113

---

[1] 40mw generator with 50mw peak capacity.

[2] New generator installed in Albuquerque or additional transmission lines from the northwestern New Mexico plant provides the additional capacity.

[3] From the table on Page 27.

[4] High excess capacities will probably be used by the USBR or the Plains Co-operative.

APPENDIX IV

COMPUTATION OF FIXED CHARGES PERCENTAGE

An investment of an electric utility company must, as a minimum, either EARN or SAVE enough money to offset all annual fixed charges, including income return on the property, over and above operation and maintenance expense associated with the investment. The following tabulation shows the elements involved in the fixed charges and the approximate percentage annual charges of each element in terms of investment dollars.

Depreciation--recovery of investment	3.0%
Advalorem property tax--assessed at 4% on 50% of value	2.0%
Net rate of return on company rate base--or total investment as fixed by the Public Service Commission	6.05%
State and Federal income tax[1]	4.05%
TOTAL	15.10%

---

[1] Interest on borrowed money is deductible for income tax purposes, and assuming that 60 per cent of the investment dollar is borrowed at 4 per cent interest, then the interest deduction is 0.60 (0.04) = 2.4% which is deductible from the allowed earnings.

Earnings are as allowed after income tax. Therefore, it is necessary to compute the gross earnings necessary to return 6.05% after taxes, except that interest on borrowed money is deductible for tax purposes. Thus, to compute the annual income tax increment to be assigned the investment dollar, a composite Federal and State income tax rate of 52.5% is assumed and the following computation is made:

$$\frac{6.05 - 2.4}{47.5} = 7.7\% \text{ gross earning required}$$

The per cent of investment required for the income tax increment is:

$$7.7\ (52.5) = 4.05\%$$

APPENDIX IV

[illegible]

An investment of [illegible] must earn, as a minimum, either [illegible] charges, including [illegible] operation and [illegible] The following [illegible] charges and the [illegible] ment in terms of [illegible]

Depreciation [illegible]
Advalorem property [illegible]
[illegible] of value [illegible]
Net rate of [illegible]
[illegible]
[illegible]
State and Federal income tax[illegible]
TOTAL [illegible]

---

[1] Interest on borrowed money is deductible for income tax purposes, and assuming that [illegible] borrowed at [illegible] per cent interest, [illegible] (0.04) = 2.40 which is [illegible]

Earnings are [illegible] after income tax. Therefore, it is necessary to compute the gross earnings necessary to return [illegible] after taxes, [illegible] for tax purposes. [illegible] to be assigned the investment [illegible] income tax rate of [illegible] is made:

[illegible]

The per cent of investment required [illegible]

[illegible]

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