ECE 524

TRANSIENTS IN POWER SYSTEMS

SESSION no. 16
Synchronous closing break

\[ V_{\text{cont}} \]

\[ V_{\text{CO}} = 0 \]

Vsyst

\[ V_{\text{CO}} \]

\[ 2V_{\text{in}} \]

Vcont with tapped caps
- V_system probably down when cap is out
- Coolant system since VCO is E5
Timing of command

- Need to know closing time response - approx

- Anticipate voltage zero

\[ t_{closy} + T_{cvo} \]
Impacts of inductance & capacitance

- general for feeder

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[Diagram with labeled points and curves]

1.21

seen from a specific point

Resonance Points

Different for pos & zero sequence

R + jωL (no caps)
Adding inductance in series with capacitor increases Vccp

When capacitor in circuit:

\[ I_c = \frac{\text{current} \cdot V_{ccp}}{JX_L - JX_C} = \left| I_c \right| e^{j90^\circ} \]
\[ V_L = \text{I}_c \cdot X_c \]
\[ = -\left| \text{I}_c \right| X_L \angle 180^\circ \]

\[ V_{cap} = V_{\text{bus}} + \left| \text{I}_c \right| X_L > \text{Min } V_{\text{bus}} \]

\[ \left| V_{\text{cap}} \right| = \frac{V_{\text{bus}}}{\sqrt{n^2 - 1}} \]

\[ n = \sqrt{\frac{X_C}{X_L}} \]
ECE 524:
Reducing Capacitor Switching Transients

Define units: \( MW := 1000 \text{kW} \quad \text{MVA} := \text{MW} \quad \text{MVAr} := \text{MVA} \)
\[ f := 60 \text{Hz} \quad \omega := 2 \pi f \quad \omega = 376.99 \frac{\text{rad}}{\text{s}} \]
\[ t := 0 , 0.000001 \text{sec} . \frac{2}{60} \text{sec} \]

Example 1:

Add inductive reactance to limit the worst case inrush current to 1000A when closing into C1 with C2 open, with an X/R ratio of 10 in the source reactance and an X/R ratio of 12 for the added reactor.

Assume source and capacitors are Y connected.
\[ V_{\text{LL}} := 34.5 \text{kV RMS} \]

Capacitor Banks:
\[ Q_1 := 18 \text{MVAr at 34.5kV} \]
\[ Q_2 := 10 \text{MVAr at 34.5kV} \]
\[ L_1 := 19.2 \mu \text{H between caps} \]

Source \( I_{\text{sc}} := 25 \text{kA} \)
Determine circuit parameters:

Find capacitance using: \[ Q = \left( \frac{|V_{LL}|}{X_c} \right)^2 \]

\[ X_{c1} := \frac{V_{LL}^2}{Q_1}, \quad X_{c1} = 66.13 \, \Omega \]
\[ X_{c2} := \frac{V_{LL}^2}{Q_2}, \quad X_{c2} = 119.03 \, \Omega \]

\[ C_1 := \frac{1}{\omega \cdot X_{c1}}, \quad C_1 = 40.11 \cdot \mu F \]
\[ C_2 := \frac{1}{\omega \cdot X_{c2}}, \quad C_2 = 22.29 \cdot \mu F \]

\[ V_m := V_{LL} \cdot \sqrt{\frac{2}{3}}, \quad V_m = 28.17 \cdot \text{kV} \]
\[ \phi := 0 \text{deg} \]
\[ v_s(t) := V_m \cdot \cos(\omega \cdot t + \phi) \]

Case 1: approximate with resistances ignored.

Find source impedance using: \[ I_{sc} = \frac{V_{in}}{X_s} \]

\[ X_s := \frac{V_{LL}}{\sqrt{3} I_{sc}}, \quad X_s = 0.797 \, \Omega \]
\[ L_s := \frac{X_s}{\omega}, \quad L_s = 2.11 \cdot \text{mH} \]

\[ Z_0(L_{lim}) := \sqrt{\frac{L_s + L_{lim}}{C_1}}, \quad Z_0(0 \text{mH}) = 7.26 \, \Omega \]

\[ \text{Same as earlier example} \]
\[ \omega_n(L_{lim}) := \frac{1}{\sqrt{(I_s + L_{lim})C_1}} \quad f_n(L_{lim}) := \frac{\omega_n(L_{lim})}{2\pi} \quad f_n(0) = 546.61 \text{· Hz} \]

Initial conditions:
- \( V_{c1,0} := 0 \text{V} \) capacitor is discharged
- \( i_{Ls,0} := 0 \text{A} \) no load current

Homogeneous solution:
\[ i_{h,1}(t, L_{lim}) := \left( \frac{V_m - V_{c1,0}}{Z_0(L_{lim})} \right) \sin(\omega_n(L_{lim})t) \]

If we ignore the 60Hz current we can solve for \( L_{lim} \)

\[ \left( \frac{V_m - V_{c1,0}}{Z_0(L_{lim})} \right) = 1000 \text{A} \quad \text{or} \quad Z_0(L_{lim}) = \left( \frac{V_m - V_{c1,0}}{1000 \text{A}} \right) \]

Substitute:
\[ Z_0(L_{lim}) := \sqrt{\frac{I_s + L_{lim}}{C_1}} \]

\[ L_{Lim1} := C_1 \left( \frac{V_m - V_{c1,0}}{1000 \text{A}} \right)^2 - L_s \quad L_{Lim1} = 29.72 \text{· mH} \]

Now find the resulting natural frequency
\[ f_n(L_{Lim1}) = 140.85 \text{· Hz} \]
One quarter cycle at that frequency takes:

\[ t_{\text{topeak}} := \frac{1}{4 f_n(L_{\text{lim1}})} \quad t_{\text{topeak}} = 1.77 \cdot \text{ms} \]

\[ t_{\text{topeak}} \cdot 60 \text{Hz} \cdot 360 \text{deg} = 38.34 \cdot \text{deg} \]

So we probably can't neglect the particular solution, let's check

\[ R_s := 10^{-10} \text{ohm} \]

\[ \eta(L_{\text{lim1}}) := \text{atan} \left( \frac{\omega (L_s + L_{\text{lim}}) - \frac{1}{\omega C_1}}{R_s} \right) \quad \eta(L_{\text{lim1}}) = -90 \cdot \text{deg} \]

\[ i_{p-1}(t, L_{\text{lim1}}) := \left[ \frac{\sqrt{2} V_{\text{LL}}}{\frac{1}{\omega C_1} - \omega (L_s + L_{\text{lim}})} \right] \cdot \cos(\omega t + \phi - \eta(L_{\text{lim1}})) \]

\[ i_{p-1}(t_{\text{topeak}}, L_{\text{lim1}}) = -322.85 \text{ A} \]

So, the actual first positive peak current is:

\[ i_{h-1}(t_{\text{topeak}}, L_{\text{lim1}}) + i_{p-1}(t_{\text{topeak}}, L_{\text{lim1}}) = 677.15 \text{ A} \]
But now look at first negative peak at the natural frequency.

\[ t_{\text{tongepeak}} := \frac{3}{4f_n(L_{\text{lim1}})} \quad t_{\text{tongepeak}} = 5.32 \text{·ms} \]

\[ i_{h-1}(t_{\text{tongepeak}}, L_{\text{lim1}}) + i_{p-1}(t_{\text{tongepeak}}, L_{\text{lim1}}) = -1471.61 \text{A} \quad \text{bigger than 1000A, need larger } L_{\text{lim}} \]

Now try a simultaneous solution, note that the time to the peak value varies, and is not necessarily at 1/4 cycle of the natural frequency.

\[ L_{\text{lim}} := 30\text{mH} \]

Given

\[ i_{h-1}\left(\frac{3}{4\cdot f_n(L_{\text{lim}})}, L_{\text{lim}}\right) + i_{p-1}\left(\frac{3}{4\cdot f_n(L_{\text{lim}})}, L_{\text{lim}}\right) = 1000\text{A} \]

\[ L_{\text{Lim2}} := \text{Find}(L_{\text{lim}}) \quad L_{\text{Lim2}} = 131.72\text{·mH} \]

\[ L_{\text{Lim2}} := 56.293\text{mH} \]

- Check the results:

\[ f_n(L_{\text{Lim2}}) = 103.98\text{·Hz} \]
\[ f_d(L_{\text{lim}}) := \frac{\omega_d(L_{\text{lim}})}{2 \cdot \pi} \]

\[ f_d(0) = 547.96 \cdot \text{Hz} \]

Particular solution:
\[ \eta(L_{\text{lim}}) := \text{atan} \left[ \frac{\omega \cdot (L_s + L_{\text{lim}}) - \frac{1}{\omega \cdot C_1}}{R_s + \frac{\omega \cdot L_{\text{lim}}}{12}} \right] \]

\[ \eta(0) = -89.93 \cdot \text{deg} \]

\[ i_{L_p}(t, L_{\text{lim}}) := \left[ \frac{\sqrt{\frac{2}{3}} \cdot V_{LL}}{\sqrt{\left( R_s + \frac{\omega \cdot L_{\text{lim}}}{12} \right)^2 + \left[ \frac{1}{\omega \cdot C_1} - \omega \cdot (L_s + L_{\text{lim}}) \right]^2}} \right] \cdot \cos(\omega \cdot t + \phi - \eta(L_{\text{lim}})) \]

Boundary conditions:
\[ i_L(0) = 0 \quad \text{Switch was open.} \]

\[ 0 = e^0 \cdot (k_1 \cdot 1 + k_2 \cdot 0) \quad \text{Therefore \quad } k_1 := 0 \]

\[ v_L(0) = V_m - 0 = L \cdot \frac{d}{dt} i_{L_p} \]
\[ V_m = (L_s + L_{lim}) \cdot k_2 \cdot e^{\alpha \cdot 0 \cdot (\alpha \cdot \sin(\omega_d \cdot 0) + \omega_d \cdot \cos(\omega_d \cdot 0))} \]

\[ k_2(L_{lim}) := \frac{V_m}{(L_s + L_{lim}) \cdot 1 \cdot \omega_d(L_{lim}) \cdot 1} \quad k_2(0) = 3890.61 \text{ A} \]

\[ i_{L_{-h}}(t,L_{lim}) := k_2(L_{lim}) \cdot e^{\alpha(L_{lim}) \cdot t} \cdot (\sin(\omega_d(L_{lim}) \cdot t)) \]

\[ i_L(t,L_{lim}) := i_{L_{-h}}(t,L_{lim}) + i_{L_{-p}}(t,L_{lim}) \]

\[ L_{lim} := 15 \text{ mH} \]

Given

\[ i_L \left( \frac{3}{4 \cdot f_d(L_{lim})}, L_{lim} \right) = 1000 \text{ A} \quad L_{Lim3} := \text{Find}(L_{lim}) \quad L_{Lim3} = 138.62 \cdot \text{mH} \]

- Check the results:

\[ f_d(L_{Lim3}) = 107.11 \cdot \text{Hz} \]

\[ L_{Lim3} := 52.9085 \text{ mH} \]

One quarter cycle at that frequency takes:

\[ t_{topeak} := \frac{3}{4 f_d(L_{Lim3})} \quad t_{topeak} = 7 \cdot \text{ms} \]
**Switch in capacitor 2 through a resistance:**

Eliminate the source resistance again. Suppose the bank 2 is energized through a resistor with bank 1 already in the system. Determine the resistance needed to limit the peak line to ground voltage on either bank to 33.5kV.

\[
C_{eq} := \frac{C_1 \cdot C_2}{C_1 + C_2} \quad C_{eq} = 14.33 \, \mu F
\]

**Simulation Results**

With \( R = 25.01 \) ohm, switching at \( t = 15.61 \) ms. Results identical with \( L_1 \) ignored.