Topics for today and onward:

- Intro to Lightning (Chapter 14)
- Surges (Switching & Lightning)
- Insulation Coordination (Chapter 15)
- Overvoltage Protection (Chapter 16)

Recommended Homework Problems:

- 15.1, 15.3, 15.5, 15.6

ATP Simulation Pointer for the day:

More on stranded steel-core conductors:

If we neglect current carrying capability of inner steel core, then inductance is assumed to be due only to the outer aluminum strands. If you make this assumption, you are approximating the conductor as a hollow tube (like a bus bar). This is arguably much more correct than assuming that the stranding is all aluminum.

4" ⇒ Actual Radii
Double-Circuit Lines:

Short-Circuit Studies make use of: \( z^+ = z^- \)

\[ z_0, z^+, z_{\text{mutual}} \]

\[
\begin{bmatrix}
  Z_p \\
  6 \times 6
\end{bmatrix} \Rightarrow \\
\begin{bmatrix}
  Z_{aa} & Z_{ab} & \cdots & Z_{az} \\
  Z_{ba} & Z_{bb} & \cdots & Z_{bz} \\
  \vdots & \vdots & \ddots & \vdots \\
  Z_{za} & Z_{zb} & \cdots & Z_{zz}
\end{bmatrix}
\]

\[ \text{ckt } #1 \]

\[ \text{ckt } #2 \]
\[
\begin{bmatrix}
Z_3 \\
\end{bmatrix}
= \begin{bmatrix}
[A]' & 0 \\
0 & [A]' \\
\end{bmatrix}
\begin{bmatrix}
Z_0 \\
Z_1 \\
Z_2 \\
\end{bmatrix}
\begin{bmatrix}
A & 0 \\
0 & A \\
\end{bmatrix}
\]

\[
= \begin{bmatrix}
Z_{00,1} & \cdots & \cdots & Z_{01,1} \\
Z_{11,1} & \cdots & \cdots & Z_{12,1} \\
Z_{22,1} & \cdots & \cdots & Z_{22,2} \\
\end{bmatrix}
\]

If \( Z^+, Z^0, Z^- \Rightarrow Z_{\text{off-diag}} \)

Then we can approximate as decoupled (except for \( Z_0 \)).
untransposed case, because they would become zero for the balanced line. For
the untransposed case, these off-diagonal elements are used to define
unbalance factors [47, p. 93]. The full symmetrical component matrices are
no longer symmetric, unless the columns for positive and negative sequence
are exchanged [27]. This exchange is made in the output of the supporting
routine LINE CONSTANTS with rows listed in order "zero, pos, neg, ...", and
columns in order "zero, neg, pos, ...". With this trick, matrices can be
printed in triangular form (elements in and below the diagonal), as is done
with the matrices for individual and equivalent phase conductors.

Symmetrical components for two-phase lines are calculated with the
transformation matrix of Eq. (4.63), while those of three-phase lines are
calculated with

\[ [v_{\text{phase}}] = [S][v_{\text{symm}}], \text{ and } [v_{\text{symm}}] = [S]^{-1}[v_{\text{phase}}], \quad (4.68a) \]

identical for currents,

\[ [v_{\text{symm}}] = \begin{bmatrix} v_{\text{zero}} \\ v_{\text{pos}} \\ v_{\text{neg}} \end{bmatrix}, \]

where

\[ [S] = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \quad \text{and} \quad [S]^{-1} = \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \quad (4.68b) \]

and \( a = e^{j120^\circ} \).

The columns in these matrices are normalized*); in that form, \([S]\) is unitary,

\[ [S]^{-1} = [S^*]^t \quad (4.69) \]

where "*" indicates conjugate complex and "t" transposition.

*The electric utility industry usually uses unnormalized transformation, in
which the factor for the \([S]\)-matrix is 1 instead of \(1/\sqrt{3}\), and for the \([S]^{-1}\)-
matrix \(1/3\) instead of \(1/\sqrt{3}\). The symmetrical component impedances are
identical in both cases, but the sequence currents and voltages differ by a
factor \(1/3\).
For \( M > 3 \), the supporting routine LINE CONSTANTS assumes three-phase lines in parallel. Examples:

- \( M = 6 \): Two three-phase lines in parallel
- \( M = 9 \): Three three-phase lines in parallel
- \( M = 8 \): Two three-phase lines in parallel, with equivalent phase conductors no. 7 and 8 ignored in the transformation to symmetrical components.

The matrices are then transformed to three-phase symmetrical components and not to \( M \)-phase symmetrical components of Eq. (4.62). For example for \( M = 6 \) (double-circuit three-phase line),

\[
[Z'_\text{symm}] = \begin{bmatrix}
[S]^{-1} & 0 \\
0 & [S]^{-1}
\end{bmatrix}
\begin{bmatrix}
Z'_\text{phase} \\
0
\end{bmatrix}
\begin{bmatrix}
[S] \\
0
\end{bmatrix}
\]

(4.70)

with \([S]\) defined by Eq. (4.68), Eq. (4.70) produces the three-phase symmetrical component values required in Eq. (4.67).

Balancing of double-circuit three-phase lines through transpositions never completely diagonalizes the respective symmetrical component matrices. The best that can be achieved is with the seldom-used transposition scheme of Fig. 4.22, which leads to

\[
[Z'_\text{symm}] = \begin{bmatrix}
Z'_\text{zero-I} & 0 & 0 & Z'_\text{zero-coupling} & 0 & 0 \\
0 & Z'_\text{pos-I} & 0 & 0 & 0 & 0 \\
0 & 0 & Z'_\text{pos-I} & 0 & 0 & 0 \\
Z'_\text{zero-coupling} & 0 & 0 & Z'_\text{zero-II} & 0 & 0 \\
0 & 0 & 0 & 0 & Z'_\text{pos-II} & 0 \\
0 & 0 & 0 & 0 & 0 & Z'_\text{pos-II}
\end{bmatrix}
\]

(4.71)
If both circuits are identical, then $Z'_{\text{zero-I}} = Z'_{\text{zero-II}} = Z'_{\text{zero}}$, and $Z'_{\text{pos-I}} = Z'_{\text{pos-II}} = Z'_{\text{pos}}$; in that case, the transformation matrix of Eq. (4.65) can be used for diagonalization. The more common transposition scheme of Fig. 4.23 produces positive and zero sequence coupling between the two circuits:

\begin{align*}
\text{CI} & \quad \text{BI} \\
\text{AI} & \quad \text{CI} \\
\text{AII} & \quad \text{CII} \\
\text{BII} & \quad \text{AII} \\
\text{CII} & \quad \text{BII}
\end{align*}

(a) barrels rolled in opposite direction

(b) barrels rolled in same direction.

**Fig. 4.23** - Double-circuit transposition scheme

as well, with the nonzero pattern of the matrix in Eq. (4.71) changing to

\[
\begin{bmatrix}
X & 0 & 0 \\
0 & X & 0 \\
0 & 0 & X \\
X & 0 & 0 \\
0 & X & 0 \\
0 & 0 & X
\end{bmatrix}
\begin{bmatrix}
X & 0 & 0 \\
0 & X & 0 \\
0 & 0 & X \\
X & 0 & 0 \\
0 & X & 0 \\
0 & 0 & X
\end{bmatrix}
\]

where "X" indicates nonzero terms. Re-assigning the phases in Fig. 4.23(b) to CI, BI, AI, AII, BII, CII from top to bottom would change the matrix further to cross-couplings between positive sequence of one circuit and negative sequence of the other circuit, and vice versa,
The transposition scheme of Fig. 4.22 would produce such a matrix form, which implies that the two circuits are only coupled in zero sequence, but not in positive or negative sequence. Such a complicated transposition scheme is seldom, if ever, used, but the writer suspects that positive and negative sequence couplings in the more common double-circuit transposition scheme of Fig. 4.23 is often so weak that the model discussed here may be a useful approximation for the case of Fig. 4.23 as well.

\[
\begin{bmatrix}
Z'_s & Z'_m & Z'_m & Z'_p & Z'_p & Z'_p \\
Z'_m & Z'_s & Z'_m & Z'_p & Z'_p & Z'_p \\
Z'_m & Z'_m & Z'_s & Z'_p & Z'_p & Z'_p \\
Z'_p & Z'_p & Z'_s & Z'_m & Z'_m & Z'_m \\
Z'_p & Z'_p & Z'_m & Z'_s & Z'_m & Z'_m \\
Z'_p & Z'_p & Z'_p & Z'_m & Z'_m & Z'_s \\
\end{bmatrix}
\tag{4.64}
\]

The matrix of Eq. (4.64) is diagonalized by modifying the transformation matrix of Eq. (4.58) to

\[
[T] = \frac{1}{\sqrt{6}}
\begin{bmatrix}
1 & 1 & \sqrt{3} & 1 & 0 & 0 \\
1 & 1 & -\sqrt{3} & 1 & 0 & 0 \\
1 & 1 & 0 & -2 & 0 & 0 \\
1 & -1 & 0 & 0 & \sqrt{3} & 1 \\
1 & -1 & 0 & 0 & -\sqrt{3} & 1 \\
1 & -1 & 0 & 0 & 0 & -2 \\
\end{bmatrix}
\tag{4.65}
\]
Lightning - Ch. 14

KV 230 - Causes 26% of Outages
345 - " 65% " "

\[ V_{\text{wave}} = \frac{1}{2} I Z_c \]

\[
\begin{align*}
Q &= +5 \times 10^5 \text{C} \\
Q &= -5 \times 10^5 \text{C} \\
\left| E \right| &= 0.13 \frac{\text{KV}}{\text{M}}
\end{align*}
\]

Atmosphere
Air
Earth
See p. 466 - How Lightning develops.

Air Breakdown
@ ~30 kV/cm
Humid Air:
~10 kV/cm

See Isokeraunic Map, p. 473
which is defined as the number of days per year on which thunder is heard at

within the continental United States. [21]

473 INTERACTION BETWEEN LIGHTNING AND THE POWER SYSTEM
Waveshapes:

- "Double Exponential"

\[ V(t) = V_{\text{MAX}}(e^{-at} - e^{-at}) \]

Difference:

CRUDE APPROX:

[Diagram showing a triangular wave shape]
Actual Lightning or Switching Surges:

Standard Reference:

\[ tf \times tt \]

\[ tf = 1.6(x_2 - x_3) \]

\[ tt = (x_4 - x_0) \]

C57.12.90

Stds: 1.2 x 50 ms (Lightning Surges)

5 x 200 ms (Impulse)
Switching Surges (Impulse)

"Front of Wave"

Switching Surges:  JEC Standards:

250 x 2500 μs

BIL: Basic Insulation Level

BSL: (Impulse & Light) (Switching)
Fig. 15.2. Development of a volt/time curve. (1) Critical flashover voltage. (2) Withstand voltage.

At first there are no flashovers; the voltage is simply not high enough. Breakdowns begin to occur as the voltage is increased. On each occasion the time of the breakdown is recorded (time being measured from the start of