ECE 529

UTILITY APPLICATIONS OF POWER ELECTRONICS

SESSION no. 37
Harmonic Cancellation:

- Three phase square wave: Y-Y transformer (or Δ-Δ)

Array indices: \( i := 0,1,2 \ldots 2000 \)

Time vector: \( t_i := 0.001 \cdot i \)

- Sinusoidal harmonic terms for first 15 harmonics of a square wave (magnitude will be added later):

\[
\begin{align*}
    f_{11} &:= \sin(2 \cdot \pi \cdot t) \\
    f_{31} &:= \sin(2 \cdot \pi \cdot 3 \cdot t) \\
    f_{51} &:= \sin(2 \cdot \pi \cdot 5 \cdot t) \\
    f_{71} &:= \sin(2 \cdot \pi \cdot 7 \cdot t) \\
    f_{91} &:= \sin(2 \cdot \pi \cdot 9 \cdot t) \\
    f_{111} &:= \sin(2 \cdot \pi \cdot 11 \cdot t) \\
    f_{131} &:= \sin(2 \cdot \pi \cdot 13 \cdot t) \\
    f_{151} &:= \sin(2 \cdot \pi \cdot 15 \cdot t)
\end{align*}
\]

- Harmonic amplitudes (assume three phase, thyristor rectifier with stiff dc current source, 3rd harmonic removed). Note the negative signs and 0's:

\[
\begin{align*}
    a_1 &:= 1 \\
    a_3 &:= 0 \\
    a_5 &:= \frac{1}{5} \\
    a_7 &:= \frac{1}{7} \\
    a_9 &:= 0 \\
    a_{11} &:= \frac{1}{11} \\
    a_{13} &:= \frac{1}{13} \\
    a_{15} &:= 0
\end{align*}
\]

- Harmonic current equation:

\[
f_Y := a_1 \cdot f_{11} + a_3 \cdot f_{31} + a_5 \cdot f_{51} + a_7 \cdot f_{71} + a_9 \cdot f_{91} + a_{11} \cdot f_{111} + a_{13} \cdot f_{131} + a_{15} \cdot f_{151}
\]
• Plot phase current on one phase:

![Graph](image)

• Three phase square wave: Y-Δ ---Δ is LV side

\[ i := 0, 1 \ldots 2000 \quad \phi := -30\text{deg} \]

\[ t_i := 0.001 \cdot i \]

• Sinusoidal harmonic terms for first 15 harmonics (magnitude will be added later), includes angle offset due to transformer phase shift, not multiplied by harmonic order:

\[ f_{12} := \sin(2 \cdot \pi \cdot t - \phi) \quad f_{32} := \sin(2 \cdot \pi \cdot 3 \cdot t - 3\phi) \]

\[ f_{52} := \sin(2 \cdot \pi \cdot 5 \cdot t - 5\phi) \quad f_{72} := \sin(2 \cdot \pi \cdot 7 \cdot t - 7\phi) \]
f_{92} := \sin(2 \cdot \pi \cdot 9 \cdot t - 9\phi) \quad f_{112} := \sin(2 \cdot \pi \cdot 11 \cdot t - 11\phi)

f_{132} := \sin(2 \cdot \pi \cdot 13 \cdot t - 13\phi) \quad f_{152} := \sin(2 \cdot \pi \cdot 15 \cdot t - 15\phi)

- Harmonic amplitudes (assume three phase, thyristor rectifier with stiff dc current source). Note the negative signs and 0's. Same as for Y-Y

a_1 := 1 \quad a_3 := 0 \quad a_5 := \frac{-1}{5} \quad a_7 := \frac{-1}{7} \quad a_9 := 0 \quad a_{11} := \frac{1}{11} \quad a_{13} := \frac{1}{13} \quad a_{15} := 0

- Harmonic current equation:

f_D := a_1 \cdot f_{12} + a_3 \cdot f_{32} + a_5 \cdot f_{52} + a_7 \cdot f_{72} + a_9 \cdot f_{92} + a_{11} \cdot f_{112} + a_{13} \cdot f_{132} + a_{15} \cdot f_{152}

"LV side"

< converter side
\[ f_{12HV} := \sin(2 \cdot \pi \cdot t - \phi + \phi) \quad f_{32HV} := \sin(2 \cdot \pi \cdot 3 \cdot t - 3\phi) \]

\[ f_{52HV} := \sin(2 \cdot \pi \cdot 5 \cdot t - 5\phi - \phi) \quad f_{72HV} := \sin(2 \cdot \pi \cdot 7 \cdot t - 7\phi + \phi) \]

\[ f_{92HV} := \sin(2 \cdot \pi \cdot 9 \cdot t - 9\phi) \quad f_{112HV} := \sin(2 \cdot \pi \cdot 11 \cdot t - 11\phi - \phi) \]

\[ f_{132HV} := \sin(2 \cdot \pi \cdot 13 \cdot t - 13\phi + \phi) \quad c \cdot f_{152HV} := \sin(2 \cdot \pi \cdot 15 \cdot t - 15\phi) \]

- Amplitudes again, really don't need to be repeated, assume effective 1:1 transformation ratio

\[ a_1 := 1 \quad a_3 := 0 \quad a_5 := -\frac{1}{5} \quad a_7 := -\frac{1}{7} \quad a_9 := 0 \quad a_{11} := \frac{1}{11} \quad a_{13} := \frac{1}{13} \quad a_{15} := 0 \]

- High voltage side current equation:

\[ f_{DHV} := a_1 \cdot f_{12HV} + a_3 \cdot f_{32HV} + a_5 \cdot f_{52HV} + a_7 \cdot f_{72HV} + a_9 \cdot f_{92HV} + a_{11} \cdot f_{112HV} + a_{13} \cdot f_{132HV} + a_{15} \cdot f_{152HV} \]
• Now compare....

[Graph with two lines labeled \( f_Y \) and \( f_D \)]

• Now refer to HV Side for the Y-Y and the Y-\( \Delta \) (no phase shift for Y-Y). Note the following for the Y-\( \Delta \) case:

  1. The 1, 7, 13 are positive sequence rotations so add 30 degrees (\( \phi \))
  2. The 5, 11, etc are negative sequence rotations so subtract 30 degrees (\( \phi \))
  3. The 3, 9, 15 are zero sequence terms to no phase shift. Since amplitude is 0, it really doesn't matter

• No phase shift for Y-Y (1:1 transformation ratio): \( f_{YHV} := f_Y \)
Plot comparing current on Y and Δ sides of the transformer:
- Sum of the HV side currents (looks similar, but look at individual harmonics below):
- Add fundamental components on HV side:

\[ a_1(f_{11} + f_{12HV}) \]
• Now add the 5th and 7th harmonic terms on HV side. Note the cancellation. We largely see rounding errors—note the vertical scale):

\[ a_5(f_{51}+f_{52HV}) \]
\[ a_7(f_{71}+f_{72HV}) \]
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\[ MW := 1000 \text{kW} \quad MVA := MW \quad MVAR := MW \quad pu := 1 \]

**Problem 1:** For the system below we want to increase the power transfer from Bus 1 to Bus 2 by adding a SVC at the midpoint.

A. Calculate the power transfer from bus 1 to bus 2 if the SVC is disconnected.

B. Suppose the SVC is connected through a 18:1 transformer with a leakage reactance of .005 \( \Omega \) on low voltage side, determine the MVAR requirements for the SVC to do the following:

1. Increase P12=650MW with the TCR is not gated.
2. How much capacitance and inductance is needed to increase P12 to 633MW with the TCR operating with \( \sigma = 75 \text{ deg.} \) Assume delta connection of the TCR and capacitors.
3. Modify your solution for a 12 pulse SVC (one TCR in \( \Delta \) and the other in \( Y \))

C. Implement your solution for the 12 pulse SVC in ATP.

![Diagram of power system with SVC](image-url)
A. Calculate the power transfer from bus 1 to bus 2 if the SVC is disconnected.

Sending and Receiving End Voltages

\[ V_{1L} := 345kV \quad V_{1p} := \frac{V_{1L}}{\sqrt{3}} \quad V_{1p} = 199.186kV \]

\[ V_{2L} := 345kV \quad V_{2p} := \frac{V_{2L}}{\sqrt{3}} \quad V_{2p} = 199.186kV \]

Sending and Receiving End Angles

\[ \theta_1 := 0\text{deg} \quad \theta_2 := -17.605\text{deg} \]

Line Reactance \( X_{\text{line}} := 60 \text{ohm} \)

\[ P_{12} := \frac{|V_{1L}| \cdot |V_{2L}| \cdot \sin(\theta_1 - \theta_2)}{X_{\text{line}}} \quad P_{12} = 599.991 \text{MW} \]

B. Suppose the SVC is connected through a 18:1 transformer with a leakage reactance of .005 \( \Omega \) on low voltage side, determine the MVAR requirements for the SVC to do the following:

1) Increase \( P_{12} = 650 \text{MW} \) with the TCR is not gated.

\[ X_{\text{half}} := \frac{X_{\text{line}}}{2} \quad X_{\text{half}} = 30 \text{ohm} \]

- Lossless line, so the following relationships holds:

\[ P_{12\text{max}} := 650 \text{MW} \]
\[ P_{1m} := P_{12\text{max}} \quad P_{m2} := P_{12\text{max}} \]
\[ \theta_m := \frac{\theta_2 - \theta_1}{2} \quad \theta_m = -8.803 \text{ deg} \]

- Assuming that the angles at the ends of the line do not change with change in \( P_{12} \), start from:

\[ P_{1m} = \frac{|V_{1L}| \cdot |V_{mL}| \cdot \sin(\theta_1 - \theta_m)}{X_{\text{half}}} = \frac{3 |V_{1p}| \cdot |V_{mp}| \cdot \sin(\theta_1 - \theta_m)}{X_{\text{half}}} \]

- Then

\[ V_{mp} := \frac{P_{1m} \cdot X_{\text{half}}}{3 \cdot |V_{1p}| \cdot \sin(\theta_1 - \theta_m)} \quad V_{mp} = 213.246 \text{ kV} \]

\[ V_{mL} := \sqrt{3} \cdot V_{mp} \quad V_{mL} = 369.353 \text{ kV} \]

\[ \text{OverVolt} := \frac{V_{mL}}{V_{1L}} \quad \text{OverVolt} = 107.059\% \]

\[ Q_{m1} := \frac{V_{mL}^2}{X_{\text{half}}} - \left( \frac{V_{mL} \cdot V_{1L} \cdot \cos(\theta_m - \theta_1)}{X_{\text{half}}} \right) \quad Q_{m1} = 349.861 \text{ MVAR} \]

\[ Q_{m2} := \frac{V_{mL}^2}{X_{\text{half}}} - \left( \frac{V_{mL} \cdot V_{2L} \cdot \cos(\theta_m - \theta_2)}{X_{\text{half}}} \right) \quad Q_{m2} = 349.861 \text{ MVAR} \]

\[ Q_{\text{compensator max}} := Q_{m1} + Q_{m2} \]
Q_{compensator\_max} = 699.721 \text{ MVAR} \quad \text{This is the net capacitive injection to increase P12 to 650MW.}

- On the secondary of the transformer (18:1)
  \[ V_{sec\_max} := \frac{V_{mL}}{18} \quad V_{sec\_max} = 20.52 \text{ kV} \quad \text{line to line} \]

  \[ X_{xfmr\_low} := 0.005 \text{ ohm} \quad X_{xfmr\_low} \]

  \[ \frac{X_{xfmr\_low}}{2\pi \cdot 60 \text{Hz}} = 0.0133 \text{ mH} \]

- Since the TCR is not gated, this leaves capacitor only. Assume it is connected in Delta, so mult by 3
- The capacitive will also need to supply some reactive power to transformer leakage

\[ Q_{comp} = \frac{3 \cdot V_{mL}^2}{X_{eff}} = \frac{3 \cdot V_{mL}^2}{X_{xfmr\_low} - X_c} \]

- Solving for effective compensating reactance:

\[ X_{eff} := 3 \cdot \frac{V_{sec\_max}^2}{Q_{compensator\_max}} \quad X_{eff} = 1.805 \Omega \]

\[ X_{c1} := X_{eff} + X_{xfmr\_low} \quad X_{c1} = 1.81 \Omega \]

\[ C_{comp} := \frac{1}{2 \cdot \pi \cdot 60 \text{Hz} \cdot X_{c1}} \quad C_{comp} = 1465.3203 \mu\text{F} \]

- If we split the capacitance into two banks (one associated with each 6 pulse bridge). Capacitors in parallel add, so we divide by two.
\[
\frac{C_{\text{comp}}}{2} = 732.66 \, \mu \text{F}
\]

Now calculate how much inductance is needed for \( P_{12} = 633 \text{MW} \)

\[
P_{1m} := P_{12} \quad P_{m2} := P_{12}
\]

\[
\theta_m := \frac{\theta_2 - \theta_1}{2}
\]

Assuming that the angles at the ends of the line to not change with change in \( P_{12} \)

\[
V_{mp} := \frac{P_{1m} \cdot X_{\text{half}}}{3 \cdot V_1 \cdot \sin(\theta_1 - \theta_m)}
\]

\[
V_{mp} = 207.669 \, \text{kV}
\]

\[
V_{mL} := \sqrt{3} \cdot V_{mp} \quad V_{mL} = 359.693 \, \text{kV}
\]

\[
\text{OverVolt} := \frac{V_{mL}}{V_{1L}} \quad \text{OverVolt} = 104.259\% 
\]

\[
Q_{m1} := \frac{V_{mL}^2}{X_{\text{half}}} - \left( \frac{V_{mL} \cdot V_{1L} \cdot \cos(\theta_m - \theta_1)}{X_{\text{half}}} \right) 
\]

\[
Q_{m2} := \frac{V_{mL}^2}{X_{\text{half}}} - \left( \frac{V_{mL} \cdot V_{2L} \cdot \cos(\theta_m - \theta_2)}{X_{\text{half}}} \right) 
\]

\[
Q_{\text{compensator}} := Q_{m1} + Q_{m2}
\]

\[
Q_{m1} = 224.889 \, \text{MVAR} 
\]

\[
Q_{m2} = 224.889 \, \text{MVAR}
\]
Q_{\text{compensator}} = 449.778 \text{MVAR} \quad \text{This is the net capacitive contribution.}

On the secondary of the transformer (18:1)

\[ V_{\text{sec}} := \frac{V_{\text{mL}}}{18} \quad V_{\text{sec}} = 19.983 \text{kV} \]

\[ X_{\text{eff33}} := 3 \cdot \frac{V_{\text{sec}}^2}{Q_{\text{compensator}}} \quad X_{\text{eff33}} = 2.663 \Omega \quad \text{Multiply by 3 for delta} \]

Subtract off transformer, leaving parallel LC

\[ X_{\text{SVC}} := X_{\text{eff33}} + X_{\text{xfmr\_low}} \quad X_{\text{SVC}} = 2.668 \Omega \]

Now solve for X_{\text{tcr}} from: \[ -jX_{\text{SVC}} = jX_{\text{tcr}} \cdot \frac{\sqrt{3}X_{\text{tcr}}}{(jX_{\text{tcr}} - jX_{\text{c}})} \]

\[ X_{\text{tcr\_\sigma}} := 1000 \text{ohm} \]

Given

\[ -j \cdot X_{\text{SVC}} \cdot \frac{jX_{\text{tcr\_\sigma}}(-jX_{\text{c1}})}{jX_{\text{tcr\_\sigma}} - jX_{\text{c1}}} = 0 \]

\[ X_{\text{tcr\_\sigma}} := \text{Find}(X_{\text{tcr\_\sigma}}) \quad X_{\text{tcr\_\sigma}} = 5.629 \Omega \]

This is X_{\text{tcr}} for \( \sigma = 75 \text{ deg} \), now find actual value of XL and then L

\[ \sigma_{633} := 75 \text{deg} \]

\[ X_{\text{L}} := X_{\text{tcr\_\sigma}} \cdot \frac{\sigma_{633} - \sin(\sigma_{633})}{\pi} \]
Power Circuit
1. Synchronization and firing circuit (shown above) is similar to that used in homework 2.
2. The delta connected TCR gets synchronization reference from the line to line voltage across each phase leg of the TCR.
3. The wye connected TCR gets synchronization reference from the line to ground voltage on each phase.
4. Initially operate with \( \alpha = 90 \) degrees (\( \sigma = 0 \)), and then move to calculated \( \alpha \) of 52.5 degrees at \( t = 100 \) ms.

**Simulation Results**

The simulations start out with \( \alpha = 90 \) deg (this corresponds to \( \sigma = 0 \) deg so the TCR’s don’t conduct) and then there is a step change to \( \alpha = 52.5 \) deg (corresponds to \( \sigma = 75 \) deg). This covers the two operating conditions used for performing the calculations.

- Firing angle \( \alpha \)
- Single phase TCR currents (one phase on each TCR)

- The current starts out at zero while $\alpha=90^\circ$ ($\alpha=0^\circ$)

- Single phase TCR currents (one phase on each TCR) after $\alpha=52.5$ deg

Note:
1. The phase shift between the currents due to the wye and delta connected TCRs
2. The magnitude difference (this difference is $\sqrt{3}$) again due to the difference between the wye and delta connections.

- Line current between the two 6 pulse SVC's and the transformer winding (includes the capacitor current) for each SVC
  1. First both currents over the entire simulation period.
2. During the initial part of the simulation the TCR is not gated and the capacitor currents dominate.
3. Note that the currents are identical when the TCR's are not conducting.

- Line current Drawn by delta connected TCR + capacitors
- Line current Drawn by wye connected TCR + capacitors
- Harmonic currents from delta SVC
- Harmonic currents from SVC with wye connected TCR
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<th>Phase</th>
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THD = 16.505%

- Note that the wye connected TCR has significant triplen harmonic
  1. This is why the transformer winding connected to it is wye (to complete the circuit path
  2. The primary winding is delta to keep these off the power system

- Phase relationship between the currents drawn by the TCR's plus capacitors (note the fundamental components are in phase)
- For comparison, here is the same waveforms without the capacitors in the circuit

- The two waveforms have nearly the same fundamental component magnitudes and angles.
- Current on this line side of the transformer:
  
  Note the transient when the thyristors start firing.

2. This shows much better damping if there is more resistance in the circuit (for example in the capacitors or the line inductances)

3. This also improves if the firing angle changes in a ramp instead of a step

- Harmonic content (after TCR's gated):

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<th>Phase</th>
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THD=0.20337%
Problem 2: Design 5th and 7th harmonic filters for a 132 kV system such that they supply 30MVAR capacitive (at 60Hz). Assume the inductors have an X/R ratio of 20, the capacitors have no resistance. Specify L to the nearest 0.1 mH and C to the nearest 0.1 μFarad. Connect capacitors in Delta.

If the filters are connected in parallel with a harmonic current source (load) and the impedance looking into the power system is $Z = 1 + j12 \, \Omega$ (at 60Hz) what percentage of the harmonic current goes into the filter and what percentage goes to the power system?

Test your filters in ATP. Rather than modeling a full SVC, just implement harmonic current sources at the appropriate frequencies (implement one at a time).

\[
\begin{align*}
V_{LL} &= 132\, kV \\
\omega_{60} &= 2\cdot\pi\cdot60\, Hz \\
V_{LL} \cdot \sqrt{\frac{2}{3}} &= 107.778\, kV \\
Q_{cap} &= 30\, MVAR \\
R_{system} &= 1\, ohm
\end{align*}
\]
\( X_{\text{system}} := 12 \text{ohm} \)  
\( L_{\text{system}} := \frac{X_{\text{system}}}{2 \cdot \pi \cdot 60 \text{Hz}} \)  
\( L_{\text{system}} = 31.831 \text{mH} \)  
\( f_5 := 5.60 \text{Hz} \quad f_5 = 300 \frac{1}{s} \)  
\( f_7 := 7.60 \text{Hz} \quad f_7 = 420 \frac{1}{s} \)

**Fifth Harmonic Filter**

- Neglect resistance since the X/R ratio is high
- Use \( X_c \) and \( C \) for Wye connected and then convert to delta later

\[
Q_{\text{cap}} = \frac{(-VLL)^2}{XL - XC_{\text{wye}}} = \frac{(-VLL)^2}{\omega 60 \cdot L_5 - \frac{1}{\omega 60 \cdot C_{5 \text{wye}}}}
\]

\[
f_5 = \frac{1}{2 \cdot \pi \cdot \sqrt{L_5 \cdot C_{5 \text{wye}}}}
\]

\[
L_5 = \frac{1}{C_{5 \text{wye}} \cdot (2 \cdot \pi \cdot f_5)^2}
\]

substitute into the \( Q_{\text{cap}} \) equation

\[
Q_{\text{cap}} = \frac{-VLL^2}{\omega 60 \cdot \frac{1}{C_{5 \text{wye}} \cdot (2 \cdot \pi \cdot f_5)^2} - \frac{1}{\omega 60 \cdot C_{5 \text{wye}}}}
\]

\[
-Q_{\text{cap}} = \frac{VLL^2 \left( \omega 60 \cdot C_{5 \text{wye}} \cdot (2 \cdot \pi \cdot f_5)^2 \right)}{\omega 60^2 - (2 \cdot \pi \cdot f_5)^2}
\]
Express this in terms of the capacitance:

\[ C_{\text{swye}} = \frac{-Q_{\text{cap}}}{V_{\text{LL}}^2} \left[ \omega_0^2 - (2\pi f_5)^2 \right] \]

\[ C_{\delta_\text{swye}} = \frac{C_{\text{swye}}}{3} \]

Convert delta by dividing \( C_{\text{swye}} \) by 3 (this is the same as \( 3 \times C_{\text{swye}} = X_{\text{Cdelta}} \)):

\[ C_{\delta_\text{delta}} = \frac{C_{\text{swye}}}{(2\pi f_5)^2} \]

\[ L_5 = \frac{1}{C_{\text{swye}}(2\pi f_5)^2} \]

\[ L_{\text{set}} = 64.2 \text{ mH} \]

Now express \( L \) and \( C \) within specified tolerances.

\[ L_{\text{set}} = 64.2 \text{ mH} \]

\[ C_{\delta_{\text{delta}} \text{ set}} = 1.5 \text{ mF} \]

\[ f_{5,0} = \frac{1}{2\pi \sqrt{L_{\text{set}} \times 3C_{\delta_{\text{delta}} \text{ set}}}} \]

\[ f_{5,0} = 296.105 \text{ Hz} \]

Effectively detuned to slightly below 300 Hz.

\[ R_{L5} = \frac{1.21 \Omega}{20} \]

\[ R_{L5} = 0.0605 \text{ ohms} \]