Three Phase Travelling Wave Examples

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R₀ := 0.32 ohm/km
R₁ := 0.025 ohm/km
L₀ := 3.2 mH/km
L₁ := 0.91 mH/km
C₀ := 0.008 μF/km
C₁ := 0.0125 μF/km

Zc₀ := \frac{L₀}{\sqrt{C₀}}
Zc₀ = 632.46 \Omega
Zc₁ := \frac{L₁}{\sqrt{C₁}}
Zc₁ = 269.81 \Omega

Applied voltage: Vₘ := 107.8\, kV

Balanced three phase set with close at peak of phase:
V_{abc₀} := \begin{pmatrix} Vₘ \\ \frac{-Vₘ}{2} \\ \frac{-Vₘ}{2} \end{pmatrix}
V_{abc₀} = \begin{pmatrix} 107.8 \\ -53.9 \\ -53.9 \end{pmatrix}\, kV

Clarke Transform:
T_i := \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & \sqrt{2} & 0 \\ 1 & -1 & \sqrt{3} \\ 1 & -1 & \sqrt{3} \end{pmatrix}
T_e := T_i
T_e \cdot T_i^T = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}
\[ V_{\text{modal0}} := T_e^{-1} \cdot V_{\text{abc0}} \]

\[ V_{\text{modal0}} = \begin{pmatrix} 0 \\ 132.03 \\ 0 \end{pmatrix} \text{kV} \]

- Close into open circuit, we expect receiving end voltage to double for each mode, and the convert back to ABC

Voltages when close all three poles

- Note that each individual phase doubles the initial applied voltage
- Suggests only one mode excited, as implied above

Initial modal current

\[ \frac{V_{\text{modal0}_1}}{Z_{c1}} = 489.33 \text{ A} \]

\[ T_e \begin{pmatrix} 0 \\ \frac{V_{\text{modal0}_1}}{Z_{c1}} \\ 0 \end{pmatrix} = \begin{pmatrix} 399.53 \\ -199.77 \\ -199.77 \end{pmatrix} \text{ A} \]
Single phase close to open circuited line:

- **Voltage**

  \[
  V_{\text{modal\_single}0} := T_e^{-1} \begin{pmatrix} 107.8\text{kV} \\ 0\text{kV} \\ 0\text{kV} \end{pmatrix} \quad V_{\text{modal\_single}0} = \begin{pmatrix} 62.24 \\ 88.02 \\ 0 \end{pmatrix} \text{kV}
  \]

  Note the cross-coupling, the first term is a ground mode term.

- Receiving end:

  \[
  V_{\text{recmodal}} := 2 \cdot V_{\text{modal\_single}0}
  \]

  \[
  V_{\text{abc\_rec}} := T_e \cdot V_{\text{recmodal}} \quad V_{\text{abc\_rec}} = \begin{pmatrix} 215.6 \\ 0 \\ 0 \end{pmatrix} \text{kV}
  \]

- Consistent with the results above for the initial transient.
Phases B and C show a zero mode response (same voltage on each).

Note effect of two different propagation times for ground and line mode.
• Current

Close 1 phase, with load 3 phase short....

• Sending end currents:
• Receiving end currents
EMTDC Implementation

- Breaker set for single pole operation (each phase can operate independently)

- Now need three trip inputs, see in circuit diagram below
Need a separate control for each phase of the breaker now

Voltages for 3 pole close, with terminal open
Currents for 3 pole close to open circuited line

Single phase close:

- Voltage (open circuited line)
• Current (open circuited line)

**Close 1 phase, with load 3 phase short.....**

• Sending end voltage (note reflections on sending end)
- Sending end currents:

- Receiving end currents
Trapped Charge and Inrush Current

- When clearing a line, breakers open at natural current zero
- If line is unloaded this is a capacitive current, so clear at voltage peak
- Potential for inrush currents
- Note that emt-programs exaggerate this effect since don't allow for self-discharge
- Mismatch in voltage between source side of breaker and line side of breaker determines:
  1. Inrush current
  2. Magnitude of worst case overvoltage at receiving end of line if that is open
- Won't see same on all three phase with 3 pole closing
Voltages at sending end of the line when energize open circuited line:
- Energize line
- Then clear it
- Then reclose

The transient voltages in the trapped charge are largely due to residual effects of the initial closing transient.

And a receiving end

Note the larger transients for the reclose
Sending end currents (combine the two switches)

Bigger current on reclose due to larger voltage across the characteristic impedance

Repeat with the system in steady-state before open the breakers.

Sending end voltages:
- note that trapped charge changed since voltage at point on wave for breaker clearing has changed
Receiving end voltages

EMTDC implementation:
Sending end voltages with two transients
Some difference from ATP

Receiving end voltages
Sending end currents

Repeat without first energization transient

Sending end voltage
Receiving end voltages
Options to Reduce Inrush

- Controlled breaker pole closing
- Pre-insertion resistor, bypass after a few travel times
- Secondary transient (small) when bypass
- Single phase case: size $R = Z_c$
- No reflection for return waves
  1. Voltage divider - apply 50% of voltage to the input of the line
  2. Reduces voltage and current
- Resistor sized for current loading and dissipation
- How about three phase line:
  1. Ideally size for the first line mode,
  2. Some mismatch if do single pole reclosing
  3. Many utilities just use one standard size resistor, rather than optimize for each line.
  4. Not ideal, but eliminates most of the transient

![Diagram showing options to reduce inrush](image_url)
Initial close with $R = Zc_1$

- No overvoltage at the receiving end
- Sending end voltage increases when after 2 travel times
Sending end current

No longer have repeated reflections, transient lasts 2 travel times.
Bypass the resistor after 1 cycle:
Repeat with $R = Z_{c0}$

Actually reduce voltages further
Reclose with $R=Z_{c0}$
EMTDC implementation (with $R_{pre} = Z_c1$)

Phase sending and receiving end voltage with $R_{pre} = Z_c1$
Sending end currents

![Graph showing sending end currents](image-url)
Repeat with $R_{pre}=Z_c0$
Reclose into trapped charge with $R_{pre}=Z_c0$