ECE 325 – Electric Energy System Components
5- Transmission Lines

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Content

(Materials are from Chapter 25)

• Overview of power lines

• Equivalent circuit of a line

• Voltage regulation and power transmission of transmission lines
Overview

• Types of transmission lines
  – Overhead lines
  – Underground Cables (less than 1%)

• Properties
  – Series Resistance (stranding and skin effect)
  – Series Inductance (magnetic & electric fields; flux linkages within the conductor cross section and external flux linkages)
  – Shunt Capacitance (magnetic & electric fields; charge and discharge due to potential difference between conductors)
  – Shunt Conductance (due to leakage currents along insulators or corona discharge caused by ionization of air)

• Line-to-line voltage levels
  – 69kV, 115kV, 138kV and 161kV (sub-transmission)
  – 230kV, 345kV, and 500kV (EHV)
  – 765kV (UHV)
Overhead Transmission Lines

Shield wires (ground wires) are ground conductors used to protect the transmission lines from lightning strikes.

(Source: wikipedia.org and EPRI dynamic tutorial)
Overhead Transmission Lines

• Materials
  – AAC (All Aluminum Conductor),
  – AAAC (All Aluminum Alloy Conductor)
  – ACSR (Aluminum Conductor Steel Reinforced)
  – ACAR (Aluminum Conductor Alloy Reinforced)
  – ACCC (Aluminum Conductor Composite Core)

• Why not copper?
  – Relative lower costs and higher strength-to-weight ratios than copper

• Bundle conductors
  – Preferred for high voltages, e.g. 2-conductor bundles for 230kV, 3-4 for 345-500kV, and 6 for 765kV
Equivalent circuit of a transmission line

![Equivalent circuit of a transmission line](image)

**Figure 25.13**
Distributed impedance of a transmission line.

**Figure 25.14**
Equivalent lumped circuit of a transmission line.

- \( R = r \times N, \quad X_L = x_L \times N, \quad X_C = x_C / N \)
- With the increase of the length of the line, \( R \) and \( X_L \) increase but \( X_C \) decreases
- For transmission lines, \( R << X_L \)

### Table 25C
TYPICAL IMPEDANCE VALUES PER KILOMETER FOR 3-PHASE, 60 HZ LINES

<table>
<thead>
<tr>
<th>Type of line</th>
<th>( x_L ) [( \Omega )]</th>
<th>( x_C ) [( \Omega )]</th>
</tr>
</thead>
<tbody>
<tr>
<td>aerial line</td>
<td>0.5</td>
<td>300 000</td>
</tr>
<tr>
<td>underground cable</td>
<td>0.1</td>
<td>3 000</td>
</tr>
</tbody>
</table>
Simplifying the equivalent circuit

Figure 25.17
Active and reactive powers of a transmission line.

Figure 25.18
Equivalent circuit of a short LV line.

Figure 25.19
Equivalent circuit of a long HV line.
Example 25-3

\[ X_L = 0.5 \times 50 = 25 \Omega \]
\[ X_C = 300,000/50 = 6k\Omega, \text{ so } 2X_C = 12k\Omega \]
\[ R = 0.065 \times 50 = 3.25\Omega \]

Note \( X_C = 480X_L \) and \( X_L = 7.7R \)
\[ P = 300/3 = 100\text{MW} \]
\[ |E| = 230/\sqrt{3} = 133\text{kV} \]
\[ |I| = 100\text{MW}/133\text{kV} = 750\text{A} \]

Loss \[ |I|^2R = 1.83\text{MW} = 0.0183P \]
\[ Q_L = |I|^2X_L = 14.1\text{Mvar} \]
\[ Q_C = |E|^2/X_C = 3\text{Mvar << Q_L} \]
Voltage regulation

Voltage Regulation = \frac{|E_{2,NL}| - |E_{2,FL}|}{|E_{2,FL}|} \times 100% 

(if ignoring \(X_C\)) \approx \frac{|E_1| - |E_{2,FL}|}{|E_{2,FL}|} \times 100%

- VR is a measure of line voltage drop and usually should not exceed ±5% (or ±10%)
- VR depends on the load power factor:
  - VR is low for a low lagging power factor
  - Perhaps, VR<0 for a leading power factor (i.e. \(|E_1|<|E_2|\)).
  - If ignore \(X_C\), three typical loads with lagging, unity and leading power factors
Resistive line

- There is an upper limit to the power the line can transmit to the load

\[ P = |E_R| \cdot |I| = |I|^2 (kR) = \left| \frac{E_S}{R + kR} \right|^2 kR \]

\[ = \frac{|E_S|^2}{R(1/k + k + 2)} \leq \frac{|E_S|^2}{4R} \]

\[ P = P_{\text{max}} = |E_S|^2/4R \text{ when } k=1, \text{ i.e. } E_R = E_S/2 \]

- If we allow a maximum VR of 5%, i.e. \( E_R = 0.95E_S \), the line can support a load that is only 19% of \( P_{\text{max}} \)

- The total power from the sender is \( P + |I|^2R \)

- VR is a key factor that limits the power transmission capacity

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[Diagram: P-V curve with labels: PF=1, \( R_R = kR \), \( k: \infty \to 0 \), and Figure 25.21: Characteristics of a resistive line.]
Inductive line

\[ P = |I|^2 (kX) = \left| \frac{E_S}{jX + kX} \right|^2 kX \]

\[ = \frac{|E_S|^2}{X |k - 1/k + 2j|} \leq \frac{|E_S|^2}{2X} \]

\[ P_{\text{max}} = |E_S|^2/2X \text{ when } k=1, \ |E_R| = |E_S|/\sqrt{2} = 0.707|E_S| \]

- A inductive line can deliver twice as much power as a resistive line (if \( X=R \))
- If we allow a maximum VR of 5\%, the line can support a load that is 60\% of \( P_{\text{max}} \), i.e. 6x as much as power as a resistive line
- VR is a key factor that limit the power transmission capacity
- The total power from the sender is \( P + j|I|^2X \)

Figure 25.22
Characteristics of an inductive line.
Inductive line connecting two systems

\[
S = E_S I^* = E_S \left( \frac{E_S - E_R}{jX} \right)^* = |E_S| \angle \delta \left( \frac{|E_S| \angle - \delta - |E_R| \angle 0^\circ}{X \angle -90^\circ} \right)
\]

\[
= \frac{|E_S|^2}{X} \angle 90^\circ - \frac{|E_S| \parallel |E_R|}{X} \angle (\delta + 90^\circ)
\]

\[
P = -\frac{|E_S| \parallel |E_R|}{X} \cos(\delta + 90^\circ)
\]

\[
= \frac{|E_S| \parallel |E_R|}{X} \sin \delta \approx \frac{|E_S| \parallel |E_R|}{X} \delta \text{(in rad)}
\]

\[
Q = \frac{|E_S|^2}{X} - \frac{|E_S| \parallel |E_R|}{X} \sin(\delta + 90^\circ) = \frac{|E_S|^2}{X} - \frac{|E_S| \parallel |E_R|}{X} \cos \delta
\]

\[
= \frac{|E_S|}{X} \left( |E_S| - |E_R| \cos \delta \right) \approx \frac{|E_S|}{X} \left( |E_S| - |E_R| \right)
\]

- If \(|E_S| = |E_R| = E\), \(Q \approx 0\), i.e. almost no reactive flow

\[
P = \frac{E^2}{X} \sin \delta \leq \frac{E^2}{X}
\]

Figure 25.30a
Power versus angle characteristic.
Compensated inductive line

- To have $|E_R| = |E_S|$, the line can fully be compensated by adding a shunt capacitor to the receiving end whose $X_C$ is adjustable so that
  
  $$\frac{|E_S|^2}{X_C} = 0.5|I|^2X$$

  while the other $0.5|I|^2X$ is provided by the source or another capacitor with $X_C$ at the sending end.

- Thus, $P_{\text{max}} = |E_S|^2/X$
Increasing the power transmission capacity

To increase $P_{\text{max}} = |E_S|^2/X$, an approach is to reduce line reactance $X$.

- **Use parallel lines:**
  - $X \rightarrow X/2$ or $X/n$, so $P_{\text{max}} \rightarrow 2P_{\text{max}}$ or $nP_{\text{max}}$
  - Improving security against a line trip.

- **Use a series capacitor**
  
  $$P_{\text{max}} = |E_S|^2/(X-X_{CS})$$

  - It may cause sub-synchronous resonance (SSR)

  $$f_{SSR} = f \sqrt{\frac{X_{CS}}{X}} = f \sqrt{\frac{1}{LC_S}}$$

  If $f=60\text{Hz}$, $f_{SSR}=30\text{Hz}$ for 25% compensation ($X_{CS}/X=1/4$)
Voltage Regulation for EHV lines

A 3-phase 735kV 60Hz 600km line, operated at 727kV, has inductive reactance of 0.5 \( \Omega/\text{km} \) and capacitive reactance of 300k\( \Omega/\text{km} \).

- At no-load (open-circuit) conditions, for each phase,
  
  \(|E_S| = 727 / \sqrt{3} = 420\text{kV} , \)
  
  \(X_L = 0.5 \times 600 = 300\Omega, \quad X_C = 300\text{k} / 600 = 500\Omega, \)
  
  \(X_{C1} = X_{C2} = 2X_C = 1000 \Omega \)
  
  \(E_R = E_S \times (-jX_{C2}) / (jX_L - jX_{C2}) \)
  
  \(= 420 \angle 0^\circ \times 1000 / (1000 - 300) = 600 \angle 0^\circ \text{kV} \)

To bring \(|E_R|\) back to \(|E_S|\), add a shunt reactor of \(X_{L2}\) at the receiving end:

- \(X_{L2} = X_{C2}\), then -j\(X_{C2} // jX_{L2} = \infty\)
  
  and \(|E_R| = |E_S|\).

The reactive power generated by \(X_{C2}\) is entirely absorbed by \(X_{L2}\) (cancelling each other)

**Figure 25.35**
EHV transmission line at no-load.

**Figure 25.36**
EHV reactor compensation.
Surge-impedance load (SIL)

- When connected to a gradually increasing load with PF=1, \(|E_R|\) decreases from \(|E_{R,NL}|\) (open-circuit) to 0 (short-circuit). When \(|E_R|=|E_S|\), the amount of load is called the surge-impedance load (SIL) and the corresponding load impedance is called the surge impedance, which has \(Z_Y \approx 400\Omega\) for aerial lines.

\[
\text{SIL} = \frac{E_L^2}{Z_Y} = \frac{E_L^2}{400} \text{ (MW)} \quad E_L: 3\text{-phase line voltage in kV}
\]

\[
\text{SIL} = \frac{727^2}{400} = 1320\text{MW}
\]
Inter-region power exchange: Example 25-8

Calculate (1) the power transmitted by the line and (2) the required phase-shift enabling transmitting 70MW from $E_a$ to $E_b$

1. $P_{ab} = \left(\frac{E^2}{X}\right) \sin(\delta_a - \delta_b) = \left(\frac{100^2}{20}\right) \sin(-11^\circ) = -95.4\text{MW}$  \hspace{1cm} (1)\hspace{1cm} (E_a \leftarrow E_b)$
2. $P_{ab} = 70 = \left(\frac{100^2}{20}\right) \sin(\delta_a - \delta_b)$, so $\delta_a - \delta_b = 8^\circ$, i.e. $8 - (-11) = 19^\circ$ phase-shift of $E_a$

Figure 25.41b
A phase-shift autotransformer can force power to flow in the desired direction (Example 25-8).
Homework Assignment #4

• Read Chapters 11, 12 & 25

• Questions:

• Due date:
  – hand in your solution to Denis at MK 205 or by email (dosipov@vols.utk.edu) before the end of 10/14 (Wed)