7-1936

Short-Circuit Study of the Norris-Wheeler Transmission Line

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University of Tennessee - Knoxville

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I am submitting herewith a thesis written by H. H. Gnuse Jr. entitled "Short-Circuit Study of the Norris-Wheeler Transmission Line." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Arts, with a major in Electrical Engineering.

J.G. Tarboux, Major Professor

We have read this thesis and recommend its acceptance:

E.J. Fabian

Accepted for the Council:

Dixie L. Thompson

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)
To the Committee on Graduate Study:

I submit herewith a thesis written by H. H. Gnuse, Jr. and entitled "Short-Circuit Study of the Norris-Wheeler Transmission Line", and recommend that it be accepted for eighteen quarter hours credit in partial fulfillment of the requirements for the degree of Master of Arts, with a major in Electrical Engineering.

[Signature]
Major Professor

At the request of the Committee on Graduate Study, we have read this thesis, and recommend its acceptance.

[Signature]
E. S. Fabian

Accepted by the Committee

[Signature]
Chairman
A decision to construct a powerhouse or substation as an addition to a power system immediately calls for an answer to several questions which affect the cost and design of the structure. Some of these questions are:

1. What circuit breaker capacity is necessary to adequately protect this installation?

2. What rating should the current transformers have to prevent saturation during subjection to maximum fault currents?

3. What size insulators and weight of bus structure are necessary to provide sufficient strength to withstand ice, wind, and short-circuit stresses?

These questions can be answered only when the magnitude of the maximum fault current is known.

It was for the determination of these fault currents at points along the Norris-Wheeler, 154 KV transmission line and to facilitate their computation on future radial feeders extending from this line that this thesis was prepared. A brief discussion of the theoretical basis of the computations and methods of application of the results is included in order to qualify the results presented.

The determination of maximum fault currents in a power system necessitates complete information of the system generating capacity, generator impedance values, transformer bank capacities and impedances, and finally, the transmission line characteristics. This information for the southeastern interconnected power system has been compiled and is presented.
SHORT CIRCUIT STUDY
OF
NORRIS-WHEELER TRANSMISSION LINE

A THESIS

Submitted to the Graduate Committee of
The University of Tennessee
in
Partial Fulfillment of the Requirements for the degree of
Master of Arts

by

H. H. GNUSE, JR.

July, 1936
in this thesis in the form of charts, diagrams, and tabulations. These constants should be of great value for future studies, especially in such cases where system reductions worked up for this thesis can be used. System reductions to various points are indicated, although most of the actual computations have been omitted due to the great length and maze of figures involved.

Unbalanced faults were solved by the method known as "Symmetrical Components" which was first developed by Dr. C. L. Fortescue in 1918. Liberal use has been made for this thesis of the recently published text on "Symmetrical Components" written by Mr. C. F. Wagner and Mr. R. D. Evans of the Westinghouse Electric and Manufacturing Company.

The author wishes to acknowledge information furnished by Mr. C. F. Wagner of the Westinghouse Electric and Manufacturing Company, and also information made available by the Tennessee Valley Authority through their files and through a report on a "TVA Stability Study" made for the Tennessee Valley Authority by the Jackson and Moreland Engineers of Boston, Massachusetts.
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SHORT-CIRCUIT STUDY OF NORRIS-WHEELER TRANSMISSION LINE

CHAPTER I

RESULTS OF STUDY

The short-circuit study of the Norris-Wheeler transmission line as presented in this thesis was conducted on the basis of several simplifying assumptions which do not appreciably affect the accuracy of the work. These assumptions, which greatly facilitate a mathematical solution and, in fact, make a mathematical solution possible from a practical standpoint, are those which are normally employed when use is made of a direct-current calculating board. Most of these assumptions, as can be noticed from the following tabulation, tend to increase the calculated short-circuit currents over their actual value, thus keeping the results on the safe side as far as the purpose for which they are to be used is concerned.

1. The system is fully loaded—that is, all available generating capacity is on the line.
2. All of the generated e.m.f.s. are of equal magnitude and in phase.
3. All of the resistances of the circuit are neglected, only the reactance of the impedances being used.
4. All of the shunt-impedance branches, such as the equivalent circuits for representing magnetizing currents of transformers and charging currents of transmission lines, as well as equivalent impedance branches representing normal loads, are neglected.
5. The mutual impedance between lines is neglected.
6. The fault resistance is negligible.
7. The TVA system interconnections will be as shown in Fig. 16a,
and Fig. 16b, included in the appendix.

The results obtained from this study are presented in a series of charts and diagrams, these forms being thought preferable to tabulated data since they present comparisons and relative values much more clearly although not quite as accurately as would tabulated information. Following is an explanation of the content and suggested use of each of these charts and diagrams.

Fig. 1. This series of curves presents the values of reactance for various types of fault plotted against miles from Wheeler. The reactances are expressed as a percentage on 200,000 kv-a. and also on 100,000 kv-a. bases. The indicated reactances are based on the symmetrical component method of short-circuit computation and consist, for the various types of faults, of the following component reactances, each reduced to the fault point in question.

For:

a. Three phase fault--positive sequence reactance only.

b. Phase-to-phase fault--sum of positive and negative sequence reactances.

c. Single phase-to-ground fault--sum of positive, negative, and zero sequence reactances.

d. Two phase-to-ground fault--sum of positive and parallel equivalent of negative and zero sequence reactances.

These curves were constructed so that either initial short-circuit currents or short-circuit currents after a definite interval of time could be obtained for faults on the Norris-Wheeler line or for faults on radial feeders. For faults on the main line, the reactance values obtained from
Equivalent Percent Reactance
for
Points along Wheeler Norris 154 Kv Line
(for use with Standard Decrement Curves)

Location of Fault - Miles from Wheeler

240 120
200 100
160 80
120 60
80 40
40 20
24 and
30

3Φ Short Circuit
0 to 0 Short Circuit
2Φ to Ground Short Circuit
1Φ to Ground Short Circuit

Wheeler
Norris
Short-Circuit Decrement Curves
for
Synchronous Machines

Notes:
1. System reactance must be based on connected synchronous kv-a.
2. Curves are based on $T_{do} = 5$ sec. For other values of $T_{do}$, multiply actual time by $\frac{T_{do}}{5}$ to get equivalent time to use in curves.

Method of Use:
1. For Three-Phase Short: Use system reactance to point of fault.
2. For Line-to-Ground Short: Use sum of positive, negative, and zero sequence reactances, and multiply ordinates by 3.
3. For Line-to-Line Short: Use sum of positive, and negative sequence reactances, and multiply ordinates by $\sqrt{3}$.

'Plotted from data presented by C. F. Wagner, Westinghouse Electric Co.
Short-Circuit Decrement Curves
for Synchronous Machines

Notes:
1. System reactance must be based on connected synchronous kva.
2. Curves are based on 120 sec. For other values of T, divide actual time by 120.
3. Seconds refer equivalent time to use in curves.

Procedure for Use of Curves:
1. Three-Phase Short: Use system reactance to point of fault.
2. For Line-to-Ground Short: Use sum of positive, negative, and zero sequence reactances, and multiply ordinates by 3.
3. For Line-to-Line Short: Use sum of positive and negative sequence reactances, and multiply ordinates by 3.5.

*Plotted from data of C.E. Wagner;
Westinghouse Elec. & Mfg. Co.*
Fig. 1 can be used directly with the decrement curves to obtain current values. For faults on radial feeders, the reactance values of the feeder must be added to the system reactance as obtained from Fig. 1 for the point where the radial feeder taps onto the main line, and the total reactance then referred to the short-circuit decrement curves, Figs. 2 and 3. The reactances must be on the same kv-a. base, and proper sequence feeder reactances must be used for the type of fault being considered. Examples of such computations are given in the included discussion of "Circuit Breaker Application."

The short-circuit decrement curves, Figs. 2 and 3, were included for convenience in obtaining short-circuit currents after definite intervals of time. As indicated on the figures, these curves were plotted from Westinghouse Electric and Manufacturing Company data prepared by C. F. Wagner of that company. Discretion must be used in applying these curves. A discussion of their limitations and method of use is given under "Theoretical Basis for Computations."

Fig. 4. The curves of Fig. 4 show the maximum initial asymmetrical fault currents for the various types of faults plotted against miles from Wheeler. A knowledge of the magnitude of these currents is of value in the selection of current transformers and in the design of bus structures. The current transformers must have sufficient core to prevent saturation during these maximum conditions especially if they excite relay apparatus. A discussion of the effect of fault currents on bus structures is presented in a separate chapter of this thesis.

It will be noticed from these curves that the three phase short-circuit
Initial Maximum Line Currents

Fault on 154 kV Wheeler-Norris Line

3-phase Short Circuit
0-to-0 Short Circuit
2-phase to-ground Short Circuit
1-phase to-ground Short Circuit

Location of Fault - Miles from Wheeler
produces the highest line currents at all points except points within five miles of Wheeler. Within this distance the two phase-to-ground and the single phase-to-ground faults each give higher line current values than the three phase fault. This is due to the fact that no neutral reactor is, at present, used in the transformer bank at Wheeler. However, such a reactor is planned when future units are installed. This will bring the single and double line-to-ground fault currents considerably under the three phase value.

Fig. 5. The curves of Fig. 5 present a breakdown of the curves of Fig. 4. On this sheet are shown the maximum initial asymmetrical line currents flowing from each end of the line for faults at various distances from Wheeler. There is also included on this sheet a tabulation which shows the distribution of the current at each end of the line, expressing the magnitude of the current from each source as a percentage of the total current feeding from that end of the line.

The information presented in Fig. 5 substantiates the previous statement that the high value of the single and double phase-to-ground fault currents is due to the solidly grounded neutral of the Wheeler transformer bank. It is evident from these curves that these fault currents have higher values than three phase fault currents only when considering the current from the Wheeler end of the line for a fault close to the Wheeler bus. The tabulation indicates that for single and double phase-to-ground faults, the percentage of this current that actually comes from the Wheeler substation is greater for these faults than for the other types of faults.

These curves should be of particular value in determining the proper
settings for relays. Another use of these curves and tabulated data is as a guide in selecting a proper kv-a. base for use with the standard short-circuit decrement curves. This use is explained and illustrated in the discussion of "Theoretical Basis for Computations."

Fig. 16. These drawings, included in the appendix, are single line diagrams of the interconnected power systems of this region. They contain the positive, negative, and zero sequence transformer and transmission line constants. The results shown on Figs. 1, 4, and 5 were obtained by reducing this system. These diagrams and the tabulated data on generator constants that are included in the appendix should be of considerable value for similar studies on other parts of the system.

Fig. 19. This drawing, included in the appendix, gives system reduction constants for the positive, negative, and zero sequences. Reductions are indicated to various points where generating capacities and interconnections may be increased in the future. When such additions are made, considerable time and effort can be saved by using these reductions with the new system constants. It is evident that such a procedure would eliminate the necessity of reducing the complete system for future studies.
CHAPTER II

THEORETICAL BASIS FOR COMPUTATIONS

Symmetrical Components.

The method of symmetrical components has been found to be the only practical method of solution of unbalanced electrical circuit problems. The fundamentals of this method are quite simple, yet are very powerful as an analytical tool. This simplicity lies in the fact that, although this method requires the resolution of three vectors into nine vectors, the resolution results in three symmetrical systems, each of which can be treated as a balanced polyphase system and solved by reducing the constants and voltages to per phase values and solving on a single phase basis. Of fundamental importance is the fact that, in symmetrical circuits, the currents and voltages of the different sequences do not react upon each other; currents of each sequence producing only voltage drops of their particular sequence.

The three symmetrical systems are known as the positive, negative, and zero-sequence systems, each of which is illustrated by vectors in Fig. 6. The positive-sequence system is composed of the vectors \( E_{a1}, E_{b1}, \) and \( E_{c1} \), which are of equal magnitude and are displaced 120 degrees relative to each other, the sequence of maxima occurring in the order \( a \ b \ c \). The negative-sequence system is composed of the vectors \( E_{a2}, E_{b2}, \) and \( E_{c2} \), which are also of equal magnitude and are displaced 120 degrees relative to each other, although in this case the sequence of maxima occurs in the order \( a \ c \ b \). The zero-sequence system is composed of the vectors \( E_{a0}, E_{b0}, E_{c0} \), which are of equal magnitude and are in phase.
Fig. 6.---Symmetrical vector systems.

Particular note should be taken of the subscripts which have become standardized, 1 indicating positive sequence, 2 negative sequence, and 0 zero sequence values.

Since each system acts independently, there are consequently definite impedance constants for each system. The exact method of determining the positive, negative, and zero-sequence impedances for transmission lines, transformers, rotating machinery, etc., is not included in this thesis. For such details the bibliographical references should be consulted.

The total voltage, or current, of any phase is equal to the sum of the corresponding sequence components in that phase. Therefore, the relation between the three phase vectors \((E_a, E_b, \text{ and } E_c)\) and the corresponding sequence vectors can be expressed as

\[
E_a = E_{a0} + E_{a1} + E_{a2} \quad (1)
\]

\[
E_b = E_{b0} + E_{b1} + E_{b2} \quad (2)
\]

\[
E_c = E_{c0} + E_{c1} + E_{c2} \quad (3)
\]

To express the phase vectors in terms of the sequence vectors of
the a phase alone, we obtain

\[ E_a = E_{a0} + E_{a1} + E_{a2} \]  
\[ E_b = E_{a0} + a^2 E_{a1} + aE_{a2} \]  
\[ E_c = E_{a0} + aE_{a1} + a^2 E_{a2} \]

in which \( a \) is the unit vector, \( e^{j120} = -0.5 + j0.866 \)

and

\[ a' = \text{the unit vector, } e^{j240} = -0.5 - j0.866 \]

Although these equations are written in terms of phase voltages, they apply equally well to phase currents.

Generating equipment produces voltages of only the positive sequence. It therefore follows that negative and zero-sequence voltages must be the result of voltage drops produced by the sequence currents flowing through their respective sequence impedances.

Kirchhoff's first and second laws state that, where several circuits converge, the sum of the currents in all the conductors equals zero; and that the sum of the voltage drops around a closed path must equal the e.m.f.s. Application of these laws allows the following equations to be developed for the various types of faults.

Three phase:  
\[ I_{a2} = 0 \]  
\[ I_{a0} = 0 \]  
\[ I_{a1} = \frac{E_a}{Z_1} \]  

Single line-to-ground fault. (phase a shorted)  
\[ I_{a1} = I_{a2} = I_{a0} = \frac{E_a}{Z_1 + Z_2 + Z_0} \]
Line-to-line fault.
(Phases b and c shorted)

\[ I_{a1} = \frac{E}{Z_1 + Z_2} \]

\[ I_{a2} = -I_{a1} \]  \hspace{1cm} (9)

\[ I_{a0} = 0 \]

Double line-to-ground fault.
(Phases b and c shorted to ground)

\[ I_{a1} = \frac{E_a}{Z_1 + \frac{Z_2Z_0}{Z_2 + Z_0}} \]  \hspace{1cm} (10)

\[ I_{a2} = -\frac{Z_0}{Z_0 + Z_2} I_1 \]  \hspace{1cm} (11)

\[ I_{a0} = -\frac{Z_2}{Z_0 + Z_2} I_1 \]  \hspace{1cm} (12)

Fig. 9.-Impedance diagram for line-to-line fault

Fig. 10.-Impedance diagram for double line-to-ground fault

The actual phase currents for each type of fault can be obtained by substituting the above sequence currents in the general equations (4), (5), and (6). In determining the phase currents at other points than the actual point of fault, it is necessary to substitute in equations (4), (5), and (6) the actual sequence currents existing at the point in question. These sequence currents at various points can be obtained by multiplying the fault sequence currents by the corresponding sequence distribution factors, which factors can be determined from the sequence system reductions.

Current Decrements.

A fact that makes short-circuit computation particularly difficult is that short-circuit currents, in most cases, rise to a maximum value
within the first half cycle and then decrease in an exponential manner until they reach a steady state value as shown in Fig. 11. The time required for this steady state condition to be reached depends largely on system characteristics, but will usually take from four to seven seconds.

![Fig. 11.--Short-circuit currents (asymmetrical)
(Contains d.c., subtransient, transient, and synchronous components)](image)

This decrease with time is due to the decrease of the induced direct current component, and the fact that the effective positive sequence reactances of generators vary with time when the generators are subjected to sudden changes of their currents.

The direct current component is sometimes called the equalizing current. It is obvious that, although the voltage and power factor conditions might be such as to dictate a maximum current at the instant of fault, it would be impossible for the current to instantly increase to this maximum value because of the inductance of the circuit. A direct or equalizing current is, therefore, induced in each phase, the magnitude of which depends upon the existing relations between the voltage, power factor and equivalent circuit impedance at the instant of short circuit. Thereafter
this direct current component decreases in an exponential manner at a rate proportional to the ratio of the resistance to the inductance of the circuit. This phenomenon can be seen more clearly from Fig. 12 which assumes that the fault occurs at a point on the voltage wave corresponding to maximum current and that no subtransient nor transient components are present.

Fig. 12.—Asymmetrical component of short-circuit currents (Curves include sustained and d.c. components only)

Referring to Fig. 12a, assume that the fault occurs at \( t = 0 \). The distance \( o a \) represents the peak value of the alternating current component \( \frac{\sqrt{2} E}{Z} \) and the curve \( a b c \) is a normal sine curve of current. The distance \( o d \), which is equal to \( o a \), represents the magnitude of the induced d.c. component, and the curve \( d e f \) is the exponential curve of this component. Fig. 12b shows the resulting curve obtained upon addition of these two components. It will be noticed that the new curve starts with a current value of zero at \( t = 0 \), and rises to a magnitude not quite double the value of \( \frac{\sqrt{2} E}{Z} \). The equation for such a curve is

\[
i = \frac{E_m}{Z} \sin (2\pi ft + \alpha - \phi) + \frac{E_m}{Z} \sin (\alpha - \phi) e^{\frac{-t}{T}}
\]

(13)

\[
Z = \sqrt{r^2 + (2\pi f)^2} = \text{impedance of circuit}
\]
\[ E_m = \text{crest voltage} = \sqrt{2} E \]

\[ \phi = \tan^{-1} \left( \frac{2\pi f l}{r} \right) \]

\[ \alpha = \text{displacement between the voltage wave and the reference wave} \]

which passes through zero at \( t = 0 \)

\[ f = \text{frequency} \]

\[ t = \text{time (seconds)} \]

\[ \frac{1}{r} = \text{direct current time constant} = \frac{\text{inductance}}{\text{resistance}} = \frac{T_a}{r} \]

the first term being that of the sine curve or permanent condition, and the second that of the exponential curve or direct current component.

The effective or r.m.s. value of such a curve can be expressed in terms of the two components as

\[ I_{\text{eff.}} = \sqrt{I_{ao}^2 + I_{do}^2} \quad (14) \]

Sudden changes in the magnitudes of generator armature currents induce currents in the generator field structure. These induced currents set up magnetic fields which affect the flux linkages of the generator, which in turn affect the armature current. The effects of such actions are apparent only in the positive-sequence system. To facilitate mathematical computations, these effects are taken into account by considering that the effective generator reactance varies rather than the induced voltage. This effective reactance can be expressed in the form of three components; namely, the subtransient, transient, and synchronous reactances. These component reactances can, therefore, be used to compute the sub-

- transient, transient, and synchronous components of current.
Fig. 13.--Symmetrical components of short-circuit current.

The synchronous (or sustained) component (Fig. 13) is that component of current which is finally attained as a sustained value during a prolonged short circuit. It is expressed mathematically as \[ I_s = \frac{E}{X_d} \] where \( X_d \) is the synchronous reactance which includes armature-leakage reactance and the reactance equivalent to armature reaction.

The transient component (Fig. 13) is the decaying component of current, the value of which can be obtained by subtracting the sustained component from the envelope of the current wave when projected back to zero time, neglecting the first few cycles. This current decreases as an exponential function at a rate depending on the value of the transient open-circuit time constant. The initial instantaneous sum of the sustained and transient components is expressed as \[ I' = \frac{E'}{X'd} \] where \( E' \) is the transient internal voltage and \( X'd \) is the transient reactance, which reactance includes the effect of both the armature and field flux leakages.

The subtransient component (Fig. 13) has a very rapid decrement,
being of appreciable value for only three or four cycles in most cases. This component is the difference between the envelope of the transient current and the overall envelope of the fault current. The total initial fault current \( I'' \) is expressed as 
\[
\frac{E''}{Xd''} \tag{1}
\]
where \( E'' \) is the subtransient internal voltage and \( Xd'' \) is the subtransient reactance. This subtransient component is present due to the fact that damper windings or similar circuits in machines by the action of their induced currents prevent the air gap flux from instantly decreasing. For perfect damper windings with no leakage flux, the subtransient reactance would equal the armature leakage reactance of the machine. Due to the leakage, \( Xd'' \) is somewhat higher in value than the armature leakage reactance.

Synchronous, transient, and subtransient reactances have both direct axis and quadrature axis values. The direct axis values are denoted by the subscript \( (d) \) and the quadrature axis values by the subscript \( (q) \). Since only the direct axis reactances are used for short-circuit calculations, the quadrature values are not discussed in this thesis. For information on these quadrature values, references indicated in the bibliography should be consulted.

In most cases the values of \( E, E'', \) and \( E' \) are almost equal. In fact, they would be exactly equal if the machine were not loaded at the time of short circuit. Their relative values under loaded conditions depend, as shown in Fig. 14, on the magnitude and power factor of the load.
Fig. 14.—Relation between synchronous, transient, and subtransient voltages. (Machine loaded at 80% P. F.)

Time Constants.

The subtransient, transient, and direct current components decay in an exponential manner. The equation of such a curve is

\[ I_t = I_0 e^{-\frac{t}{T}} \]  

in which

- \( I_t \) = value of current at any time (t)
- \( I_0 \) = initial value of current at \( t = 0 \)
- \( T \) = time constant

Thus the component decreases to \( \frac{1}{e} \) or 0.368 of its initial value when \( t = T \). It is also evident that the greater the time constant \( T \), the greater will be the value of the component current after an interval \( (t) \) of time.

The direct current time constants \( (T_d) \) of synchronous machines
frequently are less than 0.05 sec. In such cases this component is approximately \( \frac{1}{3} \) its initial value after 0.05 second, and increases the r.m.s. value of short-circuit current less than 5\% after 0.1 second. The value of this time constant is equal to

\[
T_a = \frac{X}{2\pi f R} \tag{16}
\]

in which

\[ X = \text{reactance of circuit (negative sequence reactance of generator)} \]

\[ R = \text{resistance of circuit} \]

The ratio of \( \frac{X}{2\pi f R} \) varies considerably with the type of apparatus: ranging from 0.04 to 0.53 second for rotating machines, 0.026 to 0.133 second for transformers, and 0.0013 to 0.026 second for transmission and distribution lines. It follows, therefore, that the contribution of the d.c. component is negligible at 0.1 second for circuits in which the transmission lines constitute an important portion of the impedance values.

The subtransient current is maintained by currents flowing in damper or similar windings. In such circuits the ratio of inductance to resistance is relatively low, giving small subtransient time constants (\( T_d'') \) of the order of 0.10 second of less. Since, as shown in Fig.12, the initial subtransient component constitutes only a small portion of the total current, its effect on the total r.m.s. current after 0.1 second is negligible.

The transient component of current is produced by induced currents in the field windings. The transient time constants of machines are usually expressed in terms of the open-circuit values. This transient
open-circuit time constant \( (T'do) \) is the time constant of the exponential curve of armature voltage obtained when the exciting voltage is suddenly removed from a synchronous machine operating at no load, the field circuit being maintained. The transient short-circuit time constant \( (T'd) \) can be computed from the open-circuit value by the following equation:

\[
T'd = \frac{X'd}{Xd} T'do \tag{17}
\]

in which

\[
X'd = \text{transient reactance}
\]
\[
Xd = \text{synchronous reactance}
\]

For short circuits involving appreciable external reactance, the short-circuit time constant may be obtained from the expression

\[
T'd = \frac{X'd + Xe}{Xd + Xe} T'do \tag{18}
\]

in which

\[
Xe = \text{external reactance}
\]

Standard Decrement Curves.

The preceding discussion indicates that mathematical computation of short-circuit currents can become very involved when the current variations with time are considered. To facilitate such computations Standard Decrement Curves, Figs. 2 and 3, have been constructed which are applicable, with sufficient accuracy for relay and circuit breaker information, to most electrical systems if sufficient care is exercised in their use. These curves are based on certain assumptions which represent typical operating conditions and machine characteristics.
The assumptions are:

1. Generators are operating at rated voltage and rated load at 80% power factor immediately preceding the short circuit.
2. No automatic voltage regulators are used.
3. Actual system subjected to fault can be represented by a single equivalent generator of the same total rating and an external reactance.
4. Load is located at the machine terminals, and the machine reactance is 15 per cent unless the total system reactance is less than 15 per cent in which event all the reactance is assumed in the machine.
5. Short circuit occurs on an unloaded feeder.
6. Short circuit occurs at the point of the voltage wave which corresponds to the maximum possible instantaneous current.
7. All resistances in the circuit including the fault resistance are negligible.
8. All machine e.m.f.s. are in phase.
9. Machine reactances and time constants are representative of modern machines. Of particular importance is the relation between transient and subtransient reactance of machines. (See Fig. 15)

The relation between the direct axis subtransient and transient reactances is shown in Fig. 15. This relation is of importance because of the fact that the current after 0.1 second is composed chiefly of the
sustained and transient components although the system reduction involves
the use of only the subtransient generator reactances.

Another very important limitation of the decrement curves is that
the fault is assumed to be located equidistant (electrically) from all
generators. In this case it is very important that the total connected
asynchronous capacity in kilovolt-amperes be used as the base for the
per cent reactance rather than an arbitrary value. This is essential since
the generators are assumed to have a reactance of 15 per cent (unless the
total reactance is less than 15 per cent) and the remainder of the re-
actance is assumed to be in external transmission lines. From the equation

\[ Xd' = 0.02 + 1.4Xd'' \]

Fig. 15: Relation between transient and subtransient reactances.

---

1. Wagner, C. F. and R. D. Evans, Symmetrical Components p. 97,
\[
T'd = \frac{X'd + Xe}{Xd + Xe}
\]

It is evident that the greater the external reactance, the greater will be the short-circuit time constant, and consequently the greater will be the transient component of current after a given time. The fact that a per cent reactance can have any value whatever, depending on the kv-a. base assumed for the computations, clearly indicates the necessity of using the total connected kv-a. as a basis. It is interesting, however, to note that the assumed kv-a. base does not appreciably affect the currents as obtained from the curves until after 0.10 second from the time of fault. This fact is true because the transient component does not decrease appreciably until after this interval of time has elapsed. It is of further interest to note that, as would be expected from the above equation, for time intervals in excess of 0.10 second, the fault currents obtained from the curves increase as the kv-a. base is increased. In fact, this increase varies from 22% at 0.15 second to 110% at 3 seconds when the kv-a. base is changed 1000%.

In cases where the fault current is fed from generators located asymmetrical with respect to the fault location, approximate fault currents after 0.1 second can be computed by using a kv-a. base equal to the sum of the kv-a. capacity of the generator bank electrically closest to the fault plus the sum of the ratios of the reactance from the fault through this generator bank to the reactance from the fault through the other system generators which deliver appreciable current to the fault, times the kv-a. capacity of the first bank.

As an example, consider a fault at the Wheeler bus. Referring to the appendix, Fig. 17a, it is seen that the Wilson station is electrically
the closest to the fault. The capacity of this station is 230,000 kv-a. The reactance through Wilson is 20.3 per cent on 100,000 kv-a. base. From Fig. 5, it is evident that Wheeler, Norris, and Gorges also deliver appreciable current to the fault. The reactance through Wheeler is 67%, through Norris 102.2%, through Gorges 65%. Therefore, the kv-a. base to be used is

\[
230,000 \times \left( \frac{20.3}{67} + \frac{20.3}{102.2} + \frac{20.3}{65} \right) 230,000 = 400,000 \text{ kv-a. approximately.}
\]

For faults at Norris bus the kv-a. base is 112,000 + \left( \frac{29.7}{139.5} + \frac{29.7}{92.8} + \frac{29.7}{71.7} + \frac{29.7}{58.2} \right) 112,000 = 300,000 \text{ kv-a. approximately,}

in which 112,000 is the kv-a. at Norris, 29.7 is the % reactance through Norris, 139.5 is the % reactance through Wheeler, 92.8 is the % reactance through Wilson, 71.7 is the % reactance through Waterville, and 58.2 is the % reactance through Alcoa, all reactances being expressed on 100,000 kv-a. basis.

The procedure for use of the standard decrement curves is outlined on the curve sheets, Figs. 2 and 3. The ordinates are "times full load current." This full load current is equal to

\[
I_{f.l.} = \frac{\text{kv-a.}}{\sqrt{3} \times \text{kv}} \tag{19}
\]

If the per cent system reactance on the connected kv-a. base is greater than 120%, currents can be obtained with sufficient accuracy for time intervals up to 0.12 second by reducing the kv-a. base until the reactance is 120% on this arbitrary kv-a. base. Where intervals of time greater than 0.12 second are considered, an approximation which would be on the safe side would be to reduce the reactance as explained above but refer
on the curves to a slightly lower value of time than the actual value desired. The curves of Fig. 3 for reactances above 30% tend to become parallel after 1.5 seconds indicating that the kv-a. base does not greatly affect the computed currents in this region. It is also important that corrections in time be made, as explained in Note 2 of Figs. 2 and 3, for machines in which the transient open-circuit time constant is other than five seconds.
CHAPTER III
APPLICATION OF RESULTS TO CIRCUIT BREAKER SELECTION

General Breaker Information.

Circuit breakers constitute probably the most important single item of electrical equipment exclusive of the fundamental items of generators and transformers. They are used in corresponding sizes for the control and protection of practically all motors, heaters, transformers, generators, transmission lines, etc. There is probably no electrical device which requires greater care on the part of the designer in its selection and application, inasmuch as the dependability and safety of service that can be maintained depend upon its suitability to the imposed duty both from the standpoint of load carrying and of fault clearing capacities.

Oil circuit breakers are used for all applications involving high voltages and high interrupting ratings; the oil serving the dual purpose of providing insulation and providing a medium for removing the heat from the breaker contacts. Such breakers have standardized AIEE and NEMA ratings with respect to:

1. The maximum voltage at which the breaker can be operated.
2. The maximum continuous current with respect to a definite temperature rise.
3. The time elapsed from the energizing of the trip coil with normal voltage until the circuit is interrupted at 25 per cent to 100 per cent of the interrupting rating.
4. The maximum r.m.s. current which the breaker will carry for any time, however small, up to a time of one second.
5. The maximum r.m.s. current which the breaker will carry for five seconds.

6. The interrupting ratings.

These ratings are defined in detail by the N. E. M. A. Switchgear Standards, Rules SG6-15-30-34-36-40-85.

The voltage and continuous current ratings of breakers depend on the ratings of the branch circuit in which they are to be placed. The minimum time required for opening the breaker is dependent only on mechanical features in the breaker design. The one second and the five second current ratings are dependent on system characteristics which control the magnitude of short-circuit currents; whereas, the interrupting rating depends upon both the system characteristics and the breaker operating duty.

While it is true that small series connected breakers are able to clear a fault almost instantly (within one cycle), the larger separately excited breakers are considered high-speed breakers if they have a minimum clearing time of eight cycles (0.133 second) from the time the trip coil is energized. Because of the importance of system stability which can be obtained by the quick clearing of faults, high-speed breakers are used extensively in present day installations. Although the breakers themselves are high speed, they are sometimes energized from time delay relays or interlocked by carrier pilot relaying to allow time for breakers on radial feeders to trip before the main system breakers are opened. From the previous discussion of current decrements, it is quite evident that such time delays will greatly affect the interrupting rating required of the breaker.
The interrupting rating of a breaker is expressed in kilovolt-amperes and is defined by the N. E. M. A. as a rating based on the highest r.m.s. current at normal voltage that a breaker can interrupt under the specified duty cycle; the value of current being taken during the first half cycle of the arc between contacts during the opening stroke. The breakers are given an interrupting rating on the basis of a standard duty cycle which consists of an open-close-open operation with a fifteen-second interval. For other duty cycles the standard rating is decreased by a percentage as indicated in the N. E. M. A. Rule SG6-85. The required interrupting rating can be computed from either of the following formulas:

\[
\text{Interrupting rating (kv-a)} = E \times \sqrt{3} \times I_{\text{sc}}. \tag{20}
\]

\[
\text{Interrupting rating (kv-a)} = \text{Normal system kv-a} \times \frac{100}{\%X} \tag{21}
\]

in which

- \( E \) = system line voltage
- \( I_{\text{sc}} \) = short-circuit current as defined above
- \( \%X \) = per cent reactance to point of fault (on normal kv-a. base)

Examples of Computation of Circuit Breaker Ratings.

Problem: It is desired to locate a substation at the end of a 154 kv. radial feeder which is to have a positive and negative sequence reactance of 6% and a zero sequence reactance of 10% on 100,000 kv-a. base. This feeder taps the Norris-Wheeler line at a point fifty miles from Wheeler. What should be the circuit breaker rating if a high-speed breaker is to be used which is capable of opening in eight cycles (0.133 second)?
Solution: In determining circuit breaker ratings only the three major types of faults are considered; namely, three phase, line-to-line, and single phase-to-ground faults. Each of these types of faults is computed below.

**Three Phase Fault**

From Fig. 1, the reactance of the system to the fifty mile point is 20.0% on 100,000 kv-a. base.

The total reactance to fault is, therefore,

\[ X_t = 20 + 5 = 25\% \text{ on 100,000 kv-a. base.} \]

This reactance should be expressed on 400,000 rather than 100,000 kv-a. base as explained previously in the chapter "Theoretical Basis for Computations."

\[ X_t = \frac{25 \times 400,000}{100,000} = 100\% \text{ on 400,000 kv-a. base.} \]

From Fig. 3, \( k \) for 0.0083 second = 1.69

From Fig. 2, \( k \) for 0.133 second = 1.1

Interrupting rating = 400,000 \( \times 1.1 = 440,000 \) kv-a.

One second rating = \( \frac{400,000}{\sqrt{3} \times 154} \times 1.69 = 2520 \) amps.

**Line-to-Line Fault**

From Fig. 1, the reactance to fifty mile point is 42% on 100,000 kv-a. base.

The total reactance to fault \( X_t = 42 + 5 + 5 = 52\% \text{ on 100,000 kv-a. base.} \)

\[ X_t = \frac{52 \times 400}{100} = 208\% \text{ on 400,000 kv-a. base.} \]

This reactance is too high to use with curves, reduce base until
reactance is 120% 

\[ \text{base} = 400,000 \times \frac{120}{208} = 231,000 \text{ kv-a.} \]

From Fig. 3, \( k \) for 0.0083 second = \( 1.39 \times \sqrt{3} = 2.41 \)

From Fig. 3, \( k \) for 0.10 second = \( 0.98 \times \sqrt{3} = 1.70 \)

(Note that 0.10 second was used rather than 0.133 to compensate for lower kv-a. base required. See discussion under Standard Decrement Curves)

Interrupting rating = \( 231,000 \times 1.7 = 393,000 \text{ kv-a.} \)

One-second rating = \( \frac{231,000 \times 2.41}{\sqrt{3} \times 154} = 2,080 \text{ amps.} \)

Single Line-to-Ground Fault.

From Fig. 1, reactance to fifty mile point is 93% on 100,000 kv-a. base.

Total reactance to fault = \( 93 + 5 + 5 + 10 = 113\% \) on 100,000 kv-a. base.

From Fig. 3, \( k \) for 0.0083 second = \( 1.47 \times 3 = 4.42 \)

From Fig. 3, \( k \) for 0.10 second = \( 1.05 \times 3 = 3.15 \)

(Note 0.10 second was used to compensate for lower kv-a. base)

Interrupting rating = \( 100,000 \times 3.15 = 315,000 \text{ kv-a.} \)

One-second rating = \( \frac{100,000 \times 4.42}{\sqrt{3} \times 154} = 1,660 \text{ amps.} \)

The three phase fault necessitates the maximum ratings. A breaker would, therefore, be ordered to meet these three phase requirements for the operating duty to which it is to be subjected.
CHAPTER IV

APPLICATION OF RESULTS TO BUS STRUCTURE DESIGN

Mechanical Stresses.

Electrical currents are usually conducted between generators, transformers, and oil circuit breakers by means of bus-bars of copper or aluminum. Due to power house and switchyard space limitations, such conductors are usually spaced relatively close together, making possible high stresses between phases when the buses are subjected to short-circuit currents. Since such stresses are set up before a circuit breaker has time to clear the fault, it is necessary that the bus structures be made sufficiently strong to withstand the maximum stresses to which the structures might be subjected.

Computation of the short-circuit stresses for bus structures involves consideration of the following factors:

1. The magnitude of the short-circuit current.
2. The rate of current decrement.
3. The magnetic force due to the current.
4. The natural frequencies of the bus-bar structure.
5. The shape of the bus-bars.
6. The spacing of the bus-bars.
7. The length of the span.

The equation of the force per span is

\[ F = \frac{5.4 \times 10^7 I_0^2 L_p}{s} \]  

in which

\[ F = \text{force per span (lbs.)} \]
$L =$ length of span (feet)

$S =$ center spacing between bus-bars (in.)

$I_0 =$ initial value of r.m.s. total short-circuit current for phase-to-phase fault

$k =$ shape correction factor

$P =$ stress factor

The shape correction factor ($k$) is readily obtained from curves\(^1\) that have been constructed in which the factor $k$ is expressed in terms of the spacing and physical dimensions of the bus-bars. This factor has a value of 1 for tubing and is generally between 0.9 and 1.1 for rectangular bars with 6" or greater spacing.

The stress factor ($P$) is the most difficult term in the equation to evaluate and, unfortunately, may vary through a considerable range (from 1 to 6). This stress factor is present in bus-bar computations because of the fact that the frequencies of the natural periods of vibration of bus-bars are often approximately equal to the frequency of the fault current; thus producing cumulative stresses in the structure when subjected to short-circuit currents.

Bus-bars and their supports have been found by experiment to be flexible and capable of being treated mathematically as having elastic properties. Experiments have also shown that the motion of the bus-bar span as well as the motion of the support itself shows two dominant natural frequencies of vibration which occur in combination in each of the two structural members when electromagnetic forces are suddenly applied. These

\(^1\) *NEEMA* Switchgear Standards, p 20, National Electrical Manufacturers Association, New York, May, 1931.
natural frequencies may be determined by test or by calculation from the mechanical constants of the bus-bar and support. Since mathematical computations are very involved and tests are not always feasible, tables 2 & 3 have been prepared which give the stress factor directly for various bus designs.

The lateral stresses, as determined from the above formula, will in turn create longitudinal stresses in the supports due to the fact that, as the bus-bars deflect, their effective span becomes shorter, tending to pull the supports inward from each end. The magnitude of such stresses is negligible for heavy bus-bar installations in which the deflection is not appreciable, but may become quite significant where light bus-bars are used. The following formula expresses the relations that exist.

\[ F' (F' + B)^2 = CP^2 \]  \hspace{1cm} (23)

\[ B = \frac{0.296 E I C}{L^2} \]  \hspace{1cm} (24)

\[ C = \frac{0.37 L S A E}{AE \times 12L S} \]  \hspace{1cm} (25)

in which

- \( F' \) = longitudinal stress (lbs.) for condition of 2 spans
- \( I \) = moment of inertia of bus-bar in direction of force
- \( C \) = number of laminations in bus-bar
- \( E \) = modulus of elasticity = 17.2 \times 10^6 for copper
- \( L \) = length of span (ft.)

A = total cross-sectional area (sq. in.)

S = support stiffness (lb. per sq. in.)

For designs involving more than 2 spans, the following constants (q) should be multiplied by F' to determine the total longitudinal stress for each condition.

**TABLE I** --LONGITUDINAL STRESS FACTORS

<table>
<thead>
<tr>
<th>No. of equal spans</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3/4</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>1.5</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>2.5</td>
</tr>
<tr>
<td>8</td>
<td>2.5</td>
</tr>
<tr>
<td>10</td>
<td>2.75</td>
</tr>
</tbody>
</table>

The total bending load on the bus support will be

a. For end insulator where P is applied perpendicular to axis of insulator

\[ R_1 = \sqrt{q^2 F^2 + p^2} \]  
(26)

for next to end support

\[ R_2 = \sqrt{(q - 0.8)^2 F^2 + p^2} \]  
(27)

b. For end insulator if P is applied parallel to axis of insulator

\[ R_1 = \frac{qF + PB}{T} \]  
(28)

for next to end support

\[ R_2 = (q - 0.8)F + \frac{PB}{T} \]  
(29)

in which

B = ultimate insulator cantilever load at center-line of bus-bar

The fiber stresses of the bus-bar should not be above the elastic limit for the material used. These stresses can be computed from the following formulae.

a. For flat buses

\[ t = \frac{9 PL}{a^2 b} \]  

(b. For tubular buses

\[ t = \frac{15 PLD}{D^2 - d^2} \]

in which

- \( t \) = fiber stress (lb. per sq. in.)
- \( L \) = length of span (ft.)
- \( P \) = lateral stress (lb.)
- \( a \) = bus-bar dimension parallel to force \( P \) (inches)
- \( b \) = bus-bar dimension perpendicular to force \( P \) (inches)
- \( D \) = outside diameter (inches)
- \( d \) = inside diameter (inches)

The elastic limit for copper is from 12,000 to 15,000 lb. per sq. in., but the working stress should be taken at a lower value.

Methods of Stress Limitation.

Bus-bar short-circuit stresses can be reduced by the following means:


b. Increasing spacing between conductors.

c. Selecting bus-bar designs for which the stress factors are low.

However, it may often be desirable to design the structure for
a somewhat higher value of lateral stress than the minimum in order to avoid excessively high longitudinal stresses.

d. Clamping bus-bars at the supports (to avoid slapping) rather than loosely guiding them.

e. Placing rigid supports at tap connections to avoid heavy stresses due to the "kick" of the tap connection during short circuits.

f. Avoid extra long spans for buses in which the bars are face-to-face, since the longitudinal stresses increase rapidly with the length of span for flexible buses.

g. Providing uniform current distribution among the laminations of each phase by suitable transpositions. In buses whose laminations are not transposed, the proximity effect tends to increase the stresses.

Example of Stress Computation.

Problem: Four equal spans each four feet long consisting of one 4 in. by 1/4 in. copper bar placed face-to-face with respect to adjacent phases and supported edge-on on 15,000 volt moderate duty porcelain insulators are to carry the current from the secondary of a 154 to 13.8 kv, 25,000 kv-a. transformer bank to the distribution circuit breakers at the substation located as described in the examples in Chapter III, "Application of Results to Circuit Breaker Selection." What are the short-circuit stresses if the buses are to be placed 6" apart?

Solution: From the example under "Circuit Breaker Selection" the per cent reactance to the substation for a phase-to-phase fault is
The reactance of the transformers on 100,000 kv-a. base is
\[ X = \frac{9 \times 100,000}{25,000} = 36\% \]

The total reactance to fault \( = 52 + 72 = 124\% \)

The initial fault current \( = 3 \times 100,000 \times 100 = \frac{13.8 \times \sqrt{3}}{124} \)

10,100 Amps. Asymmetrical

from NEMA Switchgear Standards, p. 18 and p. 20

\[ k = 0.97 \]

\[ p = 1.5 \]

The lateral force is then, from equation 22

\[ F = 5.4 \times 0.97 \times (10,100)^2 \times 4 \times 1.5 = \frac{53.7 \text{ lb. per support}}{10 \times 6} \]

The longitudinal stress is, from equation 23

\[ F' (F' + B)^2 = CP^2 \]

\[ B = 0.296 E I c \]

\[ c = 1 \]

\[ L = 4 \]

\[ E = 17.2 \times 10^6 \]

\[ I = \frac{bd^3}{12} = \frac{4}{12} \times \left(\frac{3}{4}\right)^3 = \frac{1}{192} \]

\[ B = 0.296 \times 17.2 \times 10^6 \times 1 \times 1 = 1660 \]

\[ C = \frac{0.37 \times \text{LSAE}}{AE + 12 \text{ LS}} \]
\[ S = 9,100 \]
\[ A = 4 \times \frac{1}{4} = 1 \text{ sq. in.} \]
\[ C = \frac{0.37 \times 4 \times 9,100 \times 1 \times 17.2 \times 10^6}{17.2 \times 10^6 + 12 \times 4 \times 9,100} = 13,200 \]

Then

\[ F'(F' + 1660)^2 = 13,200 \times (53.7)^2 \]
\[ F' = 13.5 \text{ lb.} \]

The longitudinal stress on the end insulator for four spans is

\[ F = q F' \]

From Table I:
\[ q = 2 \]
\[ F = 2 \times 13.5 = 27 \text{ lb.} \]

The total stress on the end insulator is then, by formula 26

\[ R_1 = \sqrt{q^2 F'^2 + F^2} \]
\[ R_1 = \sqrt{2^2 \times 17^2 + (53.7)^2} \]
\[ R_1 = 63.5 \text{ lbs.} \]

The fiber stress in the bus-bar is then, by formula 30

\[ t = \frac{9 \times PL}{a^2 b} \]
\[ t = \frac{9 \times 53.7 \times 4}{(\frac{1}{4})^2 \times 4} \]
\[ t = 7.740 \text{ lbs. per sq. in.} \]

Note: These stresses are low due to the low short-circuit current. If this current had been 20,000 amperes instead of 10,000 amperes, the lateral stress would have been four times as great (214 lb.) and the longitudinal stress would have been approximately thirteen times as great or 360 lbs. which would have necessitated a change in the bus design due to excessive fiber stresses.
BIBLIOGRAPHY


APPENDIX

Computation Procedure.

The first step necessary in making this short-circuit study was to set up certain assumptions which would make a mathematical solution feasible and yet would not impair the accuracy of the work. These assumptions have been outlined and included in this thesis under "Results of Study." Particular note should be made of the fact that an interconnection was assumed between Arlington and Norris through a 50,000 kv-a. auto-transformer bank.

With these assumptions in mind, the next step was to set up the interconnected system of this area in terms of the constants required by this method of solution. The impedance diagrams (Figs. 16a and 16b) were used as a basis for setting up the positive, negative, and zero sequence systems. Since Fig. 16a includes only transmission line and transformer constants, it was necessary to complete the sequence systems by use of information from other sources. This information is tabulated in Tables II and III. Table II contains the necessary information on generators and synchronous condensers. From this table the various lump plant constants were obtained by paralleling the constants of the machines in that station and expressing the final reactance as a percentage on 100,000 kv-a. base. Table III was used to obtain the zero sequence transformer constants and also to supplement the available information in Figs. 16a and 16b on the other sequences. With this information, the sequence systems were set up as shown on Figs. 17a, 17b, and 18.

The ensuing work consisted of the slow, tedious process of reducing
the various systems. This reduction was accomplished by the so-called "star-delta" method of simplifying circuits which consists of replacing a star connection by an equivalent delta, or the converse, in order that the various reactances may be rearranged for parallel and series combination. The object of this reduction was, of course, to obtain an ultimate single equivalent reactance to the point of fault which reactance could be used with the decrement curves. The equations for such reductions are as follows:

\[
\begin{align*}
A_1 &= \frac{B_2 B_3}{B_1 + B_2 + B_3} \\
A_2 &= \frac{B_2 B_1}{B_1 + B_2 + B_3} \\
A_3 &= \frac{B_1 B_2}{B_1 + B_2 + B_3} \\
B_1 &= A_2 + A_3 + \frac{A_2 A_3}{A_1} \\
B_2 &= A_3 + A_1 + \frac{A_3 A_1}{A_2} \\
B_3 &= A_1 + A_2 + \frac{A_1 A_2}{A_3}
\end{align*}
\]

Reduction of the sequence systems to various points is indicated in Fig. 19. These reductions should be of value for short-circuit studies when future additions to the present system are made.
TABLE IIa. -- SYSTEM GENERATOR DATA

<table>
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<td>*110 - 6.6 Delta</td>
<td>15,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>*44 - 6.6 Delta</td>
<td>15,000</td>
</tr>
<tr>
<td>Gadsden</td>
<td>0.1 ohm. #1</td>
<td>*110 - 46Y</td>
<td>30,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>*110 - 13.2 Delta</td>
<td>15,000</td>
</tr>
<tr>
<td></td>
<td>Auto Trans.</td>
<td>Y 46 - 13.2 Delta</td>
<td>15,000</td>
</tr>
<tr>
<td>Gorges</td>
<td>#2, #3, #5</td>
<td>*115 - 13.2 Delta</td>
<td>70,000</td>
</tr>
<tr>
<td></td>
<td>#4</td>
<td>*46 - 13.2 Delta</td>
<td>40,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>*44 - 13.2 Delta</td>
<td>20,000</td>
</tr>
<tr>
<td>Huntsville</td>
<td>#1</td>
<td><em>110 - 44</em></td>
<td>13,500</td>
</tr>
<tr>
<td></td>
<td></td>
<td>*110 - 6.6 Delta</td>
<td>7,500</td>
</tr>
<tr>
<td></td>
<td></td>
<td>*44 - 6.6 Delta</td>
<td>7,500</td>
</tr>
<tr>
<td>Jordan Dam</td>
<td>#1, #2</td>
<td>*115 - 11.4 Delta</td>
<td>60,000</td>
</tr>
<tr>
<td>Lay Dam</td>
<td>0.2 ohm. #1</td>
<td>*44 - 6.6 Delta</td>
<td>9,000</td>
</tr>
<tr>
<td></td>
<td>#2, #3, #5</td>
<td>*110 - 6.6 Delta</td>
<td>13,500</td>
</tr>
<tr>
<td></td>
<td>#4, #6</td>
<td>Y110 - 6.6 Delta</td>
<td>13,500</td>
</tr>
<tr>
<td>Martin Dam</td>
<td>#1</td>
<td>*123 - 12 Delta</td>
<td>42,000</td>
</tr>
<tr>
<td></td>
<td>#2, #3</td>
<td>Y123 - 12 Delta</td>
<td>42,000</td>
</tr>
<tr>
<td>Mitchell Dam</td>
<td>#1, #2, #3</td>
<td>*110 - 6.6 Delta</td>
<td>22,500</td>
</tr>
<tr>
<td>Pinckard</td>
<td>1.0 ohm.</td>
<td><em>110 - 46</em></td>
<td>10,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>*110 - 6.6 Delta</td>
<td>7,500</td>
</tr>
<tr>
<td></td>
<td></td>
<td>*46 - 6.6 Delta</td>
<td>7,500</td>
</tr>
<tr>
<td>Tallassee</td>
<td></td>
<td><em>115 - 46</em></td>
<td>20,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>*115 - 6.6 Delta</td>
<td>40,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>*46 - 6.6 Delta</td>
<td>20,000</td>
</tr>
<tr>
<td>Turlow Dam</td>
<td></td>
<td>*115 - 13.2 Delta</td>
<td>70,000</td>
</tr>
<tr>
<td>West Point</td>
<td>1.1 ohm.</td>
<td>*110 - 13.2 Delta</td>
<td>13,500</td>
</tr>
</tbody>
</table>

* indicates Y connected transformer with neutral solidly grounded.  
Y indicates Y connected transformer with neutral isolated. 
Where no ground resistance is shown it may be considered as 0.5 ohm or less.

### TABLE IIIb. -- SYSTEM GROUNDING POINTS

**Georgia Power Company--110 KV System**

<table>
<thead>
<tr>
<th>Station</th>
<th>Trans. Bank Kv-a.</th>
<th>Ground Resistance Ohms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dalton</td>
<td>2,000*</td>
<td>2.0</td>
</tr>
<tr>
<td>East Point</td>
<td>20,000**</td>
<td>6.5</td>
</tr>
<tr>
<td>Lindale</td>
<td>15,000***</td>
<td>1.0</td>
</tr>
<tr>
<td>Atkinson</td>
<td>70,000/</td>
<td></td>
</tr>
<tr>
<td>Bartletts Ferry</td>
<td>56,250/ (3 banks)</td>
<td></td>
</tr>
<tr>
<td>Goat Rock</td>
<td>24,000/ (2 banks)</td>
<td></td>
</tr>
<tr>
<td>Tallulah</td>
<td>72,000/ (6 banks)</td>
<td></td>
</tr>
<tr>
<td>Terrora</td>
<td>12,000/</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20,000/</td>
<td></td>
</tr>
<tr>
<td>Tugalo</td>
<td>48,000/ (2 banks)</td>
<td></td>
</tr>
<tr>
<td>Yonah</td>
<td>25,000/</td>
<td></td>
</tr>
</tbody>
</table>

**Notes:** 0.5 ohms for ground resistance unless specified

- * Auto Bank 110/66 KV, star connected
  Tertiary Delta connected capacity of primary and secondary windings 10,000 kv-a.
  Tertiary 2,000 kv-a.

- ** Auto Bank 110/66 star connected
  Tertiary Delta connected primary and secondary windings 30,000 kv-a.
  Tertiary 20,000 kv-a. supplies condenser.

- *** Auto Bank 110/66 KV, star connected
  Tertiary Delta connected primary and test windings 15,000 kv-a.
  Secondary 10,000 kv-a

/ Low side connected Delta.
### TABLE II - SYSTEM GROUNDING POINTS

Tennessee Electric Power Company--110 and 154 KV. System

<table>
<thead>
<tr>
<th>Station</th>
<th>Ground Resistance</th>
<th>Number of Grounded Banks</th>
<th>Bank Kv-a.</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centerville</td>
<td>1.01 ohm.</td>
<td>1-3 φ</td>
<td>7,500</td>
<td>Ygnd.-Delta</td>
</tr>
<tr>
<td>West Nashville</td>
<td>0.5 ohm.</td>
<td>1</td>
<td>45,000</td>
<td>Auto Trans.</td>
</tr>
<tr>
<td>South Nashville</td>
<td>0.9 ohm.</td>
<td>2</td>
<td>10,500 ea.</td>
<td>Ygnd.-Delta</td>
</tr>
<tr>
<td>Great Falls</td>
<td>0.2 ohm.</td>
<td>1-3 φ</td>
<td>10,000</td>
<td>Ygnd.-Y</td>
</tr>
<tr>
<td>Hales Bar</td>
<td>0.25 ohm.</td>
<td>1-110 KV.</td>
<td>40,000</td>
<td>Steam Plant</td>
</tr>
<tr>
<td></td>
<td>0.25 ohm.</td>
<td>1-3 φ on 44 KV Bus</td>
<td>25,000</td>
<td>Low Side Delta</td>
</tr>
<tr>
<td>Valdeau</td>
<td>0.25 ohm.</td>
<td>1</td>
<td>40,000</td>
<td>Low Side Delta</td>
</tr>
<tr>
<td>Ridgedale</td>
<td>0.15 ohm.</td>
<td>2</td>
<td>30,000</td>
<td>Low Side Delta</td>
</tr>
<tr>
<td>Ocoee #1</td>
<td>0.13 ohm.</td>
<td>1-3 φ on 110 KV Bus</td>
<td>7,500</td>
<td>Low Side Y</td>
</tr>
<tr>
<td>Ocoee #2</td>
<td>5.5 ohm.</td>
<td>2-3 φ</td>
<td>9,375 ea.</td>
<td>Low Side Delta</td>
</tr>
<tr>
<td>Alcoa</td>
<td>0.9 ohm.</td>
<td>1</td>
<td>25,000</td>
<td>Auto Trans.</td>
</tr>
<tr>
<td>Arlington</td>
<td>0.62 ohm.</td>
<td>2</td>
<td>7,500</td>
<td>Auto Trans.</td>
</tr>
<tr>
<td>Lenoir City</td>
<td>0.22 ohm.</td>
<td>2</td>
<td>7,500</td>
<td>Auto Trans.</td>
</tr>
<tr>
<td>Wilson</td>
<td>0.5</td>
<td>4</td>
<td>65,000</td>
<td>Resistance assumed</td>
</tr>
</tbody>
</table>

### TABLE III Id. - SYSTEM GROUNDING POINTS

T.P.S. and Carolina P. and L. Company--Interconnection Transformers

<table>
<thead>
<tr>
<th>Station</th>
<th>Bank Designation</th>
<th>No. of Phases</th>
<th>% Rating (ea.bank)</th>
<th>Voltage Ratio Connection</th>
<th>Reactance % on Kv-a. base</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waterville</td>
<td>#1,#2,#3</td>
<td>1</td>
<td>45,000</td>
<td>115-13.2 Ygnd.-Delta</td>
<td>8.54</td>
</tr>
<tr>
<td>ElkMntain</td>
<td>60KV.</td>
<td>3</td>
<td>7,500</td>
<td>61.1-11.9 Delta-Ygnd.</td>
<td>6.74</td>
</tr>
</tbody>
</table>
Fig. 16a

POSITIVE, NEGATIVE AND ZERO SEQUENCE IMPEDANCE DIAGRAM

NOTES

- Elements include elements of plants of equipment generators and lines for AC operating load positions.
- Impedances are in percent of 100 kva base.
- Impedances of transformers are for separate installation.
- Transformations are in percent or ohms for base.

Figures in parentheses are for zero sequence components.
SANTETLAH PLANT
25000 kVA

66 KV
6250 kVA

CHEOAH PLANT
20000 kVA, 20000 kVA, 20000 kVA 20000 kVA

CALDERWOOD PLANT
45000 kVA 45000 kVA

154 KV 120 KV

ALCOA SUBSTATION

TO T.E.P.CO.

42000 kVA
Xt = 10.0% X+ =10.0% X+ = 9.5%

42000 kVA
Xt = 10.0%

42000 kVA
Xt = 10.0%

SYSTEM REACTANCE DIAGRAM
ALUMINUM COMPANY OF AMERICA

Fig. 16b

Xd - Syn. React. Direct Axis
Xq - Syn. React. Quadrant
X'd - Trans. React. Direct Axis
X'q - Trans. React. Quadrant
Xp - Neg. Phase Seq. React.
Xl - Leakage Reactance
Xt - Transformer Res. kV
Line resistance & reactance are in % on 100,000 kVA base
Constants used in Positive & Negative Sequence Reductions

0 indicates synchronous condenser

Reactances are in percent on 100,000kva base
Constants used in Positive & Negative Sequence System Reduction

(Generator constants are for complete generating equipment connection)

Gorges System

Reactances are in percent on 100,000 kva.
Constants used in Zero Sequence Reduction

Reactances are in percent on 100,000 kv-a base

Fig. 18
Sequence Reductions

Positive Sequence Reduction

Negative Sequence Reduction

Reactances are in percent on 100,000 kV.

Fig. 19